Introduction to Alan G. Young, The Fourth ISSMGE McClelland Lecturer

Alan G. Young was born in Pittsburg, Texas in 1946. He received his B.S. in Civil Engineering from Texas A&M University in 1970, MSc in Civil Engineering from the University of Texas at Austin in 1971, and graduated from the Executive Management Program at Harvard Business School in 1991. He spent his entire professional career based out of Houston, Texas.

Inspired by the reading of Mr. Bram McClelland's papers, he joined McClelland Engineers Inc. in 1971 as a project engineer. His first job was to work with Prof. Lymon Reese on the Ekofisk Gravity Base Foundation in the North Sea, performing finite element analyses and conducting cyclic triaxial testing to evaluate the liquefaction potential of the sands strata during storm loading.

Alan rose to the positions of Vice President in 1984, President of Fugro-McClelland Marine Geosciences in 1987, and President of Fugro International Inc. in 1992. Throughout his tenure with McClelland Engineers, he was a close associate of Mr. Bram McClelland and he helped establish the company as a worldwide leader in offshore geotechnics. In 1997 he co-founded and became Vice President of Geoscience Earth & Marine Services, Inc. (GEMS), a company established in Houston, TX.

For over 45 years Alan has been a major contributor to the advancement of offshore geotechnical engineering. His contributions have been worldwide, encompassing a wide range of technical, operational and business applications. He was a leading member of the team that developed the Remote Vane and performed the first offshore testing with the tool in 1972 at the Shell and Arco structure sites that failed in the South Pass area Gulf of Mexico (GoM) due to a mudslide.

Early in his career, he managed the Thistle field site investigation, performed foundation analyses for the first drilled and grouted piles used to support a fixed offshore platform in the North Sea, and led the integrated foundation studies for the Conoco Joliet Platform – the first TLP installed in the GoM.

Alan also managed the site investigation and foundation studies for Exxon and Chevron for the first deepwater structures installed offshore California and helped establish the practice and methods for conducting site investigation for offshore jack-up rigs and the procedures for analysing their foundation stability.

His contributions in the field of geotechnical site investigation have been substantial. In addition to the Remote Vane, he developed and patented the concept of the offshore mini-Cone Penetration Test (CPT), managed the development of the Dolphin downhole CPT and sampling system, established the method of push sampling with a standard rotary drilling rig without motion compensation equipment, and, most importantly, implemented the use of these key technology advancements in standard offshore site investigations.

Alan also conceived and patented the concept of the DeepSea CPT and promoted its development with a Joint Industry Program (JIP). He also helped develop and patent a method for using seismic amplitudes for extrapolating strength and other soil properties. As the industry moved into ever increasing water depths he saw the potential of the Jumbo Piston Core sampler, a tool until then confined to usage by Academia. He pioneered its implementation for deepwater site investigations through an industry JIP. He helped develop the concept of the CPT Stinger which is now increasingly used in projects in the GoM and offshore West Africa. His innovative talents were critical in developing and patenting the concept of the Spear Anchor (Omni-Max Anchor) by performing testing and analytical studies that led to its use in the GoM.

Not content with revolutionising offshore sampling and in-situ testing practices, Alan has always been driven to optimize the benefit of these data by understanding how they could be used and applied over large seafloor areas. So he became a pioneer in integrated geoscience studies, a now ubiquitous activity in deepwater field developments, where a team of specialists in such areas as geology, environmental science, geophysics, geochemistry, oceanography, and geotechnics coordinate their efforts to yield a single, comprehensive study of the past, current, and future ground conditions at a site of interest.

He has been instrumental in implementing and leading integrated studies for numerous deepwater projects including Mad Dog, Atlantis, Mad Dog 2, Thunder Horse, Shenzhi, Blind Faith, Neptune, Puma, Tahiti, Stones, Kaskida, Who Dat, Great White, Tubular Bells, Delta House, Joliet, Thunder Hawk, Cascade, and Heidelberg.

Alan's areas of expertise include: 1) offshore geotechnical analyses and geohazard assessment, 2) marine foundation analyses of seafloor and subsurface installations and mobile jack-up rigs, 3) specialized laboratory testing and strength interpretation for different sampling and in situ testing methods, and 4) planning and managing marine operations involving geophysical and geotechnical investigations.

His work has resulted in more than 50 journal and conference publications with two of his papers receiving the Offshore Technology Conference (OTC) Best Paper award and three others receiving the ASCE/OTC Hall of Fame Award. In addition he has been the author and coauthor on two books and most recently contributed two chapters in Deepwater Foundations and Pipeline Geomechanics.

Alan has served the industry through his memberships in many committees. In particular, he joined the American Petroleum Institute (API) committee on offshore geotechnics and foundation in 1978 and remained a member for 39 years, the longest tenure on record, during which he made great contributions to the Foundation Section of the API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms.

Alan also served as member of the Society of Underwater Technology OSIG Committee, the Oceanographic Department Steering Committee at Texas A & M University, the Marine Board of the National Research Council - Executive Committee and as Lecturer for the University of Texas at Austin Short Courses on Design of Fixed Platforms and Design of Floating Production Systems.

He has delivered many invited lectures and chaired numerous sessions at industry conferences. In 2012 he received the Distinguished Graduate award from Texas A&M's Zachry Department of Civil Engineering.

Alan tirelessly seeks to recognize his colleagues in the industry. He has chaired the ASCE OTC Hall of Fame Awards Committee for nine years and spends an enormous amount of time and energy to select key historical OTC publications so that their authors are honoured at a special ceremony.

Alan has also been an extraordinary mentor for generations of geotechnical engineers. It is remarkable that, over the years, roughly 200 engineers have been hired or mentored by Alan, who always looked out to give the best and brightest engineers their first chance in the industry, all the while keeping a keen eye for diversity and inclusion.

In October 2015, the United States Board on Geographic Names approved the naming of an underwater feature in the Gulf of Mexico as "Young Knoll" to honor Alan's *Major Contributions Advancing Geological and Geotechnical Engineering Knowledge of the Seafloor in the Gulf of Mexico.* Young Knoll (Lat: 26° 08' 00" N, Long: 093° 01' 00" W) is fittingly located along the Sigsbee escarpment, which has been the focus of several of Alan's studies, in 2,000m of waters in Block KC810 of the Keathley Canyon area. It is truly a special recognition and the first time that a geotechnical engineer is honored in such a way.

Alan and his beloved wife of 46 years, Melinda Marie, live in Sugar Land, TX. Melinda is a retired kindergarten teacher, and they have three sons: Russell, Matthew, and Samuel and four grandchildren.

Over more than twenty years, I have had the privilege and honor to work with Alan on many challenging deepwater projects. It is therefore with great pride and pleasure that I, on behalf of the International Society of Soil Mechanics and Geotechnical Engineering and its Technical Committee 209 on Offshore Geotechnics, hereby present him with the Fourth ISSMGE McClelland Lecture award.

Philippe Jeanjean, Ph. D., P.E., M. ASCE
Chairman, ISSMGE TC209, Offshore Geotechnics

with contributions from Dr. J.D. (Don) Murff, First McClelland Lecturer, who was lab partner with Alan during their first soil mechanics course at Texas A&M University in 1968.

UNDERSTANDING THE FULL POTENTIAL OF AN INTEGRATED GEOSCIENCE STUDY

Alan G Young PE, M ASCE

Consultant, Sugar Land, Texas, USA
Formerly Vice President, Geoscience Earth & Marine Services (GEMS), Houston, Texas, USA

Abstract
This paper describes innovative changes in geophysical and geotechnical equipment and advances in marine technology that allows the offshore industry to conduct integrated geoscience studies. This holistic approach allows an interdisciplinary team to develop the five components of a 4D Geo-Site Model. The model defines the three-dimensional building blocks of subsurface geologic structure, geotechnical conditions, and geo-constraints. Age dating is critical for defining the fourth dimension (time) since it provides the framework for understanding the geologic history and the frequency of geologic processes. Correlating sequence stratigraphy, geotechnical soil properties, and horizon age control is a model benefit that allows extrapolation of spatial subsurface conditions. The capability to assess site favorability for various installation and operational criteria is another benefit. Regulations should not be too prescriptive and allow experienced engineers and geologists to plan the scope of site investigations. The paper indicates that if we change our way of collectively studying the seafloor; then an integrated study will reduce uncertainty in the overall design process.

1 Introduction

The opportunity to give the Fourth McClelland Lecture is the epitome of my professional career. During my graduate studies in geotechnical engineering, I read many of Bram McClelland’s technical papers and decided that I wanted to work for this pioneer in offshore geotechnical engineering. I first met Bram in 1971 after joining McClelland Engineers, a company he started in 1946. He was my mentor for the next 40 years.

Bram had impressed me with his broad range of expertise including: 1) offshore engineering geology; 2) site investigation methods; 3) laboratory testing methods appropriate for marine sediments; and 4) analytical methods applicable to offshore foundation design. His leadership, ingenuity, and zest for knowledge inspired his peers and many young geotechnical engineers. The first three McClelland Lecturers (Don Murff, Mark Randolph, and Knut Andersen) either knew Bram or were inspired by him to pursue their areas of special interest and make major contributions to the field of geotechnical engineering.

2 Background

Bram seemed to recognise early in his career that a holistic approach was required to improve the state of practice for offshore geotechnical engineering. He appreciated the challenges of the harsh marine environment. Bram realised at the start that a group of experts in a wide range of disciplines was needed to understand the design risks and provide economic solutions for successful offshore developments.

His first offshore paper, presented at the 1952 ASCE Convention, described the Quaternary Geology of the Continental Shelf in the Gulf of Mexico and the physical properties of the Recent and Pleistocene soils (McClelland, 1952). This paper was the first to present many of the building blocks of an integrated geoscience study that are still applicable today. In it, he discussed structure and foundation design requirements, and the type of site investigation needed to acquire soil samples and integrate geology with geotechnical engineering. Various types of storm loading forces and simplified methods for determining the lateral and axial capacity of foundation piles were also included.

Bram’s last paper entitled “Frontiers in Marine Geotechnical Engineering” was presented in 1991 as an Honors Lecture for the Offshore Technology Research Center at Texas A&M University. The lecture was presented the year he retired and described advances in marine technology made during each prior decade. Bram emphasised the progress that had been made in developing tools and techniques for marine site investigations – both geotechnical and geophysical and in combining geology with geotechnical engineering investigations. These advances allowed the offshore industry to extend marine geotechnical engineering practice into extreme water depths (>300m). He described projects that had benefitted from this multi-discipline, integrated approach. Finally, he pointed out shortcomings in the practice that needed to be addressed and advised that our goal should be "to use every available means to expand our knowledge of the deep ocean processes and their engineering implications."

Mr. McClelland also understood that many geotechnical engineers have little or no background in geology and its implications. He recognised this shortcoming as early as 1956, and credited Professor Raymond Dawson of the University of Texas for calling attention to this weakness in our practice. Professor Dawson invited Dr. Karl Terzaghi and Dr. Harold Fisk (head of Humble geology research) to participate in the 8th Texas Conference on Soil Mechanics and Foundation Engineering. In Mr. McClelland's opinion, the seed of multi-discipline collaboration was planted at this time and would continue to grow over the next sixty years.

Even though the idea of collaboration between geotechnical engineers and geologists on offshore developments was introduced in 1956; there was limited application until the 1970s. Advances in geophysical survey technology (high-resolution acoustic profiling, side-scan sonar, and bathymetric surveys) combined with soil borings and testing allowed the collaboration to take hold. Project professionals recognised that geological and geotechnical data was needed on a regional scale when planning studies were conducted in frontier areas for oil and gas companies. These regional datasets proved to be extensive enough to develop geologic models and to define site conditions, which were necessary to assess drilling and production hazards critical to operations. Since that time, the integrated geoscience approach has been more widely recognised and the benefits better understood and appreciated.

3 Lessons Learned from Bram McClelland

Mr. McClelland published over 25 papers applicable to offshore geotechnics during the 20 years prior to his retirement. It is important to emphasise that his interest was not in being published, but to clearly benefit the development of the offshore marine geosciences. Despite all his achievements, Bram remained humble and an excellent listener. Attentive to even the most junior engineer, he always encouraged them to pursue new solutions to technical problems. He was a beautiful writer and crafted every illustration to tell a precise story. I coauthored four papers with him and worked with him on dozens of projects. This experience was incredible since he was a great teacher and a source of inspiration.

Over this period, I learned many lessons from Mr. McClelland that are critical to understanding and implementing the full potential of an integrated geoscience study.

Lesson 1. Employ an interdisciplinary team of experts to understand the regional processes and geologic structure.
Lesson 2. Use high-resolution geophysical equipment to thoroughly investigate seafloor and stratigraphic features over an extensive seafloor region.
Lesson 3. Conduct the geotechnical investigation with equipment capable of performing *in situ* testing accompanied with high quality undisturbed samples.
Lesson 4. Rely heavily on the *in situ* testing data to interpret the undrained strength profile and, in particular, to identify the disturbance effects of sampling on laboratory test data.
Lesson 5. Rely on experimental testing and case studies to calibrate the empirical foundation design methods
Lesson 6. Develop an integrated geologic/geotechnical model to assess risks and define constraints to site development.

These six lessons highlight the critical components of an integrated geoscience study and are still applicable today. Since Mr. McClelland published his last paper in 1991, many significant developments in field equipment, seismic processing, mapping software, visualisation renderings, stratigraphic modeling, and radiocarbon (^{14}C) dating methods have been implemented. These developments have resulted in much-improved data quality and geophysical data being available today.

3.1 Potential of an Integrated Study

My hope for this paper is to convey to each reader two ideas to promote the advancement of the marine geosciences and integrated study. The first is the importance of geologic time when conducting an integrated study and second is the importance of a multi-disciplinary team in developing the Geo-Site Model.

My lecture provides an overview of the advancements available to the current state of practice using case studies to illustrate the potential of an integrated geoscience study. Please note, this paper will not be reiterating current standards that cover operational and data acquisition procedures. Instead, it describes recent innovations in both geophysical and geotechnical equipment that has improved the quality of data needed to conduct an integrated study.

Unfortunately, the most common practice in the development of a 3D (three-dimensional) ground or site model is engineers and geologists each doing their part but with minimal collaboration. So much more can be realised from the data sets when a team of multi-disciplinary geoscientists is assembled from the start and they work together. Such a team can identify the Geo-constraints and Geologic-Geotechnical conditions and interpret their evolution over geologic time. This four-dimensional integrated approach allows the description of the environmental processes and spatial variability of sediments throughout the development area. To provide the most accurate representation, the context of geologic time must be interwoven into the 3D site model to develop a four-dimensional (4D) Geo-Site Model (Geologic-Geotechnical Site Model).

The principal objectives of an integrated geoscience study are to accurately define seafloor site conditions to achieve the following:

1. reliable site selection for all facilities;
2. realistic assessment of potential geohazard exposure;
3. successful foundation designs and installation; and
4. safe operations of all planned seafloor-supported structures.

The project work is performed using all available geoscience data sets throughout the process. Each geoscience discipline must collaborate as part of a mutually supportive team while developing the 4D Geo-Site Model.

3.2 Integrated Approach

The integrated approach is a process for evaluating seafloor subsurface conditions for a planned offshore development. By conducting an integrated study in a logical sequence of phases as illustrated in Figure 1, the geophysical and geotechnical programs can be carefully planned to acquire relevant data needed to characterise the range of geologic/geotechnical conditions in a cost-effective manner. The iterative process of analyzing the integrated data sets defines the state of knowledge, uncertainty, consequences, and risks associated with the development of offshore facilities.

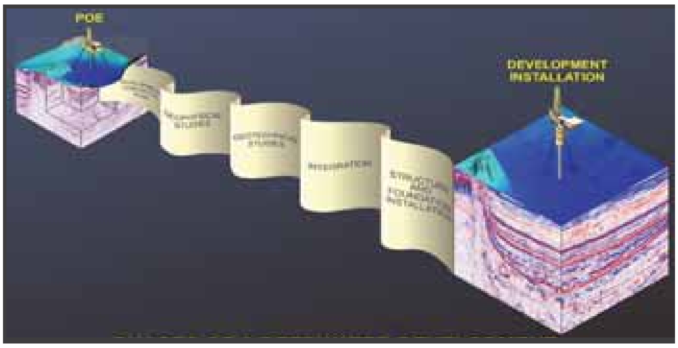


Figure 1: Phases of an integrated study (figure provided courtesy of Alan G Young)

A regional desktop study is conducted first to understand regional geologic conditions and plan the scope of the geophysical program. The high-resolution geophysical investigation is then conducted since it provides an opportunity to achieve maximum data coverage most economically over the entire project area. It provides a framework for collecting other forms of *in situ* data and sediment samples, understanding environmental processes, and for achieving an optimal engineering design.

Data collection in deepwater is expensive and generally requires coverage of a very large seafloor area as compared to most shallow-water developments. The coverage needs to be extensive enough to adequately characterise the geologic and geotechnical conditions throughout the planned area of the field development. In some areas, the coverage needs to extend beyond the planned area of the development to confirm that the risks associated with geological processes such as slope instabilities upslope or down-slope will not adversely influence the development.

Close interaction of an integrated team of geologists, geophysicists, geotechnical engineers, facility designers, and other supporting geoscience professionals is essential throughout all phases. We should remember Mr. McClelland's Lesson No. 1 when assembling the integrated team as stated:

> *LESSON 1: Employ an interdisciplinary team of experts to understand the regional processes and geology structure.*

Communication among different disciplines should begin at the start of the project, to achieve a more comprehensive and truly integrated field-investigation program – including both geophysical and geotechnical investigations. Clear communication is essential to ensure that the final field architecture places all seafloor infrastructures at an optimum site with uniform geological and geotechnical conditions. Information must be shared; open, clear communication is required among all team members, including representatives of the owner/operator.

Integration is not a stand-alone task; rather, integration is a way of thinking and questioning to be adopted by all team members. Communication is especially important when more information is needed or when unfavorable conditions present obstacles.

3.3 Phases of an Integrated Geoscience Study

The recommended general sequence of phases is as follows:

- regional desktop and planning study;
- geophysical systems and equipment planning;
- geophysical acquisition and data interpretation to develop initial geologic/geotechnical model;
- preliminary site and/or route selections;
- geotechnical planning and data acquisition;
- geological and geotechnical laboratory assignments and testing;
- integration of geophysical/geotechnical data and finalization of site-characterization model; and
- final foundation design, geohazard assessment, and final facilities site optimization.

As the project progresses through the different phases the 3D Geo-Site Model will be re-evaluated and reconfirmed as new data is acquired and interpreted and the project matures. Some of the phased activities may need to be recycled or refocused as knowledge of the ground conditions grows and the end-uses of the 4D Geo-Site Model evolve, as shown on Figure 2.

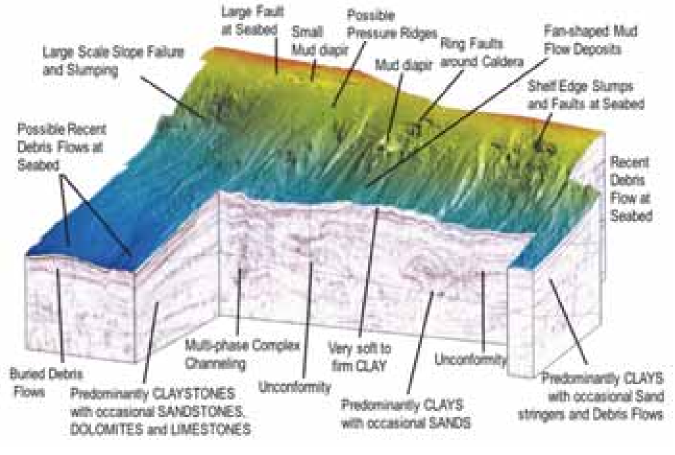


Figure 2: 3D geo-site model – enhanced seafloor rendering (Horsnell et al. 2009) reprinted with permission from Horsnell, Little, and Campbell with Fugro Geoconsultants.

4 Regional Desktop and Planning Study

A desktop study should be performed using all data available at the onset of the project to plan the general field architecture. A good understanding of the seafloor conditions, shallow stratigraphy, and sediment properties is required to select the best corridors for pipeline routes and sites for seafloor-supported infrastructure.

Exploration 3D seismic data is an initial key input for conducting the desktop study. The frequency content of the 3D data is usually sufficient to evaluate seafloor topography, shallow geologic conditions, and potential constraints for evaluation of preliminary production options. It is also useful to evaluate sub-seafloor features and geological processes using commonly available work stations and associated software.

A methodology described by Doyle et al. (1996) provided a breakthrough in identifying near-surface geohazards using conventional 3D seismic data instead of performing high-resolution deepwater surveys at this early stage in a project. The methodology has also proven quite valuable for the shallow engineering evaluations required for field development plans and assessment of the potential risks posed by different geo-constraints as shown in Table 1.

Table 1: Potential foundation risks for various geo-constraints (Young and Kasch, 2011) © reprinted with permission of J. Ross Publishing. Further reproduction prohibited without permission.

Geologic Process or Condition (Geo-Constraint)	**Seafloor Lineaments (Pipelines, mooring lines, etc.)**	**Shallow Foundation (Mudmats, suction piles, etc)**	**Deep Foundation (Driven piles, conductors, etc.)**	**Geophysical Data Required**
Steep Slope Gradients	Medium	High	Low	Multi-Beam Bathymetry
Slope Reversal (Irregular Seafloor Topography	High	High	none	Multi-Beam Bathymetry
Fault Displacement/ Offsets	Low	Medium	High	Side Scan Sonar & Sub-bottom Profiler
Shallow/Deep-Seated Slope Instability	High	High	Medium	Side Scan Sonar & Sub-bottom Profiler
Debris/ Turbidity Flows	High	Medium	Low	Side Scan Sonar & Sub-bottom Profiler
Spatial Soil Variability	High	High	Low	Side Scan Sonar & Sub-bottom Profiler
Currents and Erosion	High	Medium	Low	Multi-Beam Bathymetry, Side Scan Sonar & Sub-bottom Profiler
Gas/Fluid Expulsion Shallow Water Flow	Low	Medium	High	3D Seismic & 2D High Resolution

The aim of the desktop study is to assess and understand the existing data and use the desktop results to plan the geophysical and geotechnical investigations. This ensures that the data collection program appropriately fulfills the requirements, and that the surveys can be performed as efficiently as possible.

The use of a Geographic Information System (GIS) is recommended to efficiently manage the large volumes of different data. The GIS database should be initiated with the desktop study and be appended and edited until the completion of the integrated study. This system allows for interpretation, mapping, and archiving of the data and serves any future needs including modifications to the field architecture. The GIS database facilitates the collaboration of key professionals to evaluate the geotechnical and geophysical relationships over geologic time.

A wide variety of computer programs are available to interpret and create 3D geologic maps. These programs can be used to construct a digital elevation model (DEM). As described by Bolstad (2002), a DEM is a grid of x and y coordinates with corresponding elevation values.

Groshong (2006) describes how to contour the DEM to produce a visualization of the topographic surface. Enhanced seafloor renderings, as shown in Figure 3, are derived from the 3D seismic data. Using closely gridded data, a three-dimensional image of identifiable seismic horizons can be produced. The 3D seismic data helps identify near seafloor geologic conditions prior to acquiring conventional side-scan or sub-bottom profiler data. Structural and stratigraphic relationships can be correlated and evaluated using the vertical cross-sectional profiles.

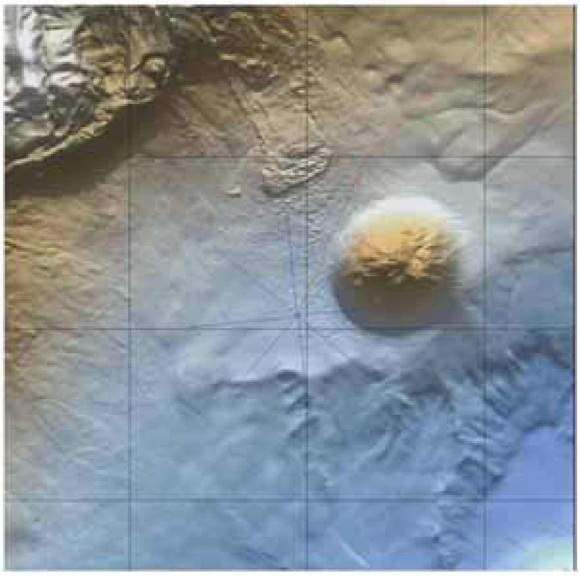


Figure 3: 3D enhanced seafloor amplitude rendering of Shell Auger Development (Doyle et al. 1996)

The enhanced seafloor renderings (ESRs) may be used to make assessments of near-seafloor geological features and provide insight towards understanding the geologic processes existing within the area of interest.

The 3D seismic amplitudes associated with the seafloor can be used to infer the physical properties of the shallow sediments and identify geologic processes as described by Roberts et al. (1996) and Brand et al. (2003 a, b). As described by Doyle et al. (1996) the amplitude of a seismic wavelet can be overlain onto a seafloor rendering as illustrated in Figure 4. The seismic amplitudes can be used to evaluate potential weak and hard sediments at the seafloor and at depth. By associating amplitudes with seafloor morphology, the rendering can indicate features such as authigenic rock outcrops, active fluid expulsion, and potential chemosynthetic communities. These types of features can pose a constraint to future production operations.

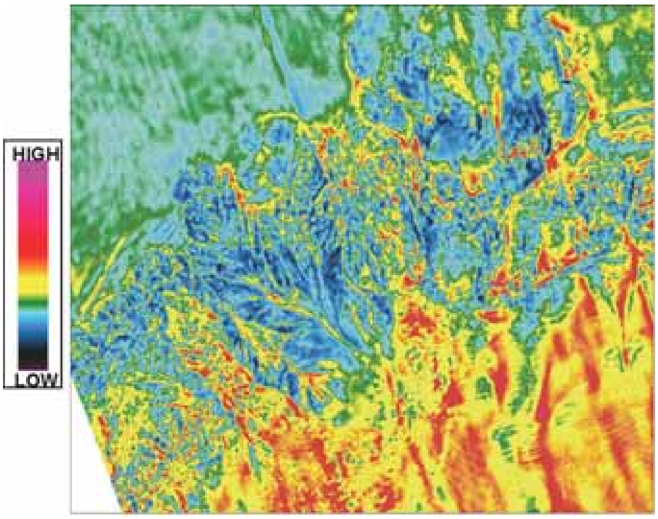


Figure 4: Peak seismic amplitude overlain over seafloor rendering at Atlantis Development (Young et al. 2009) © reproduced with permission of owner. Further reproduction prohibited without permission.

The final products of a desktop study will be an initial 3D Geo-Site Model and an operational plan stating objectives for conducting the geophysical survey. A general layout of the field architecture is required and potential geo-constraints identified to make sure that the data coverage is adequate to assess all potential risks to the planned development.

5 Geophysical Planning and Site Investigation

A critical component of an integrated geosciences study is definition of the scope of field investigations necessary to make an accurate assessment of all risks posed by seafloor and subsurface conditions. The 3D seismic data was useful during the planning study, but the next geophysical program requires better high-resolution data to accurately characterise the project area. There are several geophysical systems that provide such high-resolution data for deepwater site characterization, geohazard assessment, and foundation design. Advances in deepwater seismic systems over the last decade have dramatically improved the quality and resolution of the geophysical data allowing the 3D Geo-Site Model to be produced with high confidence. Mr. McClelland would be very pleased to know that current system capabilities satisfy his Lesson No. 2:

LESSON 2: Use high-resolution geophysical equipment to thoroughly investigate seafloor and stratigraphic features over an extensive seafloor region.

A planning study is a critical component for conducting a successful high-resolution geophysical survey to insure the acquired data serves all survey objectives. Critical components of the plan should include a checklist including: 1) survey grid layout; 2) equipment specifications and operating parameters; 3) geodetic and projection parameters; 4) calibrations; 5) existing seafloor infrastructure and potential obstructions; and 6) a copy of the desktop study and 3D Geo-Site Model.

The plan should verify that appropriate equipment is selected that can operate throughout the depth of water to be surveyed. The equipment must provide high-quality resolution data in the existing sediment types down to the depth of foundation interest with adequate data density for completing interpretation and mapping activities. The field operations need to be managed by a survey specialist. He/she will provide quality control supervision, verify regulatory requirements are satisfied, and assure operations are conducted in accordance with the HSE standards.

The systems used to acquire the higher resolution data are generally deployed as a suite of geophysical systems that are simultaneously transported over the seafloor as a towed fish behind a vessel or part of an Autonomous Underwater Vehicle (AUV). The high-resolution systems are more accurately classified a "multi-sensory acoustic systems" since each system has a sound-generating device, sound receiver, and data recorder. These systems are generally low energy, high-frequency devices designed to provide high-quality resolution data instead of greater seafloor penetration.

Prior to 2000, deepwater geophysical investigations were conducted by towing a system of sonars and other sensors behind the vessel as it transits a planned grid of survey lines (Prior et al. 1988; Doyle, 1998). The surveys were conducted in two phases. Phase 1 was conducted with surface-tow equipment consisting of narrow-beam echo-sounder for bathymetric profiles, a sparker for subsurface stratigraphy to depth of 400 to 500m, and a mini-sparker for subsurface stratigraphy to depths of 100 to 200m. The Phase 2 survey was conducted by towing a side-scan sonar, sub-bottom profiler, and other sensors (Deep-Tow System) relatively close to the seafloor. These surveys were very expensive due to the slow survey speeds, the extensive time required to make the turns at end of track line, and the need to perform two surveys. Thus, the industry sought an improved and more efficient system for conducting deep-water geophysical surveys.

Today high quality, digital, geophysical data are routinely acquired very efficiently in deepwater with an AUV (See Bingham et al. 2002). The AUV as shown in Figure 5 is equipped with a large suite of geophysical equipment to acquire high-resolution data such as swath bathymetry, sub-bottom profiles, and side-scan sonar imagery. These digital data are then processed and interpreted to develop a clear 3D picture of the seafloor and subsurface geologic conditions.

Figure 5: HUGGIN 3000 launch and recovery system (figure provided courtesy of Mr. Charlie Spann with C&C Technologies)

The volume and quality of subsurface data that can be acquired today in the offshore environment allows the team to develop a much clearer picture of sediment variability throughout the project area (Young and Kasch, 2011). The credibility of the integrated assessment depends upon the resolution and quality of the geophysical and geotechnical data as described by Moore et al. (2007). Figure 6 shows the range of equipment and sampling resolution that can be acquired with current AUV systems and geotechnical equipment.

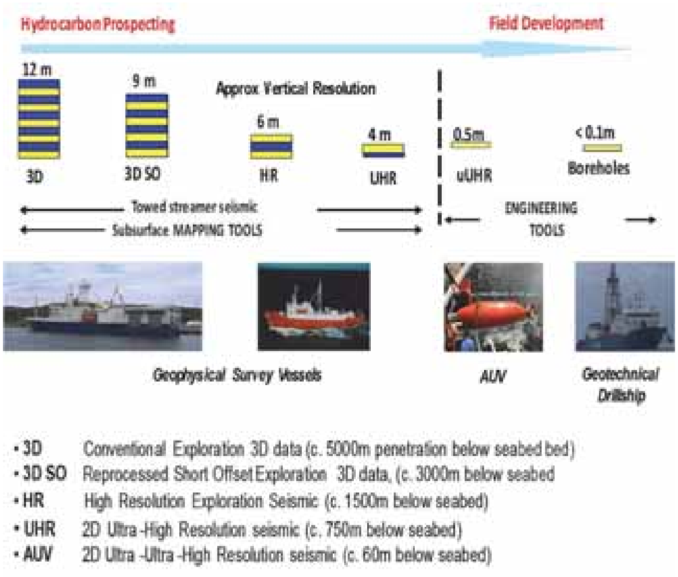


Figure 6: Data acquisition technologies and vertical resolution (Moore et al. 2007) Reprinted with permission from Moore with Halcrow Group Ltd., Usher and Evans with BP.

The quality of current ultra-high-resolution data obtained with the AUV systems provides a far better opportunity to understand the subsurface conditions than could be attained with older generations of equipment. Moore et al. (2007) has compared the excellent data quality of the AUV with seabed images acquired with 3D seismic data used for hydrocarbon exploration. Examples of seabed images obtained with the different geophysical systems are shown in Figure 7 illustrating the excellent quality of the AUV data.

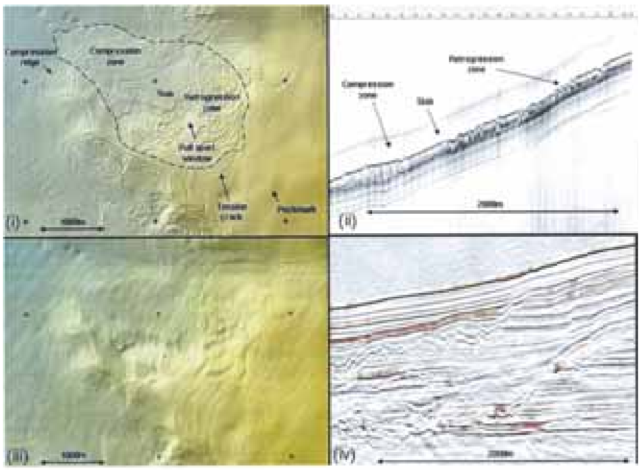


Figure 7: Contrasts in resolution between 3D imagery for landslides on the West Nile Delta (Moore et al. 2007) reprinted with permission from Moore with Halcrow Group Ltd., Usher and Evans with BP.

These improvements in the data provide two important benefits when used appropriately: 1) the cost of the site investigations is reduced and 2) the entire foundation design process is conducted with less uncertainty.

There are other high-resolution 2D (HR2D) and 3D (HR3D) systems available that provide deeper penetrating sub-bottom profiler data throughout the foundation and top-hole section. These systems may be needed if there is a concern for shallow gas, shallow-water flow, or more accurate hazard assessment for slope stability and fault assessment. A comparison of the quality of the sub-bottom data obtained with a higher resolution system is shown in Figure 8 as compared with the conventional exploration 3D seismic data.

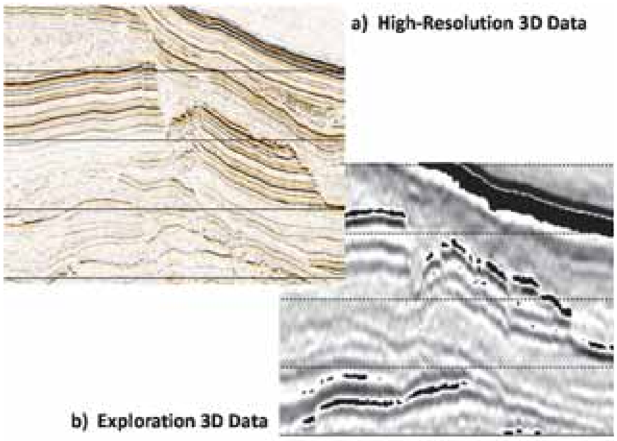


Figure 8: High-resolution 3D sub-bottom profiler data compared to exploration 3D seismic data (figure provided courtesy of Mr. Earl Doyle)

In more recent years the use of AUV 3D Micro (AUV3Dm) technology has vastly improved the quality of geophysical data for evaluating sediment character and the spatial variability of geologic features for placement of foundations. The data as illustrated in Figure 9 can be used to avoid anomalies such as faults, gas vents, MTD (mass transport deposit) blocks, etc. Campbell et al. (2013).

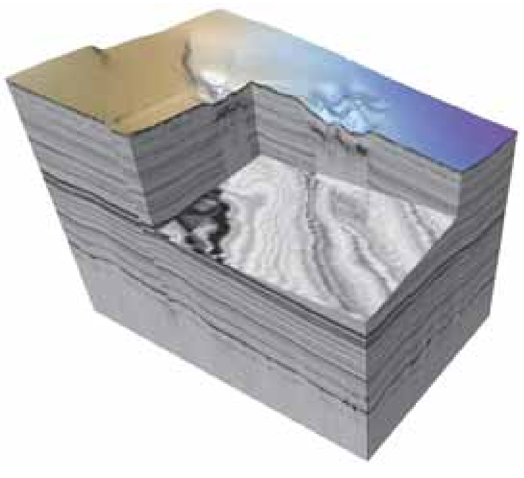


Figure 9: Perspective view of AUV3Dm subsurface data (Campbell et al., 2013) © reproduced with permission of owner. Further reproduction prohibited without permission.

During the planning study an important consideration for the geophysical investigation should be the collection of all seismic data in GIS compatible format. As a minimum, the data should include information about its location and relevant coordinate systems and elevation datum to allow it to be accurately used to develop the 3D Geo-Site Model described in a later section.

6 Geophysical Data Interpretation

The high-resolution data provides a wealth of knowledge relative to the geologic conditions of the area including stratigraphy, existence of unconformities, lithology, structural deformation, sedimentary processes, faulting, boundaries of gas charged sediments, and unstable slope areas. The acoustic systems all work on the same geophysical principle: the amounts of energy that are reflected and transmitted across various sediment interfaces depend on the contrasts in acoustic impedance at the interfaces. Acoustic impedance is the product of the sediment density and compressional wave velocity, which in turn, are functions of the sediment properties such as density, strength, and elastic properties of each material.

The very high-frequency systems such as the depth recorder or (multi-beam swath bathymetry system) and the side-scan sonar reflect their energy from the first acoustic interface, typically interpreted as the seafloor. The side-scan sonar image along each side of the vessel transit provides swath imagery on both sides along the vessel transit. The objective of a seafloor mapping is to use the data to map the bathymetry and to define the seafloor morphology and to identify man-made objects on the seafloor.

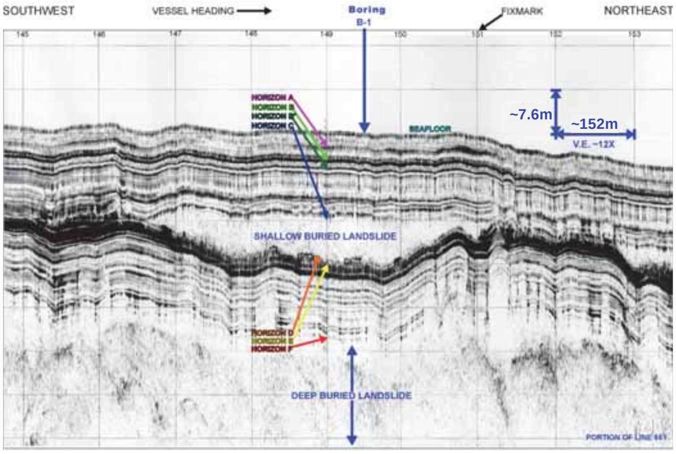


Figure 10: Comparison of seismic profiles for different sedimentary processes (Doyle, 1998) © reproduced with permission of owner. Further reproduction prohibited without permission.

The sub-bottom profiler is another important geophysical tool that provides continuous images along the path of the vessel transit showing subsurface conditions as illustrated in Figure 10. The energy transmitted from this lower energy system penetrates the seafloor with a portion of the transmitted energy being reflected at each interface. The sub-bottom profiles are very useful to understand the sedimentary processes that formed each depositional layer. For example, sediment layers formed by debris or turbidity flows exhibit different seismic signatures. Turbidity flows and debris flows, as illustrated in Figure 10, produce a very irregular signature as compared to uniform layering associated with normal deepwater deposition.

This seismic reflection system is high resolution and achieves typical seafloor penetrations of 50 to 80m. The limits of depth penetration depend upon the number and reflectively of each interface penetrated. Typical resolution is about 0.1 to 0.3m depending upon the frequency of the system and the composition of the sediments.

6.1 Evolution of 3D to 4D Geo-Site Model

Once all the geophysical data has been acquired, the geologic team will interpret the data and map the geologic conditions and processes within the three-dimensional space identified as the project area. At this stage, the initial 3D Geo-Site Model will be refined using all the data available from the recently completed geophysical investigation. The geologic team will interpret and map the structure, stratigraphic sequence, potential geo-constraints, and spatial variability in geotechnical conditions. The initial 3D Geo-Site Model will be transformed into a more well defined model to accurately plan the geotechnical investigation. Sample locations needed for radiocarbon dating should now be selected for the geotechnical investigation to define time (the fourth dimension of the 4D Geo-Site Model) that will be further explained in Section 8.

6.2 Preliminary Site and/or Route Selection

The 3D Geo-Site Model is critical to select sufficient sites to ground-truth the sediment stratigraphy, to characterise the geotechnical and geologic properties, to evaluate risk of the various geo-constraints, and to provide data for future geotechnical analyses. A general layout of the field architecture and the type of foundations being considered is needed to select the depths to be investigated at each site. The layout is also needed to determine the number of sites to be investigated in order to define spatial variability and to characterise temporal processes that might influence the foundation design.

7 Geotechnical Planning and Data Acquisition

Once the number of geotechnical sites and the depths of sampling or *in situ* testing have been determined, then the type of vessel and geotechnical tools may be selected to meet the technical objectives. A wide range of geotechnical equipment is currently available to conduct a deepwater geotechnical program. The type of vessel and most appropriate sampling and *in situ* testing methods depend upon a number of site and project specific factors. Water depth, sediment type, potential foundation depth, and soil properties all influence the type of vessel and equipment.

If deep foundations are required (>40m depth below the seafloor) and soil conditions consist of strong clays and deep deposits of sand, then a geotechnical drillship will be needed. In regions where normally consolidated to slightly over-consolidated clays or limited sand deposits exist and shallow foundation may be used (up to 40m depth below the seafloor), smaller vessels and seafloor deployed sampling and *in situ* testing equipment may be used.

A detailed field operational plan is critical and should include a description and requirements of the sampling and *in situ* testing activities for each site. Information on site conditions at the proposed work site is required such as water depth, sediment types, seafloor slopes, wave and current conditions, potential for shallow water flow, and risk for shallow gas/hydrates. An experienced geotechnical engineer should be involved throughout the planning phase to help prepare the site investigation scope and specifications. The geotechnical specialist will supervise all field operations to assure the acquired data satisfies all project requirements. They will also provide quality control supervision, verify regulatory requirements are satisfied, and assure operations are conducted in accordance with the HSE standards.

7.1 Historical Review of Geotechnical Investigations

Standard borings from a drillship or other floating platform have been the primary approach for conducting geotechnical investigation over the last 50 years (McClelland 1991). The borehole is advanced by rotary drilling methods (McClelland 1972) and down-hole samples are acquired using a wire-line sampler lowered down the bore of the drill pipe used to advance the borehole. The technology is very mature and the equipment has been continuously upgraded to improve sample quality and allow operations in deeper water.

The common practice has been to drill the borehole and take samples at intermittent intervals (about 3m). Sampling at fixed depths in the borehole can lead to a number of difficulties in interpreting the most realistic strength profile for foundation design as will be illustrated later by a number of case studies.

Although the equipment has been continuously upgraded, there are still many drilling, sampling, and testing procedures (Young et al. 1983) that impose deleterious effects upon our measurements of the undrained shear strength. Recognition of the potential negative impacts of these field operational and laboratory procedures led the offshore geotechnical industry to put more emphasis on *in situ* testing and the use of seafloor supported drilling and sampling equipment especially in deepwater. Lunne (2012) previously emphasised the importance of acquiring high quality samples by stating:

> *"It is of vital importance that the quality of the samples is good from a geotechnical viewpoint, otherwise the results of laboratory tests on the samples will not be representative for the in situ conditions".*

In the last decade, the practice of conducting deepwater geotechnical investigations has dramatically improved. New methods have emerged for obtaining large diameter continuous cores, performing continuous Cone Penetrometer Test (CPT) soundings, and combining these data into an integrated geoscience study. The following section will review the current state of practice as it has evolved from conventional soil borings up to more innovative *in situ* testing and seafloor sampling methods that are available today (Young and Murff, 2013). These methods have improved the quality of geotechnical data, so their use has led to reducing data uncertainty and improving foundation design reliability while reducing the conservatism required to achieve the target reliability. Mr. McClelland would be very pleased to know that recent innovations in geotechnical sampling and *in situ* testing tools satisfy the technical objectives of his Lesson No. 3 as stated:

LESSON 3: Conduct the geotechnical investigation with equipment capable of performing in situ testing accompanied with high quality undisturbed samples.

7.2 Seabed 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. (1999), 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 11). The system can drill, obtain continuous cores or samples, and/or perform *in situ* CPT testing to depths of 100m below the seafloor.

Figure 11: PROD seafloor sampling and in situ testing system (figure courtesy of Mr. Alan Foley with the Benthic Group)

The Rovdrill as described by Spencer (2008) is a seabed sampling and *in situ* testing system that uses an ROV. The ROV provides electrical and hydraulic power, telemetry, and high definition video and operator interface to the operator control room onboard the vessel. 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 2km of drill pipe and dramatically improves data quality.

7.3 Long Core Sampling

Large diameter drop cores such as the Jumbo Piston Core (JPC) shown in Figure 12 (Young et al. 2000), the STACOR (Borel et al. 2002), and the Deepwater Sampler (DWS) (Lunne et al. 2008) are relatively recent innovations that allow a continuous core to be obtained from the seafloor to depths up to 20 to 23m.

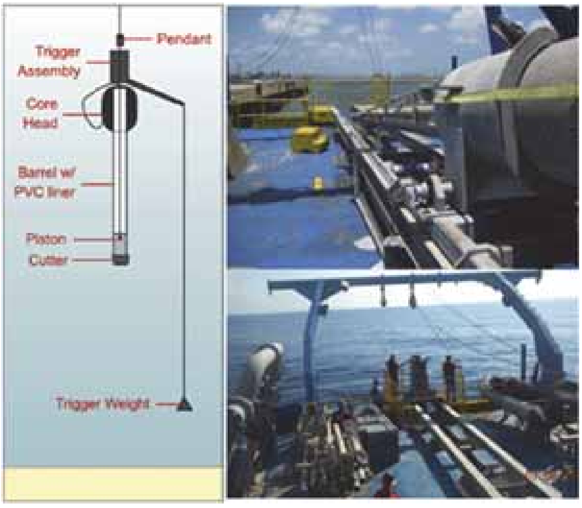


Figure 12: Jumbo piston core (JPC) operation and layout (figure courtesy of Dr. Bernie Bernard, TDI-Brooks International).

These devices are well suited for normally consolidated clays and can be used in overconsolidated clays to take continuous large diameter cores to depths up to 12 to 15m. Extensive field testing as described by Young et al. (2000) and Wong et al. (2008) has confirmed that the sample quality of long cores is as good as or better than samples from drilled borings.

The long cores have many technical benefits: 1) they yield a continuous core providing a visual image of variations in soil properties; 2) they can be continuously logged with a Multi-Sensor Logging System (MSCL); and 3) they facilitate 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 as borehole samples. The disadvantage of long cores is the depth limitation, i.e. they have limited depth range in strong soils.

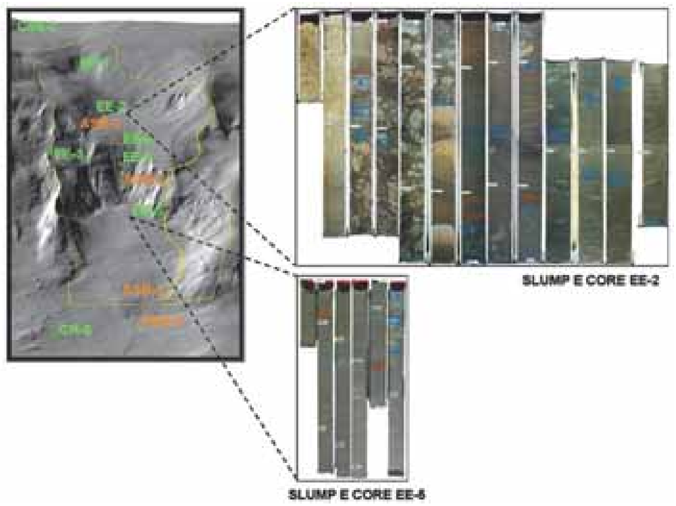


Figure 13: Photograph of Atlantis split core showing chaotic debris flow deposits in JPC (continuous 100mm diameter sample) (Young, et al. 2003) © reproduced with permission of owner. Further reproduction prohibited without permission.

Another key benefit of a continuous sample is the ability to split the sample and take color photographs as shown in Figure 13. The figure shows a color photograph of a split continuous long core with chaotic debris flow deposits. Visual inspection of the cores allows one to distinguish debris flow deposits from normal sedimentary deposits. The continuous visual picture of the sediment lithology allows the selection of appropriate intervals for radiocarbon dating and other testing with more confidence.

7.4 Cone Penetrometer Testing

The CPT has played a key role in conducting an offshore geotechnical investigation for over 40 years. Several key references such as Lunne et al. (1997), Robertson (2009), and Schnaid (2009) describe: 1) procedures; 2) equipment specifications; 3) intended use; 4) performance requirements; and 5) data interpretation methods available for the CPT. This paper cannot repeat all the details but, it will highlight the critical role that the CPT plays is performing an integrated geoscience study.

The Fourth James K. Mitchell Lecture prepared by Tom Lunne in 2011 describes the historic perspective of CPT use during an offshore site investigation. The paper provides a detailed discussion of the historic development, present status, and future challenges associated with:

- deployment methods and equipment;
- penetrometer design and construction;
- data acquisition, processing and quality control;
- standards and guidelines; and
- interpretation of result and application in foundation design.

This paper provides an excellent source for understanding the state of practice with the CPT and the importance of its use. As Lunne states:

> *"in most parts of the world it is hardly possible to consider an offshore soil investigation without the use of the CPT, and the results are essential input in establishing the soil profile and soil parameters for foundation design".*

Since Lunne published his paper, a new innovative system was developed called the "CPT Stinger" that allows CPT testing to overlap and extend below the bottom of a long core (Young et al. 2011). The system as shown in Figure 14 has been used on about 50 deepwater site investigations over the last five years, confirming key advantages.

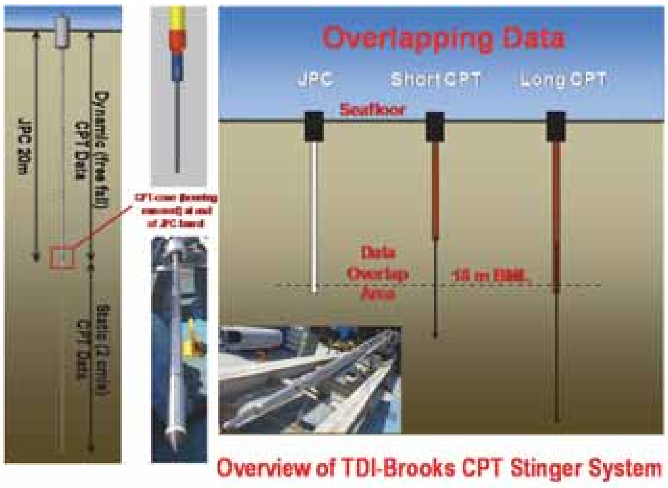


Figure 14: Overview of TDI-Brooks' CPT-Stinger system (figure courtesy of Dr. Bernie Bernard, TDI-Brooks International).

The system can be easily deployed to gather data over different testing intervals below the seafloor allowing overlap in the CPT data. Thus, a continuous sounding of point resistance, side friction, and pore pressure response can be tied to the seafloor as shown in Figure 15.

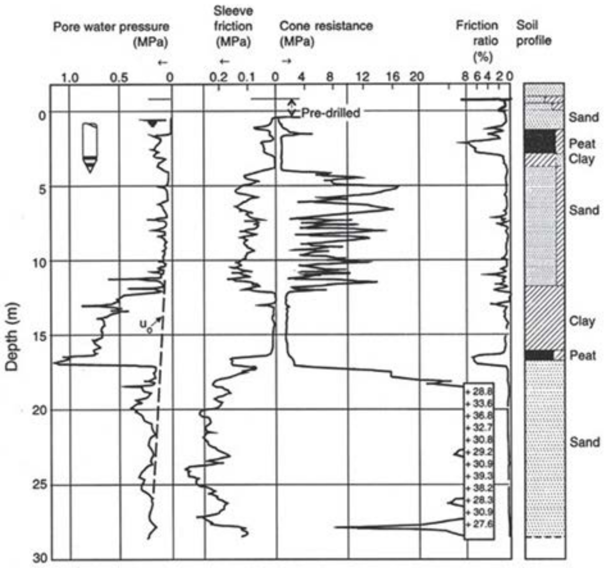


Figure 15: Continuous CPT profile of point resistance, side friction, and pore pressure. (Lunne et al. 1997) Reprinted with permission from Lunne with NGI, Robertson with Gregg Drilling, and Powell with Geolabs Ltd.

7.5 Advantages of Improved In Situ Testing and Seabed Drilling Systems

There are many advantages of obtaining continuous *in situ* testing data and samples as compared to discontinuous sampling in a standard boring. The key advantages include the following:

1. the continuous sample can be logged and compared with the sub-bottom profile data showing the individual strata and horizon breaks;
2. the continuous CPT data can be directly correlated with MSCL data obtained on the continuous cores and the sub-bottom data to obtain a continuous image of subsurface soil conditions and potential soil variability;
3. the continuous sample can be split and photographed allowing one to clearly identify depositional changes and maintain an image for the archive;
4. the effort and time for site investigations may be reduced; and
5. the entire foundation design process is conducted with less uncertainty and fewer risks.

Case studies will be presented in a later section to illustrate the advantages of integrating the multiple data sets to improve our understanding of subsurface conditions and its implications on foundation reliability.

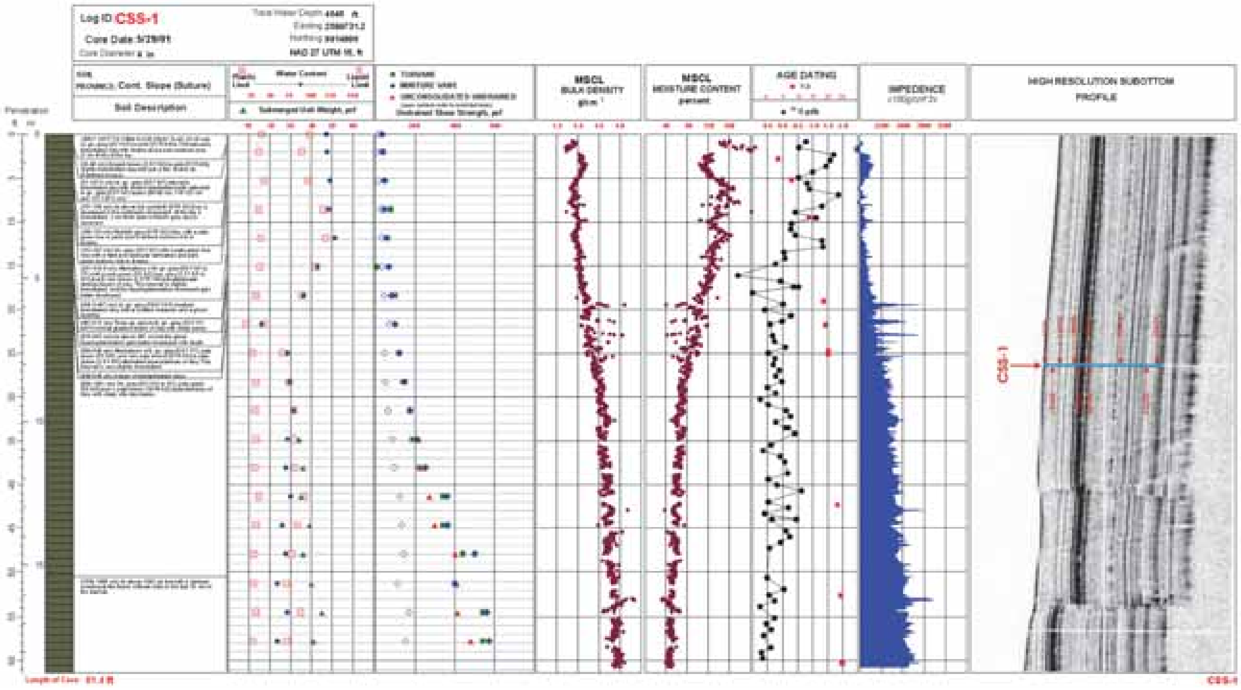


Figure 16: Boring log of JPC sample showing geotechnical laboratory data, MSCL log, and sub-bottom profiler cross-section (Young et al. 2009) ©reproduced with permission of owner. Further reproduction prohibited without permission.

7.6 Geotechnical Laboratory Assignments and Testing

Once the geotechnical investigation is completed, boring logs are prepared. Figure 16 shows all the results of the *in situ* and onboard laboratory testing. The field boring logs are then used to assign a series of standard/advanced geotechnical and geological laboratory tests.

The laboratory testing as described by Campbell et al. (2008) is performed for three different purposes:

1. characterise the soil stratigraphy and properties at specific locations where structures are to be installed to allow selection of soil parameters for foundation design;
2. define soil conditions within geologic units allowing extrapolation of soil conditions around the actual sampling site; and
3. measure the engineering properties of sediments susceptible to geohazards (landslides/slumping or erosion by seafloor currents) that may be a risk to the development.

7.6.1 Standard and Advanced Geotechnical Testing

During the geotechnical field investigation, a series of laboratory tests are performed onboard the vessel including moisture content, miniature vane, remolded miniature vane, and unconsolidated-undrained (UU) Triaxial tests. Classification tests are performed in an onshore laboratory to improve our knowledge of the soil types encountered at each depth in the soil profile. Supplemental classification tests should include: 1) moisture content; 2) Atterberg Limits; 3) grain size distribution (sieves and hydrometer); 4) bulk density; and 5) specific gravity. Once the field and classification results are available, standard and advanced testing programs are assigned to determine important geologic and geotechnical engineering parameters.

The standard testing is assigned to measure the physical properties, and advanced testing as needed to determine the stress history and strength properties. The advanced testing program as described by Al-Khafaji et al. (2003) may include: 1) controlled-rate-of-strain (CRS) one-dimensional consolidation; 2) static direct simple shear ($CK_oU' - DSS$) at lab induced OCR≥1; 3) static $CK_oU' - TC$ (triaxial-compression) and $CK_oU' - TE$ (triaxial-extension); and 4) ring shear, undisturbed and remolded. The type of tests performed will be selected to measure various soil properties needed for the design of the particular foundations being considered on the project.

7.6.2 Geological Testing

If long cores are obtained, then measurements are often made with an MSCL manufactured by Geotek (Schultheiss and Weaver, 1992). The measurements are made at very close intervals throughout the length of the core to provide a continuous profile of specialised sediment properties. The MSCL is a computer-controlled, automated system that takes non-intrusive measurements of bulk density, compressional wave (P-wave) velocity, and magnetic susceptibility of a sediment core. Physical soil properties that can be computed from the MSCL measurements include: 1) moisture content; 2) bulk density; and 3) acoustic impedance. Cores for logging should be selected based upon their importance to understanding the overall surficial geology within the study area. The continuous profiles of data as shown in Figure 16 can be correlated with the sub-bottom profile data to help identify marker horizons and confirm the variation in properties between horizons.

An understanding of the environment and/or mechanism of how the sediments were deposited help identify the character of each sedimentary unit interpreted on the seismic profiles. For example, it is important to differentiate between mass-transport deposits, turbid-flow deposits, or sediments deposited slowly and uniformly from suspension. A number of geological tests are available to help identify the depositional character of the sample including thin-slab x-ray radiography, digital CAT scan (computerized axial tomography), x-ray diffraction, and heavy minerals analysis. Experts in sedimentology and micropaleontology may use these results to verify the visual interpretation of depositional character of the split cores.

Various age determination methods should be considered to help determine the age of the sediments and the state of sea level/climate conditions at the time of sediment deposition. The three dating methods most commonly used as described by Slowey et al. (2003) are: 1) oxygen isotope analysis; 2) radiocarbon dating; and 3) nannofossil biostratigraphy.

The oxygen isotope analysis measures the ratio of stable isotopic compositions of foraminifera shells (^{18}O to ^{16}O ratio expressed in delta notation). The ratios are used to correlate variations of the downcore ^{18}O record from each core site to published, well-dated ^{18}O records from elsewhere. Recognizable differences exist between ^{18}O of glacial-aged and Holocene-aged foraminifera (glacial values are greater than Holocene values) reflecting the increase in seawater temperature and decrease in glacial ice volume that occurred during the transition from the last glaciation to the Holocene.

Radiocarbon (^{14}C) dating can be performed on foraminifera shells selected from different depths in the cores and to determine their absolute ages. The shells are analyzed with Accelerator Mass Spectrometer (AMS) equipment to obtain absolute ^{14}C dates. The absolute ages are then corrected for the surface ocean reservoir age effect to determine calendar years before 1950 (BP). ^{14}C dating is very useful to determine the age of marker horizons, sediment accumulation rates, and estimated time of mass sediment movements.

Paleontological dating indicates the occurrence of nannofossils that can provide diagnostic markers needed to constrain the age of the sediments with certain time intervals. On the Continental Slope in the Gulf of Mexico the sediments deposited during the late Neogene/Holocene period only have a resolution in the order of a few 100,000 years and sometimes less.

8 4-Dimensional Geo-Site Model

An initial 3D Geo-Site Model of the present-day environmental conditions at the seafloor and within the seabed is typically developed during the desktop study phase, and then refined after completion of the combined geophysical and geotechnical investigations. The 3D Geo-Site Model provides a three-dimensional picture of the subsurface geologic structure, geotechnical conditions, and geo-constraints. The advantages and limitations of using a 3D Geo-Site Model in the Danish Sector of the North Sea is described in a case study by Sienko et al. (2015). The study stresses the importance of high quality seismic data and time depth conversion of soil units in creating an accurate 3D integrated model.

At this early stage samples are not available for dating, so the fourth dimension (time) is unknown. Age dating provides the framework for understanding the geologic history and the timing and frequency of geologic processes (geo-constraints) that may influence the development area as described by Williams (1984).

8.1 Visualizing the 4D Geo-Site Model

A 4D Geo-Site Model can best be understood by visualizing the components of a cube of soil from the seafloor to a depth required to define the geologic structure and sediment properties for facilities design (Figure 17). The geophysical data provides an overall framework for constructing the initial 3D Geo-Site Model since it provides continuous coverage in 3-dimensional space referenced to sea level. The fixed reference (x, y, and z) datum makes it extremely convenient to construct maps, cross-sections, isopachs, and plan views of the seafloor and subsurface conditions as depicted in Figure 17. The fourth dimension (time or age, t) should be plotted to align with the vertical z-axis since sediments typically get older with increasing depth. However, the time scale for dating the marker horizons does not necessarily coincide with the depth scale for the soil boring (seafloor) possibly due to erosion, so the time scale needs to be adjusted to stratigraphic marker horizons once the age information is available. The case study reported by Hadley et al. (2017) illustrates the importance of making depth adjustments for site selection and foundation design when the seafloor has been severely eroded.

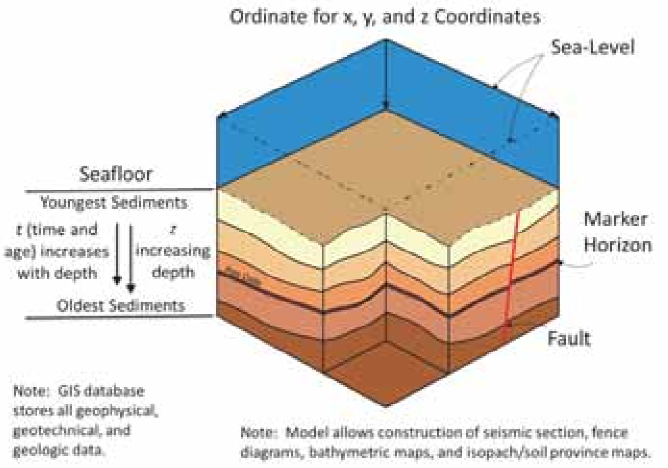


Figure 17: 4D geo-site model (figure provided courtesy of Alan G Young).

Age control is needed to define the fourth dimension (time or age), which allows the site's geologic history to be determined and the timing and frequency of past events to be understood. An understanding of historic events and their trigger mechanisms helps us evaluate the current risk of exposure and to predict the probability of occurrence in the future.

A brief description of the components of the 4D Geo-Site Model and examples showing the risks and impacts on site development are presented in the following sections.

8.2 Constructing the 4D Geo-Site Model

Proper construction of the 4D Geo-Site Model is one of the most important activities associated with conducting an integrated study as illustrated in Figure 17. The major task is to use all the available data to properly construct the model in order to characterise the seafloor and subsurface features including past and active processes. A well-constructed 4D Geo-Site Model will provide the framework for evaluating the risks and/or potential constraints to installing various types of facilities and their supporting foundations.

The activities required to develop the 4D Geo-Site Model in a systematic approach include the following:

- define the geological structure and deformation history (faults and slope failures);
- identify and map seafloor processes;

- identify stratigraphic marker boundaries (horizons);
- re-construct the sequence stratigraphy and age of each horizon;
- understand the historic geologic processes and events;
- map the lateral and vertical extent of landslides and past mass transport deposits;
- correlate the seismic stratigraphy with geotechnical data (sediment properties);
- identify geological constraints to infrastructure layout;
- develop soil province maps defining spatial variability; and
- project the historic model into the future to assess future risks.

Most offshore developments cover a fairly large seafloor footprint, and their seafloor architecture often is not finalised until late in the development phase. Thus, a 4D Geo-Site Model may require large areal coverage. *In situ* geotechnical testing and geotechnical borings and piston cores are collected later to ground-truth the geologic interpretations, to define the shallow soil conditions and the deeper stratigraphy, and to characterise sediment properties. Later sections provide a detailed description of all the data that may be required and how the data can be used to interpret the geologic processes and to determine the relevant parameters needed for various methods of analysis.

The following paragraphs will describe the components and activities required to construct the 4D Geo-Site Model in more detail.

9 Components of a 4D Geo-Site Model

The components of the 4D Geo-Site Model that need to be interpreted, analyzed, and mapped include:

- physiographic and geomorphic conditions;
- structural framework;
- stratigraphic framework and definition;
- geotechnical stratigraphy; and
- geochronologic sequence.

The different data sets are used during the integration phase to define the depositional processes, sediment stratigraphy, geologic structure, various geologic features, and event activity defined in space and time (frequency and scale). Each component can be visualised in three-dimensional space using various computer programs to produce images and the GIS system to archive all mapping and interpretation activities. Detailed descriptions and examples from different case studies illustrating the final integration product are presented in the following sections.

9.1 Physiographic and Geomorphic Conditions

The physiographic and geomorphic conditions are important factors that relate to the seafloor bathymetry, geologic features, and physical and chemical processes that formed the seascape over time and the dynamic processes that will continue to alter them in the future. All these factors help the geoscientists understand the landform history and the dynamic processes still active to predict future change by relying on field observations, physical experiments or numerical modeling.

Examples of physiographic and geomorphic conditions can best be illustrated by two projects in the deepwater Gulf of Mexico as shown in Figure 18. The Atlantis and Mad Dog projects are two developments that straddle a complex geomorphic region named the Sigsbee Escarpment. The seabed geomorphology is highly variable within this area illustrating the dynamic behavior of the allochthonous salt nappe.

The Atlantis drill center is located about 1.5km below the toe of the escarpment in 2,077m of water. The Mad Dog drill center is above the escarpment about 15km west of Atlantis in 1,350m of water.

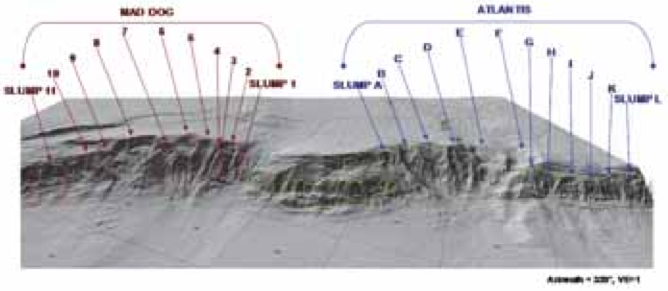


Figure 18: Seafloor rendering showing 3D perspective of Mad Dog and Atlantis Developments on Sigsbee Escarpment (Young et al. 2003) © reproduced with permission of owner. Further reproduction prohibited without permission

The thin-skinned sediment section overlying the series of enechelon, coalescing Pleistocene emplaced salt intrusions has been uplifted and deformed resulting in the seaward movement of sediments and subsequent over-steepening of the slope as described by Sweirz (1992). The upward and lateral movement of the underlying salt has deformed the sediments resulting in steep slopes, faults, and slumps as illustrated in Figure 19.

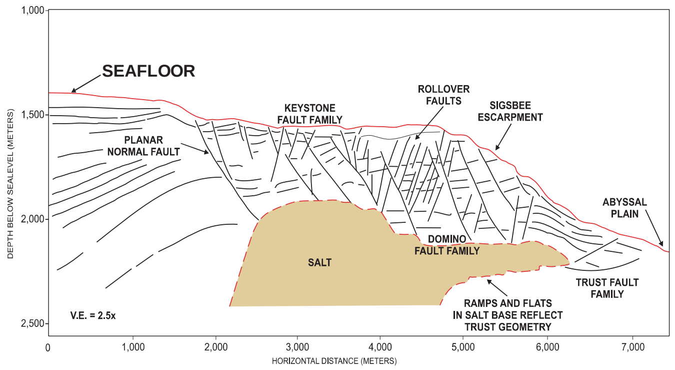


Figure 19: Seismic profile illustrating salt/fault interaction across Sigsbee Escarpment (Young and Kasch, 2011) © reprinted with permission of J. Ross Publishing. Further reproduction prohibited without permission

The Atlantis and Mad Dog Development area can be divided into three major seafloor bathymetric regions based on the general seafloor gradient variations. The bathymetric regions as shown in Figure 20 are namely, the lower continental slope (LCS), Sigsbee Escarpment (SE), and upper continental rise (UCR).

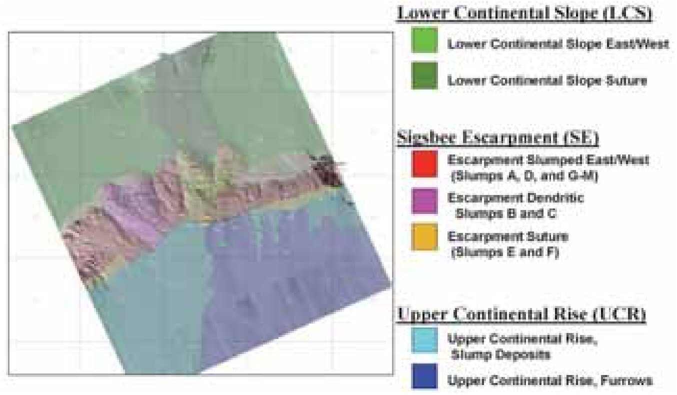


Figure 20: Atlantis bathymetric, physiographic, and geomorphic provinces (Brand et al. 2003a) © reproduced with permission of owner. Further reproduction prohibited without permission.

The regions may be further classified into provinces based on the physiographic and geomorphic characteristics of the seabed (see Figure 20). Well-defined provinces aid in understanding geologic processes and provide a better explanation of these processes to help in properly identifying risks, and mitigations for future field developments.

The seafloor geomorphology in the Atlantis and Mad Dog area was used to select the provinces based on variations in seabed appearance that reflects the differences in underlying structural deformation. These province boundaries were selected to outline areas of deformation related to geologic processes such as salt movement (ascension and withdrawal), faulting, slope failure (mass wasting and gravity flows), and bottom current processes. Provinces related to salt movement (i.e. ascension, subsidence) occur within the outer continental slope region of the Gulf of Mexico. The lateral movement, ascension, and subsidence of the salt triggered faulting, thereby demarcating major provinces of similar geologic structure. Most of these fault-derived provinces occur in the outer continental region and the remaining occur seaward of the Escarpment in the lower continental rise region.

Salt movement and associated faulting sometimes result in failure of over-steepened soils along associated scarps, ridges, and flanks. The large-scale effect of this salt movement-fault activity interaction is demonstrated along the face of the Escarpment where large scalloped slump features have incised existing seafloor (Slump 1 to Slump 11). See Figure 18.

There are an extensive number of technical papers listed in the text or tables in this paper that describe the physiographic and geomorphic conditions in this area. These references will provide more details than can be covered in this paper.

9.2 Structural Framework

The next component of the 4D Geo-Site Model is an understanding of the structural framework of the area. The structural framework helps us understand the three-dimensional distribution of different sediment units and their deformational histories. The goal is to interpret and map current sediment geometries, to understand structural evolution, and the past deformation structure and resulting stress fields that produced the current geometry. The evolutionary history will provide an understanding of the causes for the widespread patterns of sediment deformation. This is accomplished by measuring and understanding the physical and mechanical properties of the sediments in which the structural defects such as faults, folds, or internal weakness formed as shown in Figure 19.

The structural framework is generally divided into shallow and deep stratigraphy for discussion purposes. The shallow stratigraphy is interpreted using the sub-bottom profiler data, since it provides very good vertical resolution (about 0.3m) to depths between 45 to 75m below the seafloor. While the older sediments down to depths of 300m (deep stratigraphy) are typically imaged with high-resolution 3D (HR3D) seismic equipment. Vertical resolution in the HR3D data is approximately 2m.

We again will use the Mad Dog Development as an example to illustrate how the structural framework influenced the development of the 4D Geo-Site

Model. The salt underlying the Sigsbee Escarpment plays a critical role in understanding the structural evolution of the area and the formation of the stratigraphic section of the sediment overriding the salt. The deformation of the underlying coalescing salt masses is the mechanism that caused the over-steepening of the escarpment slopes and the resulting gravitational instability and slumping along the face of the escarpment as described by Orange et al. (2003) and Young et al. (2003).

The HR3D data example presented in Figure 21 shows a profile view of the Mad Dog Salt Nappe. Major structural elements and faulting are identified on the profile. Notice the differences in faulting associated with different locations of the sediment overlying the salt topography. The profile shows toe thrust faults and a sediment thrust wedge in front of the leading edge of the salt mass.

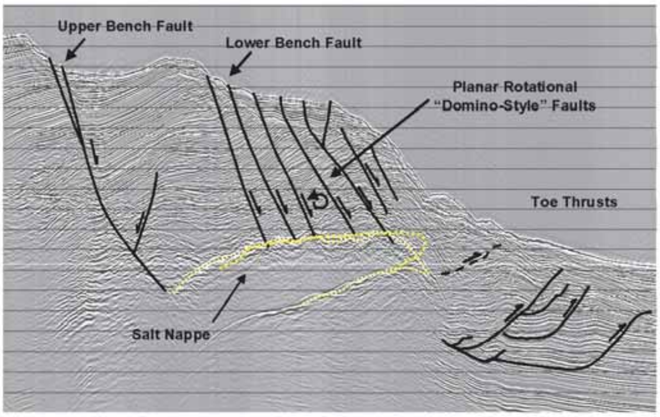


Figure 21: "Domino-style" faults over shallow, planner salt tongue, southwestern Mad Dog Development (profile view) (Angell et al. 2003) © reproduced with permission of owner. Further reproduction prohibited without permission.

9.3 Stratigraphic Framework

The next component of the 4D Geo-Site Model is an understanding of the stratigraphic framework of the area. The sub-bottom profiler is an important geophysical tool that produces shallow high-quality vertical profiles of the sediments underlying the seafloor. It is an excellent tool for interpreting and mapping the sequence stratigraphy over the entire area of a development. The continuous images obtained along the path of the vessel or AUVs transit clearly display the sediment stratigraphy, geologic structure, and various geologic features and processes such as faults, gas charged sediments, unconformities, etc.

9.3.1 Stratigraphic Definition

Stratigraphy plays a key role in constructing the 4D Geo-Site Model since it defines the lateral and vertical relationship of various sediment units. The three-dimensional framework also allows determination of the continuum of processes and features defined in space over time. Stratigraphy provides the temporal framework for all geologic sciences. Its major role in the field of geology has previously been noted:

> *"Stratigraphy is the great unifying agency of geology that makes possible the synthesis of a unified geological science from its component parts." – Weller 1947*

Stratigraphy also serves as the unifying attribute that allows integration of geologic and geotechnical engineering data into a comprehensive 4D Geo-Site Model. Dr. Niall Slowey has clearly emphasised the importance of stratigraphy by stating:

> *"To successfully carry out a program of integrated site characterisation, the key stratigraphic aspects of seafloor sediments must be understood!" – Slowey, 2016*

Marine stratigraphy is concerned with the age relations of sub-bottom sediment layers. The sediment relations that need to be defined included: form; distribution; lithologic and fossil compositions; physical and geotechnical properties; and the environmental processes and the events associated with the earth/ocean/climate histories. Improved technology over the last two decades has advanced the science past mere recognition of stratigraphic horizons. We are now able to recognise the shape of stratigraphic sequences, interpret their depositional history, and distinguish unconformities and reconstruct the transgressional-regressional history of an area.

Stratigraphic definition requires that the sediment units be characterised both laterally and with depth below the seafloor. The nature of the sediment stratigraphy is interpreted using the seismic profiles to select unit boundaries. Collection of other data sets provides the ground truth to characterise the lithology, chronology, and geotechnical properties.

9.4 Geotechnical Stratigraphy

Once the interpretation and mapping of key stratigraphic units is complete, then the spatial distribution of geotechnical properties can be extrapolated both laterally and vertically throughout the 4D Geo-Site Model. All geotechnical data available such as the CPT, MSCL, and boring logs can be correlated with the different stratigraphic units to define and interpret a suite of geotechnical parameters throughout the development area. The Mad Dog project as illustrated in Figure 18 is a good example of the extreme variation in spatial soil conditions that can be resolved by using the 4D Geo-Site Model (Berger et al. 2006 and Jeanjean et al. 2006).

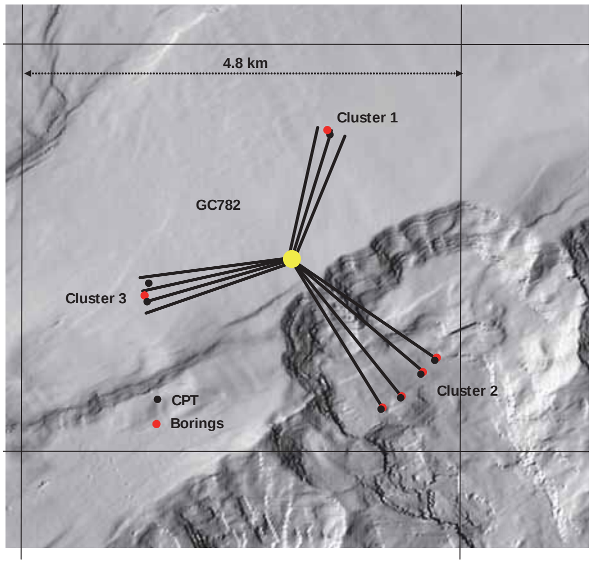
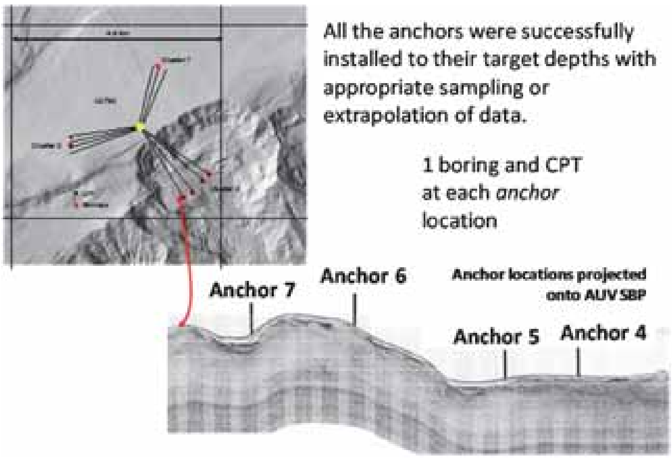


Figure 22: Mad Dog SPAR mooring spread with eleven suction piles (figure provided courtesy of BP, further reproduction prohibited without permission)

Three anchor clusters moor the Mad Dog SPAR as shown in Figure 22. Jeanjean et al. (2003) previously described the uncertainty associated with the soil conditions in Slump 8 at Mad Dog where one cluster of suction caissons was installed. The soils in Slump 8 are highly variable since they were deposited as a series of debris flows with interbedded zones of soft debris flow material, silt and sand layers, and stiff clay debris flow blocks as shown in Figure 23.


All the anchors were successfully installed to their target depths with appropriate sampling or extrapolation of data.

1 boring and CPT at each anchor location

Figure 23: Mad Dog Slump 8 – Cluster 2 geotechnical work scope piles (figure provided courtesy of BP, further reproduction prohibited without permission)

The highly variable soil conditions within the area of Anchor Cluster 2 required four CPTs, one for each anchor site. A boring was also drilled adjacent to each CPT location within Anchor Cluster 2 to more thoroughly investigate the site variability. As illustrated in Figure 24, the measured net cone resistances (q_{net}) in the debris flow deposits reveal extreme differences due to depositional nature of these materials. The wide variation is real and should not be neglected in interpreting the design strength profiles.

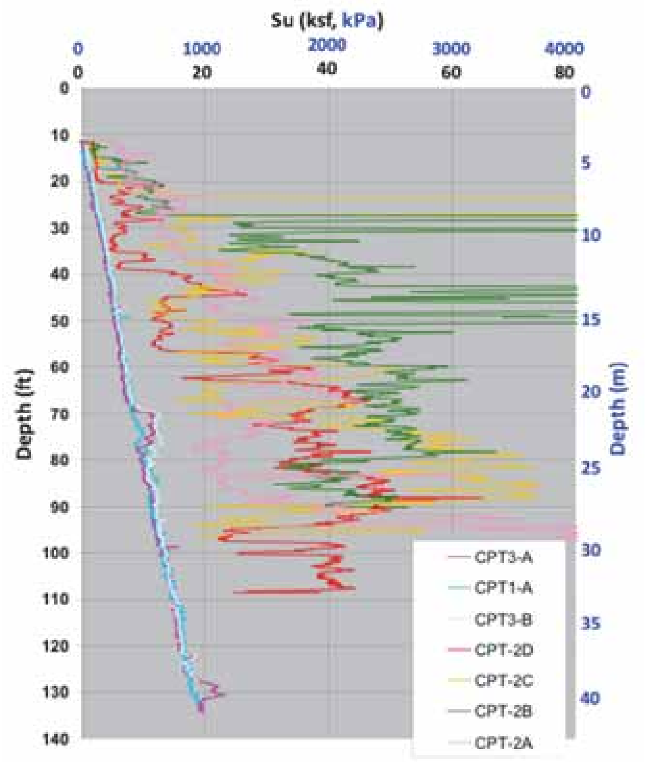


Figure 24: CPT site variability of all Mad Dog anchor clusters piles (figure provided courtesy of BP, further reproduction prohibited without permission)

In contrast, the sub-bottom profiler data shown in Figure 25 revealed very uniform soil stratigraphy between Anchor Clusters 1 and 3. The CPT profiles also shown in this figure and Figure 24 verify that the soil conditions are very uniform and continuous. The sub-bottom profiler data was used very effectively to select the appropriate number of CPTs and borings within each anchor cluster.

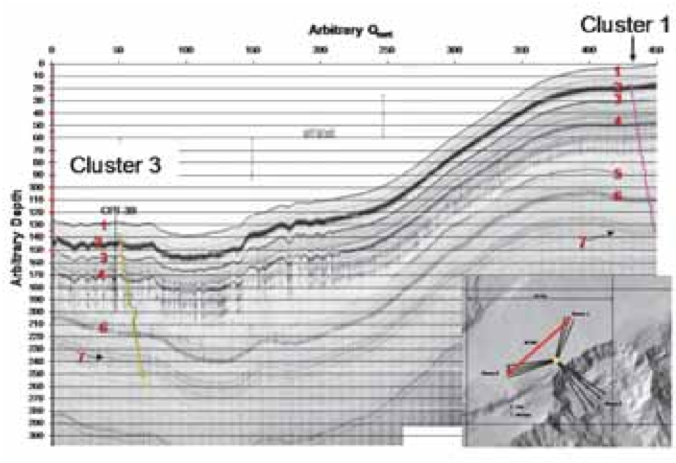


Figure 25: Sub-bottom profile data showing uniform soil stratigraphy between Clusters 3 and 1 piles (figure provided courtesy of BP, further reproduction prohibited without permission)

This case study confirms the importance of using the 4D Geo-Site Model to define the scope of the geotechnical site investigation. When uncertainty in soil conditions was apparent in the seismic data, site-specific geotechnical data was acquired at each anchor site. Confirmation with the seismic data that uniform soil conditions exist allowed a single CPT and soil boring to define the soil properties needed to design all suction caissons for Anchor Clusters 1 and 3. An additional CPT was performed within Anchor Cluster 1 to investigation an anomaly in the seismic data (a bright spot). The results of this second CPT revealed an identical soil profile as the earlier boring. Use of a 4D Geo-Site Model allowed the geotechnical work scope to be reduced resulting in significant savings.

9.5 Geochronologic Sequence

After the stratigraphic mapping has been completed throughout the area of an offshore development, then age dates should be obtained on the sediments to define the spatial and temporal distribution of the stratigraphic units. The dating of the bounding horizons is required to constrain the timing of the different depositional systems, deduce sedimentation rates, and determine the frequency of events from an age-sea level correlation. Thus, sediment age control is a fundamental aspect to achieving a reliable and useful 4D Geo-Site Model.

Key horizon markers are identified and correlated across the area in order to establish an understanding about the temporal distribution of the different depositional units and their relationship with sea level changes and sedimentation. The geochronology helps to constrain past geological events (the timing and rates), which can be used to adapt future developments to the site conditions. The geochronology and sea level/climate history help relate changes in sediment properties and lithologies to regionally persistent seismic reflectors (stratigraphy) shown in Figure 26

The Atlantis and Mad Dog projects again provide excellent examples illustrating the importance of geochronology in understanding the geologic history and assessing processes that may impact the development. The results of the Atlantis reference core (CSS-1) shown in Figure 26 illustrate how ^{14}C dating/sea level correlations can be used to understand the influence of environmental processes upon the geologic and geotechnical characteristic of the near seafloor sediments. The figure shows the correlation of radiocarbon dates versus depth in CSS-1 to the sequence of high-resolution reflectors at the core site. The ages from CSS-1 combined with the other core age results allowed regionally persistent reflectors M1 (14,900 ybp), M2 (19,800 ybp), M3 (22,500 ybp), and M4 (23,800 ybp) to be identified throughout the Atlantis and Mad Dog project area. The geochronology, as illustrated in Figure 26 was critical for these projects in terms of understanding the processes, events, and time scales associated with structural evolution of the Sigsbee Escarpment.

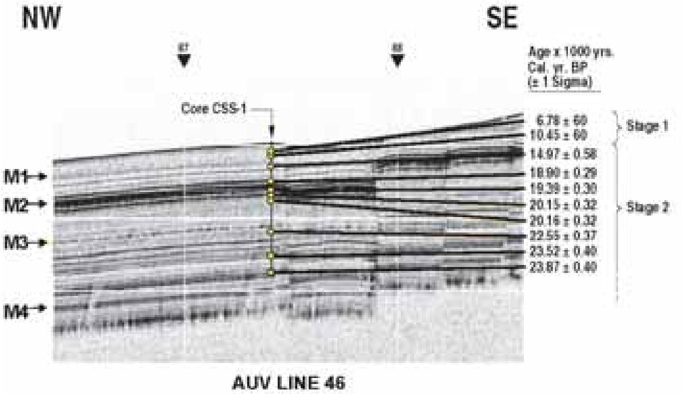


Figure 26: Results of radiocarbon analysis for Atlantis reference core CSS-1 (Slowey et al. 2003) © reproduced with permission of owner. Further reproduction prohibited without permission.

Age control for the shallow stratigraphy was derived mainly from radiocarbon (^{14}C) dating, while the deep stratigraphy dating was based on paleontological methods and oxygen isotope analysis. Tying the depositional ages with sea level revealed that most of the shallow horizon markers were deposited from the last low-stand maxima to high-stand (rising sea level). This explains why the Atlantis and Mad Dog area is interpreted to be in a state of geological quiescence because the principle trigger (e.g. high sedimentation rate) that generate the geohazards are presently inactive.

The chronology of sea level/climatic history during the last 40,000 years of the Quaternary period played a very important role in integrating the changes in sediment properties and lithology throughout the Mad Dog. The sediment accumulation during this period changed dramatically from the glacial low-stand to the present Holocene high-stand. Thus, the age dating information obtained from the ^{14}C radiocarbon method was correlated with the regionally persistent seismic reflectors as shown in Figure 26.

10 4-Dimensional Integration

Once the marine geologists have completed their interpretation and geophysical mapping, the geotechnical data should be incorporated as another layer in the framework of the 4D Geo-Site Model. Correlating all the geologic and geotechnical data into the 4-dimensional space accomplishes the maximum benefit of an integrated study.

10.1 Correlation of Geotechnical Soil Properties to Sediment Stratigraphy

Geologic processes may have deposited sediments in both predictable circumstances and under chaotic conditions. Thus, interpretation of the geotechnical soil properties throughout a region or site is probably the most difficult task to be accomplished. The scope of the geotechnical site investigation and the quality of the seismic data are critical factors associated with interpreting and mapping the spatial trends.

As early as 1956, Mr. McClelland recognised the importance of understanding the regional geology to extrapolate geotechnical soil data (McClelland, 1956). He emphasised that the depositional history is fundamental to defining typical strength versus depth profiles as shown in Figure 27. His paper also highlighted the correlation between consolidation pressure and soil strength and the rate of sedimentation. Using these concepts along with about 100 different borings throughout the continental shelf offshore Louisiana and Texas, he relied upon regional geologic history as reported by Fisk et al. (1954) to show that classic strength relationships can be generalised for different regions of the Gulf of Mexico.

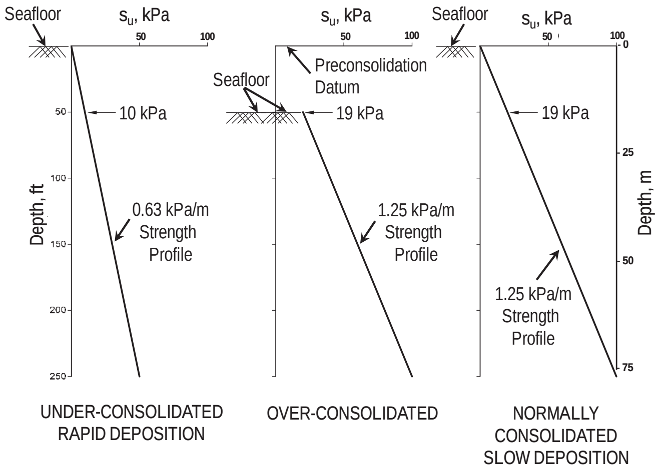


Figure 27: Idealised strength profiles – homogeneous clay (McClelland, 1956)

Figure 27 shows the variation in strength profiles that typically occur due to the rate of deposition and state of consolidation. Cohesive soils deposited at a slow rate under normal sedimentation rates is called a normally consolidated soil and has a slope of the strength profiles that increases at a rate of 1.25kPa/m. Soils deposited very rapidly are considered underconsolidated and exhibit a strength profile increasing at a rate of only 0.63kPa/m. Where seafloor erosion occurs, the soils are classified overconsolidated soils. Although the overconsolidated soils exhibit the same slope as the normally consolidated clay, the strength at the seafloor is 19kPa that is the same as the normally consolidated profile at 20m depth. These examples illustrate the importance of understanding the geologic history when trying to interpret soil properties especially spatial strength distribution.

In a later study, McClelland Engineers compiled a database of 1,200 borings acquired over 82,900sq km of the continental shelf in the North-Central Gulf of Mexico and prepared a series of maps (Parker et al. 1979). These maps depict the shear strength variations of the cohesive soils to a depth of 46m below the seafloor. An example of the strength map for a region at a depth of 3m below the seafloor is shown in Figure 28 and Figure 29. The maps were intended for desktop studies and have proven quite accurate when compared with the strength data from many thousands of subsequent borings.

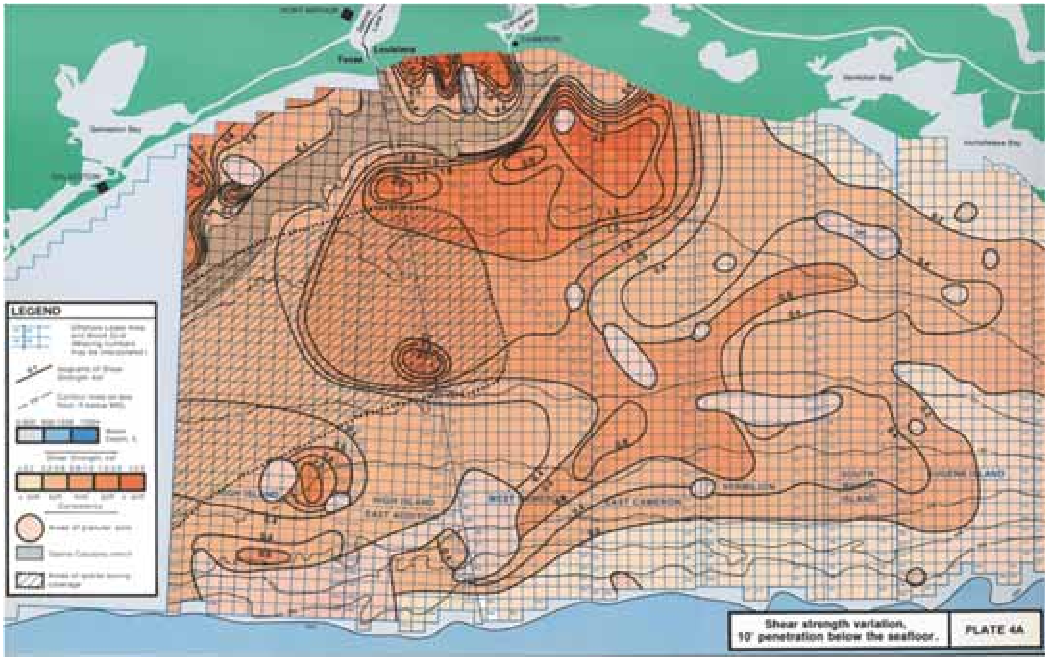


Figure 28: Example strength map from Gulf of Mexico Continental Shelf Atlas (Parker et al. 1979)

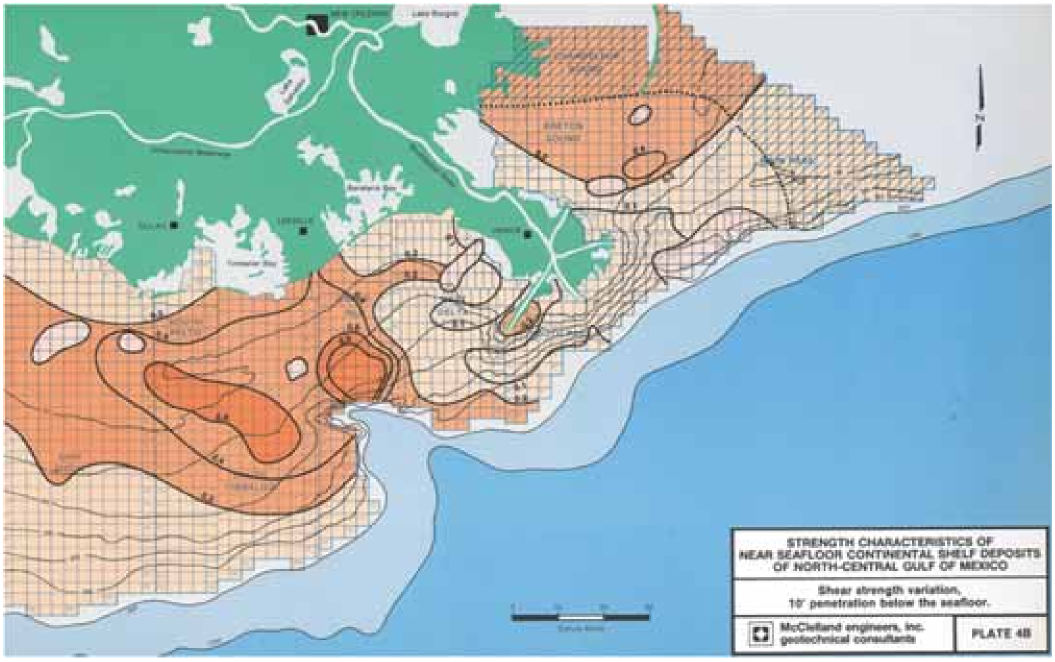


Figure 29: Example strength map from Gulf of Mexico Continental Shelf Atlas (Parker et al. 1979)

This study proved that geotechnical properties could be extrapolated over large regions using the geologic history as reflected in the geotechnical properties of the sediment. Specific signatures of the geologic processes (stress history) involved with the deposition of cohesive soils are recognizable in their strength profiles (Figure 27). The approach of extrapolating soil properties especially the strength profile throughout a project area or region based on the geologic history has been subsequently used in other regions of the world. It can be used with much confidence today due to the quality of the high-resolution geophysical data and improved consistency in the geotechnical strength data measurements. Case studies will be presented in a later section showing how geotechnical soil properties can be easily correlated with sediment stratigraphy.

10.2 Use of CPT Data and Laboratory Test Data

In more recent years a typical site investigation includes *in situ* testing with the CPT along with conventional and advanced lab testing on recovered samples obtained in a deep boring or long core. Our ability to interpret a consistent and reliable undrained shear profile is often hard to accomplish because of the impact of sample disturbance upon the laboratory test data (Young et al. 1983 and Caruthers et al. 2014).

Traditional practice has relied more heavily on the measured values of laboratory strength to interpret a design strength profile instead of values interpreted with CPT data. However, the effects of sample disturbance result in large scatter in the measured laboratory values. Other factors such as soil anisotropy, strain rate, stress history, and different loading mechanisms also cause some of the scatter. The effects of different loading mechanisms mean as quoted by Wroth (1984) in his 24th Rankine Lecture:

> *Consequently, there cannot be a unique undrained shear strength of a soil, and different values will be observed in different tests.*

Thus, the author recommends that practicing geotechnical engineers put more weight on the CPT which is a more consistent and representative measure of the depositional nature of marine sediments and avoids most of the other effects. Wroth (1984) previously indicated that the CPT is a tool of great promise for obtaining a rapid and reliable soil profile if its use is standardized to follow industry guidelines.

Interpretation of an undrained strength profile in cohesive soils may be done using either the *in situ* or laboratory data set. Using the CPT data requires an approach based on the relationship between undrained shear strength, s_u, and the net cone tip resistance, (q_{net}) expressed as follows:

$$q_{net} = N_{kt} s_u \qquad (1)$$

where N_{kt} is the cone factor that is analogous to a bearing capacity factor, N_c.

In the past, the value of N_{kt} has been computed by using a combination of laboratory or other type of *in situ* tests to represent the reference value of s_u. In most studies N_{kt} was computed using the *in situ* vane or UU-triaxial compression tests, UU-triaxial extension tests, direct simple shear (DSS), and the average strength from the triaxial compression and extension and direct simple shear.

To complicate matters more, some studies have relied upon the total cone tip resistance (q_t) and computed a value of N_k instead of N_{kt}. These studies have also used a wide range of *in situ* tests such as the *in situ* vane or a wide variety of laboratory test as the reference strength.

Some of the studies have attempted to correlate the values of N_{kt} or N_k with the plasticity index, I_P, although these correlations have yielded major scatter as shown in Figure 30.

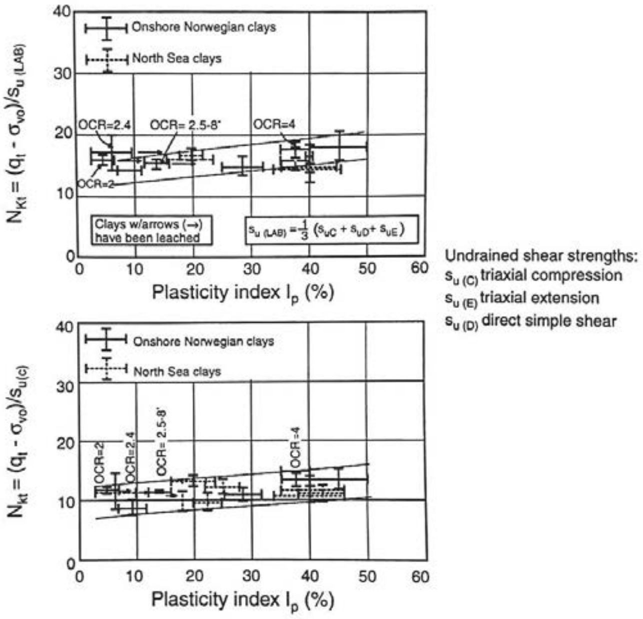


Figure 30: N_{kt} correlations with plasticity index (Aas et al. 1986 and Lunne et al. 1997) reprinted with permission from Lunne with NGI, Robertson with Gregg Drilling, and Powell with Geolabs Ltd.

The design practice during the earlier years in the Gulf of Mexico was to use N_{kt} values ranging from 15 to 20 depending on the type of reference strength. In more recent years, a value of N_{kt} of 17.5 has been used to correlate with reference strengths based on UU-triaxial compression and direct simple shear tests in normally consolidated clays (Young and Kasch, 2011).

The author believes that the wide range of reported values of N_{kt} and N_k occur because there is not a unique measure of s_u. The wide range of reported N_{kt} and N_k values occurs because we do not use a consistent set of reference strength tests and cone types. The author recommends using N_{kt} instead of N_k on offshore projects to eliminate the hydrostatic component in the measured value of q_{net}.

The DSS test on high quality samples also provides a very consistent measurement of s_u that helps negate the effects of sample disturbance. The author also recommends using the DSS strength tests as the reference strength to correlate with the values of q_{net} measured with the CPT. When these two types of tests are performed at the same site, then a majority of the human and environmental induced errors can be eliminated yielding a very consistent measure of s_u. A number of recent case studies (Caruthers et al.

2014 and Young et al. 2013) yielded an average N_{kt} of 17.5 as shown in Figure 31, Figure 32, and Figure 33 when using this approach in the Gulf of Mexico and other offshore regions.

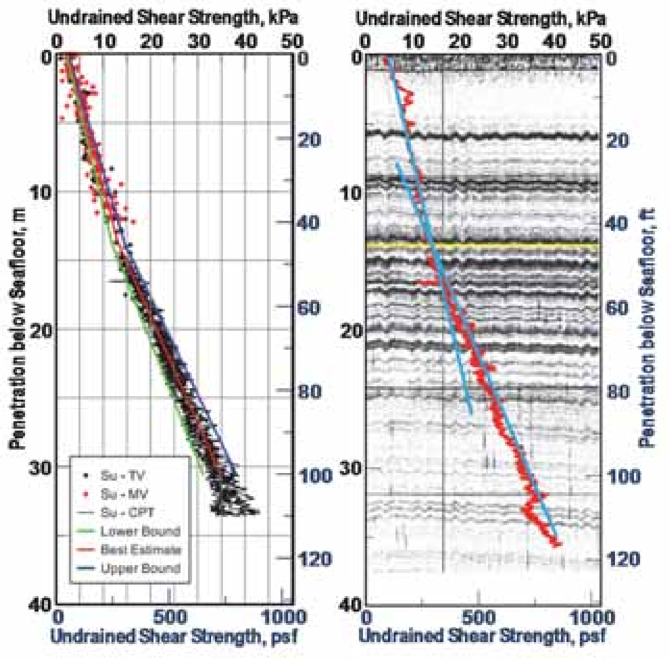


Figure 31: Site 1 – laboratory and CPT strength data for eight test sites correlated with sub-bottom profiler data (Young et al. 2011) © reproduced with permission of owner. Further reproduction prohibited without permission.

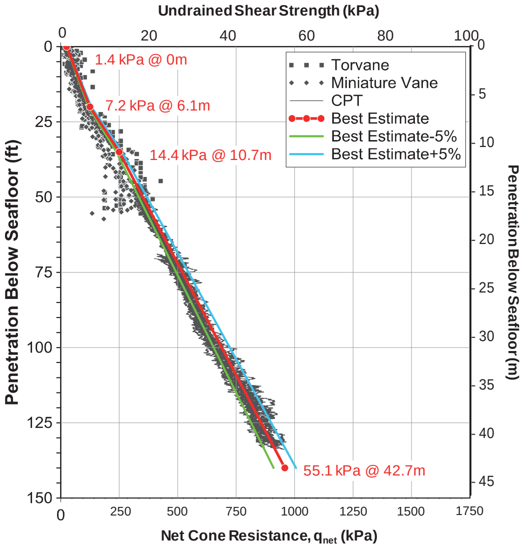


Figure 32: Site 2 – s_u derived from CPT using N_{kt}=17.5 (GEMS, 2013) further reproduction prohibited without permission

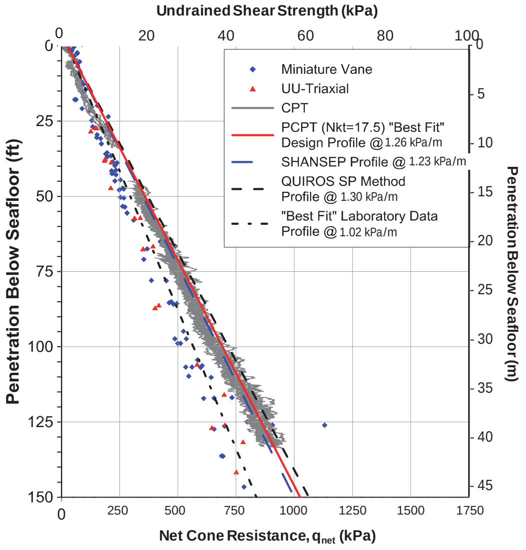


Figure 33: Site 3 – s_u derived from CPT using N_{kt}=17.5 (GEMS, 2013) further reproduction prohibited without permission.

A panel of geotechnical experts previously conducted a Joint Industry Project (Young et al. 2013) that recommended more reliance should be placed on the use of continuous CPT data to select the gradient of the strength profile. Reliance on the CPT data allows selection of the strength profile with more certainty than using only the laboratory strength data from recovered soil samples that exhibit varied degrees of sample disturbance. Relying solely on strength data obtained from soil borings in deep water locations may lead to overly conservative designs due to inevitable sample disturbance.

Baecher and Christian (2003) indicate that measured soil properties are often treated as if they are independent samplings of a random variable. Offshore soils are frequently deposited in a uniform physical process over time, so their spatial variability is often not random. The uncertainty is frequently in the model or error in soil measurements and not in the soil deposit. The soil properties resulting from depositional processes and subsequent history might be unknown to the engineer and therefore appear to be random, but the physical processes are not random and, therefore, the soil properties are not either.

In summary CPT soundings provide a continuous profile of soil strength and insight relative to the type of depositional processes throughout the soil profile. Thus, the CPT is an excellent tool for investigating the depositional variability since it provides a continuous profile of soil resistance (q_{net}). The repetitive procedure of inserting the CPT at a constant rate provides a more consistent and repeatable *in situ* process for measuring s_u than laboratory testing on recovered samples, which are disturbed to varying degrees. In other words, the CPT helps eliminate most of the critical factors that can induce error in the measured values of s_u. We need to remember and follow Mr. McClelland's Lesson No. 4 as stated:

> *LESSON 4: Rely heavily on the in situ testing data to interpret the undrained strength profile and, in particular, identify the disturbance effects on laboratory test data.*

10.3 Interpretation of Undrained Strength Profile

Once the field and laboratory programs are completed there will be a large volume of laboratory and *in situ* testing data available to characterise the physical and engineering properties of the subsurface sediments. All the available laboratory and *in situ* strength data are typically plotted on a boring log that illustrates the trends and abrupt variations with depth as shown in Figure 16. The plot of undrained strength data versus depth also allows a comparison of the difference between standard, advanced, *in situ* test data.

Recent studies (Young et al. 2013 and Caruthers et al. 2014) show that too much reliance is being placed on the laboratory strength data to interpret the undrained strength profile. There are several critical factors that can influence the quality of recovered soil samples and create the large scatter in the measured values of undrained strength. Critical factors as reported by Young et al. (1983 and 2013) that are difficult to control and must be carefully monitored included:

- weather conditions that induce motion of the drill-string during drilling and sampling;
- type of sampling procedure and size of sampling tube;
- stress relief during sampling recovery;
- type of sample extrusion procedure;
- sample handling, packaging, transportation processes;
- sample storage methods;
- adherence to laboratory testing standards;
- unusual geologic and physio-chemical properties of sediment; and
- gas expansion.

The benefit of acquiring *in situ* test data is that most of these factors can be avoided and disturbance effects can be eliminated. The large scatter in laboratory strength data reflects "human-induced" error and often is not representative of the depositional nature of classic marine sediments.

The SHANSEP method (Stress History and Normalized Soil Engineering Parameters) as described by Ladd and Foote (1974) and Ladd et al. (1977) is an approach used to help negate the effects of sample disturbance. The method relates the *in situ* undrained shear strength s_u to parameters developed from results from CRS consolidation tests and strength tests such as K_o-consolidated undrained strength tests performed with a direct simple shear (DSS) device. The state of consolidation and undrained strength can then be determined from the following equation:

$$s_u = \sigma'_v \left(\frac{s_{u_{DSS}}}{\sigma'_{vc}}\right)_{nc} OCR^m \qquad (2)$$

where s_u = computed *in situ* undrained shear strength and σ'_v = *in situ* effective vertical stress.

$\left(\frac{s_{u_{DSS}}}{\sigma'_{vc}}\right)_{nc}$ = normalised shear strength ratio

where $s_{u_{DSS}}$ is the DSS undrained shear strength obtained from a laboratory sample consolidated to the effective consolidation pressure σ'_{vc} in a normally consolidated state, OCR = overconsolidation ratio, and m = parameter relating the normalised shear strength ratio to the OCR.

The SHANSEP method relies upon the consolidation test results to estimate the state of stress (preconsolidation pressure) and then select consolidation pressures for the DSS tests.

The SHANSEP method assumes that the normalised shear strength ratio, $\left(s_{u_{DSS}}/\sigma'_{vc}\right)_{nc}$, is a constant value. However, Quirós et al. (2000) have presented DSS test results for soils from various parts of the world including significant data from the Gulf of Mexico. The data set utilised by Quirós et al. (2000) is plotted on Figure 34 in the form of normalised shear strength ratio versus effective consolidation pressure. As indicated by the plot, a trend of decreasing $\left(s_{u_{DSS}}/\sigma'_{vc}\right)_{nc}$ values with increasing values of vertical consolidation pressure is established. Quirós et al. (2000) utilised a least-squares regression on their plotted data to yield the following relationship:

$$\left(\frac{s_{u_{DSS}}}{\sigma'_{vc}}\right)_{nc} = 0.294(\sigma'_{vc})^{-0.113} \qquad (3)$$

where the equation components are as previously defined.

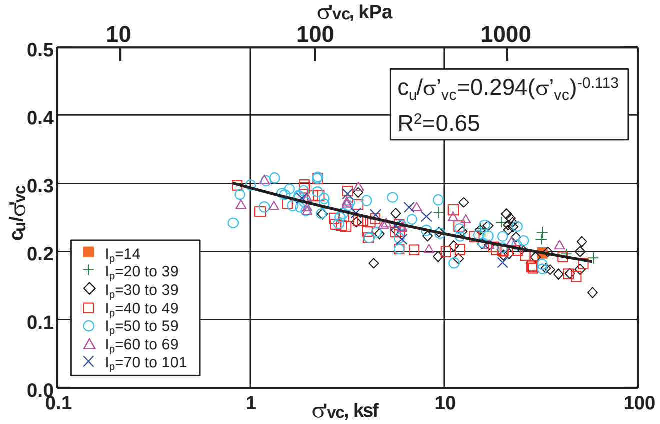


Figure 34: Quirós plot of $s_{u_{DSS}}/\sigma'_{vc}$ versus σ'_{vc} (Quirós et al. 2000) © reproduced with permission of owner. Further reproduction prohibited without permission.

The Quirós et al. (2000) paper cautions that if the above laboratory correlation is employed to estimate the *in situ* shear strength the results are likely to be unconservative due to a decrease in void ratio compared to the *in situ* void ratio. In an effort to further extend the usefulness of their DSS data set, Quirós et al. (2000) studied the possibility of relating the laboratory shear strength data with the "pressure-water content ratio," the effective consolidation pressure divided by the measured final (after consolidation) water content, (σ'_{vc}/W_c). Their data set plotted as DSS shear strength versus the (σ'_{vc}/W_c) ratio is shown on Figure 35. Their equation based on a best-fit line correlation of the data is as follows:

$$s_u = 0.258\left(\frac{\sigma'_{vc}}{W_c}\right)^{0.686} \qquad (4)$$

where the equation components are as previously defined.

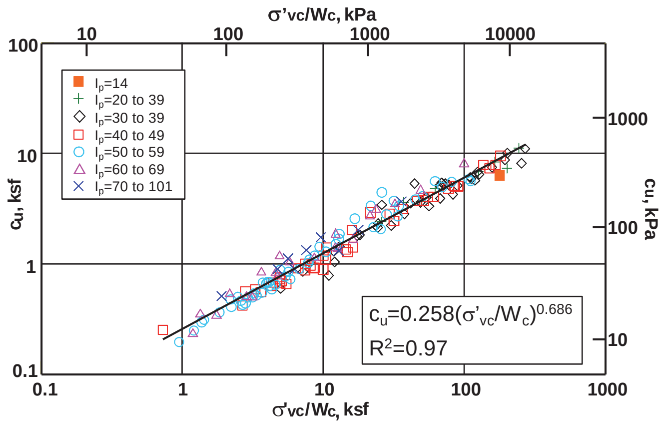


Figure 35: Quirós plot of $s_{u_{DSS}}$ versus σ'_{vc}/Wc (Quirós et al. 2000) © reproduced with permission of owner. Further reproduction prohibited without permission.

Quirós et al. (2000) states that the above equation may be useful in preliminary evaluations of shear strength where no advanced testing is available, but cautions that site-specific determination of the relation between undrained shear strength and the pressure-water content ratio (termed the "SPW" line) is advisable. They also state that the history of successful application of the stress-history approach to offshore *in situ* shear strength evaluation may demonstrate that sample strength in offshore environments generally are more strongly influenced by past maximum consolidation than soil structure. Their study also indicates that the database shows no reliable correlation between the normalised shear strength ratio and the soil plasticity indices.

The author has found on numerous deepwater Gulf of Mexico studies that the SHANSEP method and the Quirós SPW method give very consistent results for interpreting the undrained shear strength profile. The following case study shows how the CPT and SHANSEP data provide a more reliable measure of soil strength and improve our ability to interpret an undrained strength profile.

The study as reported by Caruthers et al. (2014) presents data acquired at the Tubular Bells development located at a depth of 1,250m in the Gulf of Mexico. Two geotechnical site investigations were conducted in the same geologic setting to accommodate a shift in the mooring locations ranging from about 1.6 to 5.6km. This study provides an excellent opportunity to compare both laboratory and *in situ* testing data acquired from a specialised geotechnical drillship and a seafloor-drilling unit. In addition, continuous samples were acquired with a large-diameter corer and CPT data were acquired with a vessel deployed CPT system, CPT-Stinger.

The CPT profiles as shown in Figure 36 are from data acquired by the two different CPT systems within the Tubular Bell mooring area. The total cone resistance measured from all 18 CPT soundings reveals basically no spatial variability verifying the uniform geologic/geotechnical conditions throughout this large area. Sub-bottom profile lines across the mooring spread area confirm the uniformity and consistency of the subsurface stratigraphy that allows for direct data comparison.

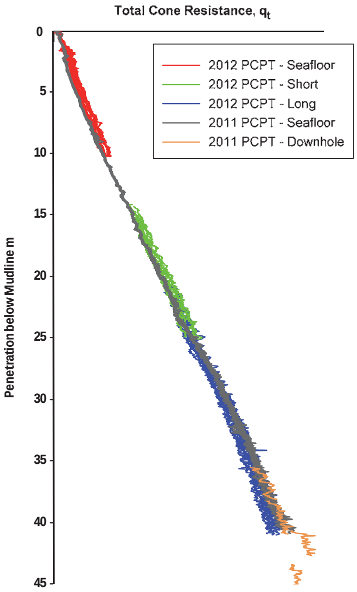


Figure 36: Comparison of CPT data from different cone systems (Caruthers et al. 2014) © reproduced with permission of owner. Further reproduction prohibited without permission.

Contrary to the CPT results, the conventional laboratory strength data shown in Figure 37 reflect a wide range in the measured values. Unconsolidated-undrained triaxial (UU) and miniature vane (MV) tests were performed on recovered samples during both site investigations. The reference line shown in Figure 37 is the same for the two site investigations and was added for comparing the results of the different types of strength results.

To overcome the effects of sample disturbance and stress relief, the SHANSEP approach was used to perform a series of direct simple shear (DSS) tests on recovered samples from the two site investigations. The effects of sample disturbance are evident in conventional strength tests (MV and UU) when compared to the SHANSEP-consolidated DSS tests. (See Figure 37).

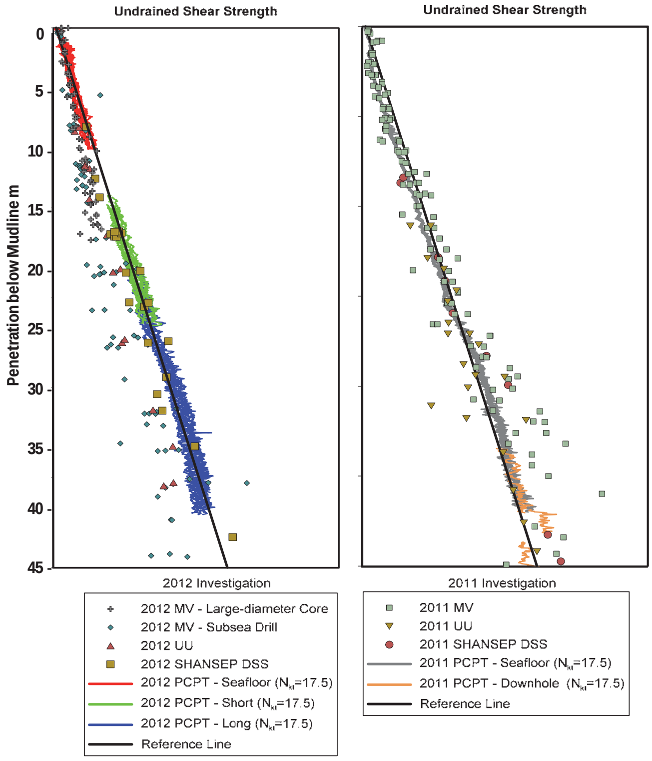


Figure 37: Laboratory and in situ strength data comparison for two investigations (Caruthers et al. 2014) © reproduced with permission of owner. Further reproduction prohibited without permission.

10.4 Sequence Stratigraphy, Geotechnical Soil Properties, and Horizon Age Control

Correlation of sequence stratigraphy, geotechnical soil properties, and horizon age control is critical to the development of the 4D Geo-Site Model. A deepwater development located in a mini-basin in the Gulf of Mexico serves as a good case study showing how the geochronology can be constructed and used. The stratigraphy within the upper 100m of the mini-basin consists of normally consolidated clays represented by parallel, closely-spaced, and continuous reflectors of varying amplitude as shown in Figure 38. The general "layer-cake" stratigraphy is interrupted in regions by geologic erosion, mudflows, shallow debris flow deposits, faults, etc. The development of the 4D Geo-Site Model is important to understand the process-driven causes and timing of these events and their impact on the facilities siting and design.

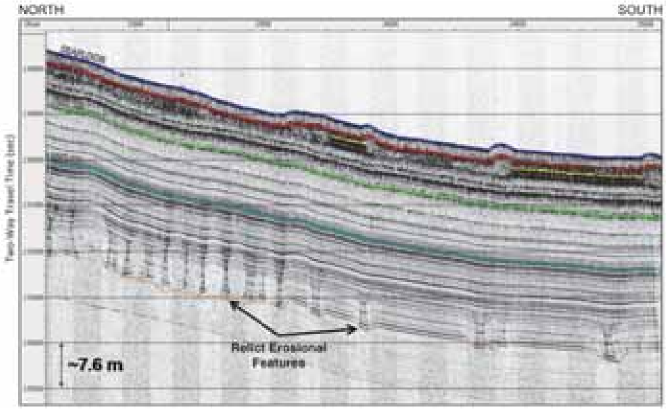


Figure 38: Sequence stratigraphy from a mini-basin in the Gulf of Mexico

A series of JPCs were obtained within the mini-basin to understand the consistency of the stratigraphic conditions. Five key JPC cores as shown in Figure 39 are used to investigate the variability in geological and geotechnical conditions.

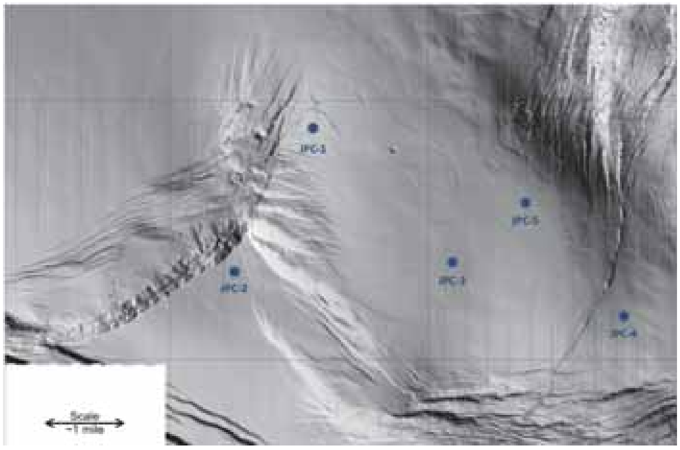


Figure 39: JPC locations in a mini-basin in the Gulf of Mexico

A series of MSCLs were performed on these cores to investigate the uniformity of the sediment stratigraphy within the area of the mini-basin.

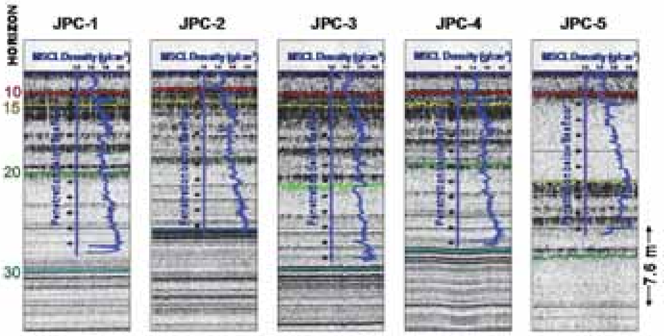


Figure 40: Correlation of JPCs MSCL with AUV profiles

Figure 40 reveals that the stratigraphic sequence is quite consistent over a large area of the mini-basin. Cores JPC-1 and JPC-3 were selected as reference cores. Core JPC-1 was taken on a bathymetric high to isolate it from sediments that moved downslope due to mass wasting processes. Thus, Core JPC-1 serves as a reference of "undisturbed" hemipelagic sediments that were deposited over the last 170,000 to 200,000 years. Core JPC-3 obtained in the middle of the mini-basin and was not impacted by any mudflow deposits except for a thin zone beneath the Triplet. The MSCL profiles and the AUV sub-bottom profiles at the two sites are very similar indicating the depositional uniformity over the entire mini-basin area.

Core JPC-5 was obtained on the western edge of the mini-basin where a 5m thick debris flow deposit was encountered below the Triplet. Figure 41 compares the MSCL logs for JPC-1 and JPC-5.

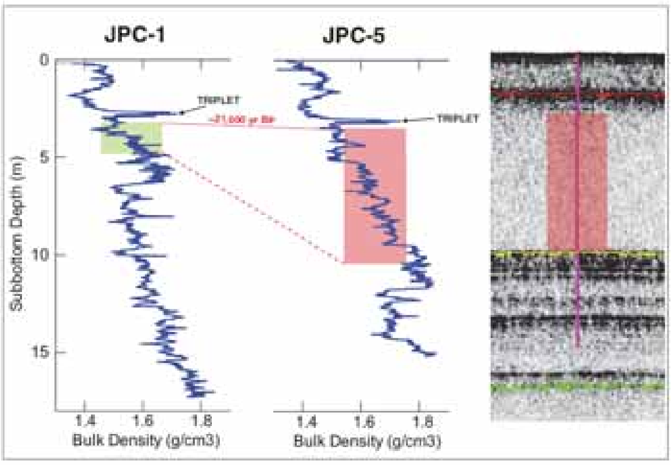


Figure 41: Comparison of JPC-1 and JPC-5 with 5-m thick debris flow deposit

A series of seismic horizons was identified and mapped using the sub-bottom profiler data. The depth range and average depth of each seismic horizon are shown and radiocarbon dating performed on samples taken from the five key JPCs is shown in Table 2.

Table 2: Horizon depth and radiocarbon dates

Horizon Designation	Depth Range (m, bml*)	Average Depth (m, bml*)	Radiocarbon Date**
Horizon 10	4 to10	6	~13,000 ybp
Horizon 15	5 to 27	11	~20,000 ybp
Horizon 20	16 to 62	32	~70,000 ybp
Horizon 30	27 to 88	65	200,000 ybp

*bml - below mudline
**ybp - years before present

The four seismic horizons were mapped across the mini-basin and correlated with the age dates obtained from JPC-1, JPC-3, and JPC-4 as shown in Table 2.

The sequence consists of very soft-to-soft hemipelagic sediments deposited over the last 170,000 to 200,000 years.

A key geologic marker was also observed in all the JPC cores. The "Triplet" marker consists of a series of high-density silt layers that occur at about 2.4m below the seafloor. Three silt seams representing the "Triplet" are evident in the MSCL data as represented by the spikes associated with the amount of silt size material.

This geologic marker was first identified around the Mad Dog and Atlantis Developments as a series of three and sometime four seismic reflectors on the sub-bottom profiler records. These silt rich sediment seams (Young et al. 2003) were deposited during a relatively short period ranging from about 18,900 to 20,160 ybp (Slowey et al. 2003).

The Triplet has also been identified at many other deepwater sites (Stanley, 2017). The wide distribution of the Triplet illustrates the importance of this key geologic marker in understanding the depositional uniformity across a large region of the Gulf of Mexico. It provides a means to understand the process-driven causes and timing of geologic events such as mudflows, seafloor slides, mass-transport deposits, faulting, etc.

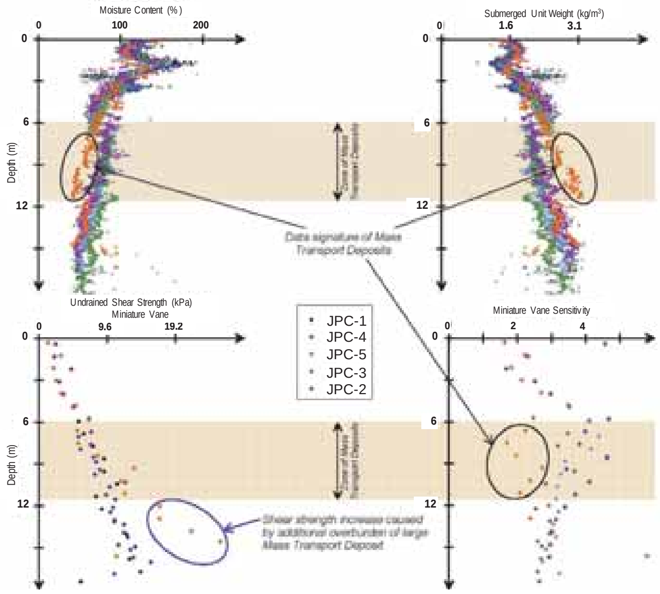


Figure 42: Correlation of geotechnical data across 5 JPC sites

A series of geotechnical tests were performed on the five JPCs to understand the spatial distribution of sediment properties within the mini-basin. The geotechnical testing consisted of moisture content, submerged unit weight, miniature vane shear strength, and remolded miniature vane strength. The results of all the geotechnical testing are presented on a series of plots for the various soil properties superimposed in a single figure as illustrated in Figure 42. The plots for the five key cores reveal a very consistent trend in most of the measured soil properties except for JPC-5. The trend verifies the depositional uniformity throughout the mini-basin and confirms that the geotechnical markers and horizons can be traced to understand the depositional variability and spatial soil properties.

Figure 42 illustrates that the normally consolidated clays generally exhibit with depth a decreasing moisture content profile, and increasing strength and submerged unit weight profiles. The existence of the 5m mass transport deposits at the site of JPC-5 is clearly evident by comparing the different measured soil properties. The moisture contents within the mass transport deposits are much lower and the submerged unit weights are much higher than the remainder of the cores with normal depositional history. It is also interesting to note the sharp increase in the shear strength below the mass transport deposit in JPC-5 due to the surcharge in the overburden pressure.

11 Site Favorability Assessment

Once the 4D Geo-Site Model is complete the integrated team can perform their final evaluation of the risks and potential constraints to the planned seafloor architecture. A proper site favorability assessment must address several key seafloor and geologic conditions/processes. The team will typically prepare a group of site favorability maps that define the installation and operational criteria appropriate for each type of planned facility/foundation. Table 3 presents an example of site favorability criteria as used on past projects.

Table 3: Site Favorability Assessment Criteria (Young and Kasch, 2011) © reprinted with permission of J. Ross Publishing. Further reproduction prohibited without permission.

SITE FAVORABILITY ASSESSMENT CRITERIA

Potential Geo-Constraint	Mudmat	Suction Caisson	Pipeline
Steep Slope Gradient	3°	15°	20°
Slope Reversal (Irregular Seafloor Topography)	3°	10°	15°
Fault Displacement/ Offset	<0.1 m for 10^{-3} annual recurrence	<1m for 10^{-3} annual recurrence	<3 m for 10^{-3} annual recurrence
Deep Seated Slope Instability	Slope < 5° FS > 1.5	Slope < 15° FS > 1.25	Slope < 18° FS > 1.2
Shallow Seated Slope Instability	Slope < 5° FS > 1.5	Slope < 15° FS > 1.25	Slope < 18° FS > 1.2
Debris/Turbidity Flows	Avoid	Limited	Avoid
Highly Variable Soil Conditions	Avoid	Possible	Acceptable
Gas/Fluid Expulsion Shallow Water Flow	Avoid	Avoid	Limited

Examples of site favorability maps prepared for the West Nile Project offshore Egypt are shown in Figure 43 as described by Moore et al. (2007). Final selection of the optimum site for each seafloor facility often requires an iterative process of shifting the architecture to place all seafloor facilities at favorable sites to satisfy each of the individual criteria. In addition, the various types of data used to construct the 4D Geo-Site Model may need to be reviewed for further analyses to understand the severity of the constraint.

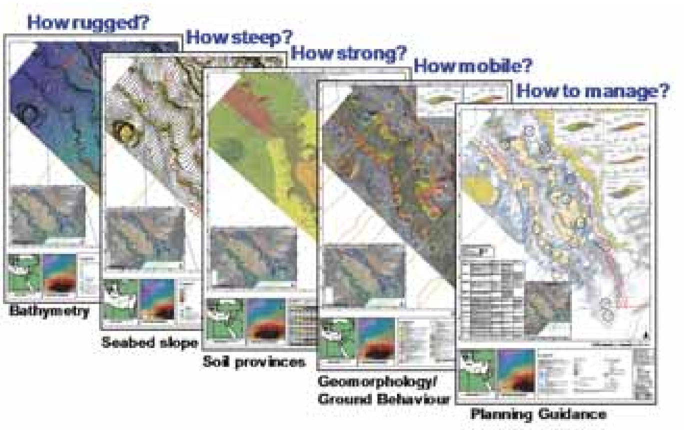


Figure 43: Example of site favorability maps for West Nile Project offshore Egypt (Moore et al. 2007) reprinted with permission from Moore with Halcrow Group Ltd., Usher and Evans with BP.

Table 4 shows the type of data required to evaluate each potential geo-constraint and provides references showing the types of analysis employed and how their evaluation may be performed.

Table 4: Data Requirements and References for Various Geo-Constraints (Young and Kasch, 2011) © reprinted with permission of J. Ross Publishing. Further reproduction prohibited without permission.

GEO-CONSTRAINT	DATA REQUIREMENTS							REFERENCES
	Deep Cores	MSCL	Borings	Sub-Bottom Profiles	Swath Bathymetry	Advanced Testing	Age Dating Control	
Steep Slope Gradients	Yes	Yes		Maybe	Yes		Yes	Young et al. (2011)
Slope Reversal (Irregular Seafloor Topography				Maybe	Yes			
Fault Displacement/ Offsets	Yes	Yes	Maybe	Yes	Yes		Yes	Angell et al. (2003) Orange et al. (2003) Slowey et al. (2003)
Deep-Seated Seafloor Instability	Maybe		Yes	Yes		Yes	Yes	Nadim et al. (2003) Orange et al. (2003) Nowacki et al. (2003) Al-Khafaji et al. 2003)
Shallow-Seated Seafloor Instability	Yes	Yes	Maybe	Yes		Yes	Yes	Brand et al. (2003b)
Debris/ Turbidity Flows	Yes	Yes		Yes	Yes	Yes	Yes	Niedoroda et al. (2003)
Spatial Soil Variability	Yes	Yes	Yes	Yes		Yes	Yes	Young et al. (2003) Brand et al (2003b)
Current and Erosion	Yes	Yes		Yes	Yes	Yes	Yes	Brand et al. (2003a) Niedoroda et al.(2003)
Gas/Fluid Expulsion Shallow Water Flow			Maybe	Yes	Maybe			Eaton (1999a,b) Pelletier et al. (1999)

The following sections describe the scope of work and methods of analyses often used to evaluate the design impact of each geo-constraint (Young and Kasch, 2011).

11.1 Slope Gradient/Reversal (Irregular Seafloor Topography)

Final placement of any facility or pipeline requires a detailed assessment of the seafloor gradient and potential irregular topography throughout the foundation footprint. As indicated in Table 4 various foundation types have different criteria in terms of the maximum slope or slope reversal that may be acceptable for placement to achieve satisfactory performance. For example, a mudmat typically must be placed on a seafloor of less than 3° to insure uniform foundation contact and skirt penetration and to avoid excessive loading on jumpers. A suction caisson may be placed at a site with seafloor gradients up to 15° and pipelines may be designed to cross seafloor slopes as great as 20°.

The designers on the integrated team will need to set the tolerances for each facility type in the assessment criteria for the planned layout of the field architecture to accommodate the requisite criteria. A slope gradient map can be prepared from the swath bathymetry data. The slope gradient map may be color coded to outline the areas that are favorable (green) compared to those areas that are off limits (red). Thus, all seafloor facilities may be shifted or foundation types changed to keep all facilities in favorable areas.

11.2 Fault Displacement/Offset

Faulting may result in significant extension along the slip zone and deformation in the general area of seafloor facilities that must be considered in their siting and design. The long-term risk must be evaluated relative to the fault displacement/offset in terms of an annual recurrence tolerable for each type of facility.

To determine the annual frequency of occurrence for different size of individual fault movements per event requires a methodology classified as a probabilistic fault displacement hazard analysis (PFDHA) as described by Angell et al. (2003). The input parameters are the selection of representative marker horizons, their age, the cumulative offset, and the average displacement per event. An accurate measurement of fault displacement of each marker horizon requires high-resolution sub-bottom profiler data and good age control as discussed in Section 9.5.

The first result of the PFDHA methodology as described by Youngs et al. (2003) estimates the fault displacement as one large discrete event (>1m). The second result estimates the fault displacement as creep movements for a large number of small events (0.1 to 1.0m). The results of the PFDHA are presented as a hazard curve. The hazard curve for each individual fault crossing shows the risk in terms of the displacement per single event as compared to the frequency of exceeding the specified displacement. The hazard curve can then be used to select the site for each facility relative to the assessment criteria indicated in Table 4 for each facility type. The probability of recurrence for the three types of facilities varies from 0.1 to 3.0m for a 10^{-3} annual frequency of exceedance.

11.3 Deep-Seated Seafloor Instability

Offshore slope failures often called submarine landslides occur in many forms within various worldwide geologic provinces depending upon the type of trigger mechanisms as described by Hampton et al. (1996) and Mulder and Cochonat, (1996). Unstable slopes may pose a direct threat to any downslope field infrastructure and must be addressed as part of the site favorability assessment.

Examples of past slope failures are readily apparent along the Sigsbee Escarpment in the deepwater Gulf of Mexico. The Mad Dog and Atlantis Developments located on the escarpment as shown in Figure 18 are examples where extensive studies were conducted to evaluate the potential risk of both shallow-seated and deep-seated slope failures. Integrated studies as described here were conducted to obtain geophysical, geotechnical, and geologic data needed to develop models for slope stability evaluation.

The upper and lateral movement of the Sigsbee Salt Nappe has resulted in the seaward movement of the thin-skinned sediment section, over-steepening of the slope, and resulting deformation of the slope sediments. The process has produced gravity driven slides resulting in 35 large-scale slumps, (13 at Atlantis, 11 at Mad Dog, and 11 between the two developments) as shown in Figure 18. Thus, installations must be assessed near the edge of the Sigsbee Escarpment and those placed downslope where they may be hit by debris flows that can travel surprisingly long distances.

Slope stability analyses to evaluate the risk for deep-seated slope failures require an extensive amount of information on the soil properties throughout the soil profile (Duncan, 1996). The available seismic data was used to locate slope areas where there is a high risk of slope instabilities. Then soil borings and *in situ* testing sites are selected to ground-truth sediment stratigraphy and to define soil properties. The objective of the field program is to gather field data and samples for laboratory testing representative of the individual soil strata.

Nowacki et al. (2003) described the slope stability analysis using the static limiting equilibrium method based on the Morgenstern and Price (1965) procedure to analyze circular and non-circular surfaces. Since a trigger mechanism was not clearly evident, both undrained and drained analyses were carried out in order to cover different causes of slope failure.

Both the deterministic as well as the probabilistic analyses indicate relatively safe slopes unless an unknown triggering mechanism brings the soil mass to failure. Probabilistic stability analyses were used to study how sensitive the pre-failed slope stability was to possible excess pore pressures (Nadim et al. 2003).

Age control of the different depositional units was also performed to constrain the timing of shallow and deep-seated slope failures. The results reveal that shallow slope collapse events were closely associated with times of low sea level and high sedimentation rates. The last deep-seated slope failure of the Sigsbee Escarpment in the Mad Dog area occurred about 137,000 ybp (Young et al. 2003). This was a period of low sea level and high sedimentation rates. Since we are presently in a time of high and rising sea levels and low sedimentation rates, the risk of shallow slope failure is considered low. The author believes that the Mad Dog and Atlantis areas are now in a state of geological quiescence since the frequency and size of mass-wasting events were greatest during the last glaciation (sea level low stand) and have since decreased.

11.4 Shallow-Seated Seafloor Instability

Although the steep slopes beneath the face of the Sigsbee Escarpment consist of competent over-consolidated soils, the face at many locations is covered by a shallow drape of soft clay. There is evidence that the soft soils have failed and more frequently in recent times than the deep-seated slides (Young et al. 2003).

The failures pose a risk of a debris slide or turbidity current that would move downslope and possibly damage or destroy existing field production infrastructure (Randolph et al. 2005). Thus, it was necessary to assess the potential for shallow-seated slope failures at the site and to select sites favorable for seafloor facilities on the escarpment face or downslope from it.

The extensive seafloor area occupied by large developments like the Mad Dog and Atlantis

Development makes it difficult to assess all areas with individual cores. A new method as described by Brand et al. (2003b) integrated available geotechnical core data and 3D seismic data to predict the location of critical areas for shallow-seated slope failures.

The data from the cores and the 3D seismic data were used to correlate acoustic impedance with seismic amplitude, and correlate shear strength with acoustic impedance as illustrated in Figure 44 and Figure 45, respectively. By combining these two correlations, it was possible to develop a relationship between seismic amplitude and soil shear strength. For the 3D data as used by Brand et al. (2003b), variations in the amplitude of an individual seismic reflection corresponds ~10m thick interval of the seabed.

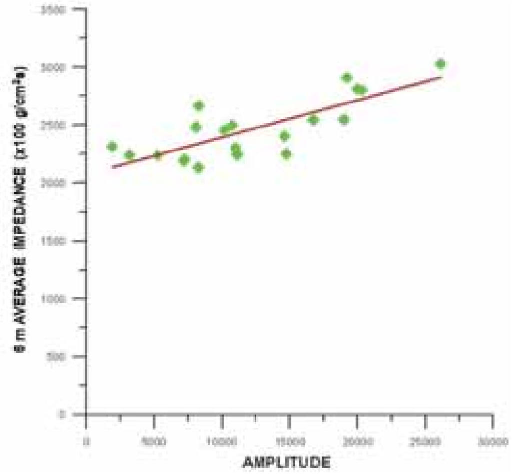


Figure 44: Seismic impedance versus amplitude correlation (Brand et al. 2003b) © reproduced with permission of owner. Further reproduction prohibited without permission.

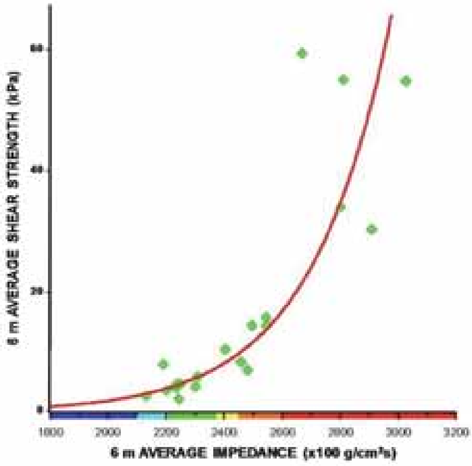


Figure 45: Seismic Impedance versus Soil Shear Strength (Brand et al. 2003b) © Reproduced with permission of owner. Further reproduction prohibited without permission.

The potential of slope instability due to shallow-seated landslides was investigated using a limit-equilibrium method based on infinite slope analyses. Drainage conditions analyzed included both long-term, drained events using effective stress parameters, and "triggered" short-term events, using total stress parameters.

The results of the slope stability analysis were used to establish criteria that allowed locations with potentially weak shallow sediments to be identified based upon steep seafloor gradients evident on multi-beam and 3D seismic data as shown in Figure 46. Potentially unstable locations exist in the gullies, channels, and other depressed areas along the edges of each slump region. Critical locations, where the computed factor of safety approached 1.0, were mapped; and the areas, volumes, and strengths of the potential failed material were computed. These values were provided as input parameters for the volume run-out analysis to be described in a later section.

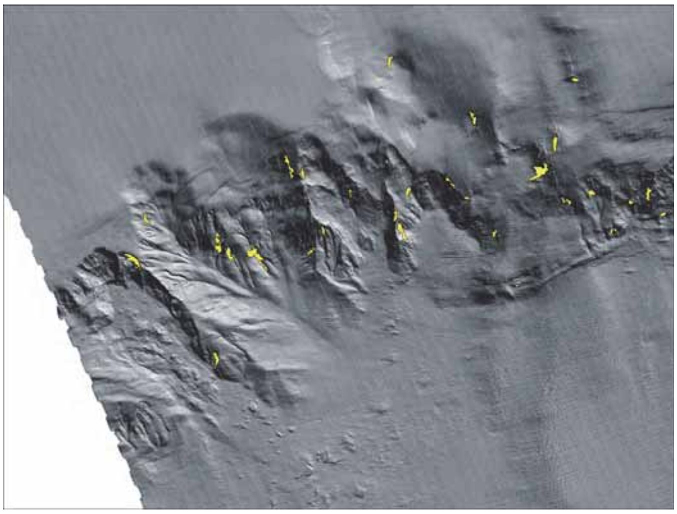


Figure 46: Critical slope areas identified from shallow-seated slope analyses (Brand et al. 2003b) © reproduced with permission of owner. Further reproduction prohibited without permission.

11.5 Debris Flows/Turbidity Currents

Mass gravity flows are a significant geo-constraint that may pose significant risk to seafloor facilities positioned within their path of travel. Seafloor instabilities on the steep slopes within the Mad Dog and Atlantis Developments reveal a rugged relief as shown in Figure 18. The excavation of failed soil masses that moved rapidly down the slope as mass gravity flows characterises these slope failures. Many seafloor features exist on and near the base of the Sigsbee Escarpment that formed as a result of mass gravity flows.

The mass gravity flows are categorised as debris flows, mudflows, and turbidity currents. As indicated by Niedoroda et al. (2000) and Niedoroda et al. (2003), the gravity flows most frequently occurring in the marine environment are divided into two broad categories, debris flows and turbidity currents. These two types are governed by different flow regimes and require different flow models.

The Bing Model (Jiang and LeBlond, 1993) was first used to simulate a number of debris flows observed in the project area. After identifying the potential unstable areas from the shallow-seated slope stability analysis, the volume and character of the soil properties of the failed area were measured for input into the debris flow analyses as described by Niedoroda et al. (2003). The turbidity current model required modification to replicate the field conditions to match observed features of turbidity current deposits

Diagnostic modeling is first performed to demonstrate that the models replicated observations of past mass gravity flows that would overrun any planned facilities. The calibrated numerical models were used to predict likely flow paths and the kinematics of potential flows. The results then helped establish the criteria to avoid their action in the design of seafloor production and transportation facilities.

As part of these analyses, the integrated team conducted a site assessment of the following conditions: (1) cataloged past mass gravity flows; (2) evaluated the causes for various events; (3) characterised the kinematics (speed, dimensions, run-out distance of each flow; and (4) compared the past flows to potential flow exposures.

The debris flow/turbidity current modeling required full use of all integrated data sets to model seafloor conditions. The models for debris flows included the size of the source sediment traveling down the slope until it came to rest as the potential energy was dissipated by friction. The turbidity current models must include the gravitational energy that drives the flow of suspended sediment and ambient water down the slope. The results of the mass gravity flow analyses allowed for successful design and installation of seafloor facilities (Niedoroda et al. 2003).

11.6 Spatial Sediment Properties (Highly Variable Soils)

Once the 4D Geo-Site Model has been completed, maps showing the spatial soil properties can be prepared to understand the potential for spatial variability and to identify areas where highly variable soil conditions exist which should be avoided. The sub-bottom profile data can be used to construct cross-sections or fence diagrams as shown in Figure 47 to correlate with the geotechnical data. The seismic amplitude data can also be used as described by Brand et al. (2003b) and Berger et al. (2006) to extrapolate soil properties such as shear strength throughout the area of the planned seafloor architecture. These capabilities may be some of the more important features of the 4D Geo-Site Model since both help limit the amount of geotechnical data acquired. In addition, the ability to extrapolate soil strength allows one to construct with confidence soil province maps that confirm foundations such as mudmats are placed at sites with uniform soil conditions.

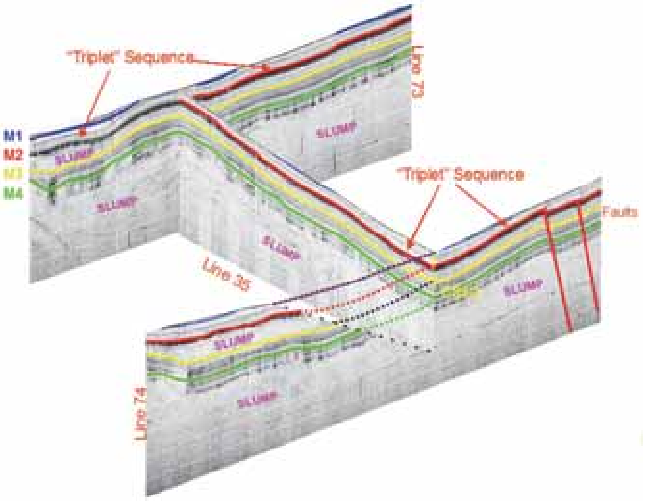


Figure 47: Fence diagram schematic of debris flows (Brand et al. 2003a) © reproduced with permission of owner. Further reproduction prohibited without permission.

To construct an accurate soil province map, a "proper reference datum" is required to understand how the sediment depositional history has influenced soil variability within 3-dimensional space associated with the site development. The seafloor has traditionally been used as the fixed vertical datum for plotting the boring log that shows soil properties versus depth below the seafloor. The seafloor reference works well for an individual site; however, this datum does not work when comparing soil properties between individual geotechnical sites if the sediments exposed at the seafloor are not the same age at all sites.

To understand how the sediment properties vary spatially throughout the development area often requires a vertical reference linked to the geologic history of how and when the sediments were deposited. Thus, age control correlated to isochronos marker horizons (such as the Triplet) identified in the sub-bottom profiler data generally serves as a better vertical reference for mapping spatial soil properties.

An example illustrating why a marker horizon is a better vertical reference is shown in Figure 48. The example shows a total of nine continuous CPTs obtained in a federal lease block in the Gulf of Mexico where seafloor currents have formed mega furrows due to erosion of the sediments from the seafloor to depths up to 10m. When s_u obtained with continuous CPTs are plotted on a single plot with seafloor as the reference, there is band of large scatter in the plot of strength versus depth (blue lines) below the seafloor as illustrated in Figure 49. If the same CPT data is plotted using a marker horizon (Triplet) as the appropriate vertical reference, then the plot of strength versus depth shows a single strength profile for all nine CPTs. The strength at the marker horizon depth is also the same for all CPTs. (See right depth scale).

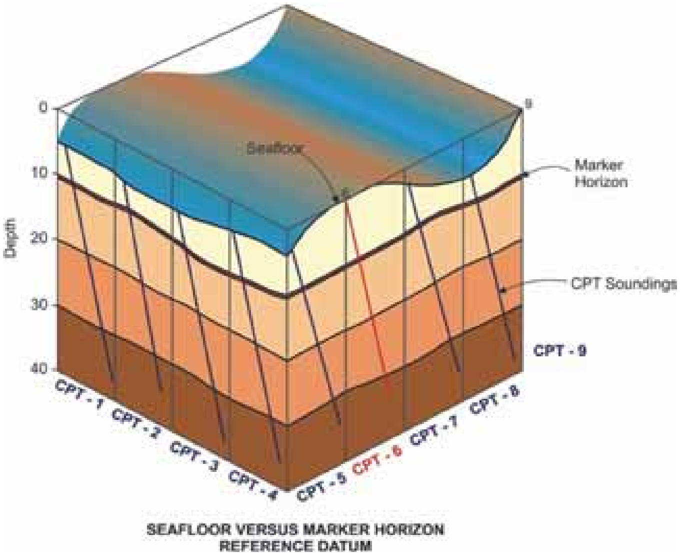


Figure 48: 3D geo-site model showing 9 CPT strength profiles (figure provided courtesy of Alan G Young).

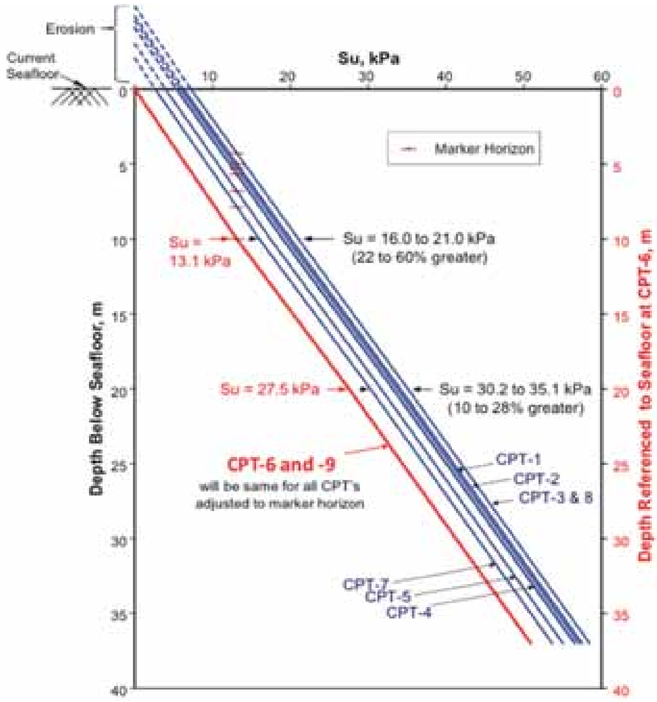


Figure 49: CPT strength profiles using seafloor and marker horizon at CPT-6 as reference datum (figure provided courtesy of Alan G Young).

The variation in strength makes it very difficult to extrapolate soil profiles throughout the development area since the seafloor reference does not take into consideration the depositional history as reflected by the stratigraphic sequence observed in the sub-bottom profiler data. Figure 49 shows that the strength at 20m depth is 27.5kPa for all marker horizon adjusted CPT profiles compared to a range of 30.2 to 35.1kPa for all the CPT profiles using the seafloor as the reference depth.

The process of integration means that the geotechnical properties should be tied to the depositional history as reflected in the stratigraphic horizons that can be identified and mapped in the sub-bottom profile data. Representative samples taken near each marker horizon share the same stress history, so the undrained shear strength will be the same as verified by the CPT plots adjusted to the same vertical reference using a marker horizon. If the samples used for SHANSEP testing are selected to correlate with identifiable marker horizons, then the undrained shear of the marker horizon can be extrapolated throughout the area of the seismic data.

11.7 Shallow Water Flow

Shallow water flow occurs when water from a saturated sand aquifer flows up the casing string eroding the surrounding sediment supporting the casing. The problem was first identified in 1996 within some deepwater areas of the Gulf of Mexico associated with setting the conductors for the Ursa Development as described by Eaton (1999a and 1999b). Shallow water flow reduced the lateral stability of the casing resulting in structural damage and lost circulation as described by Pelletier et al. (1999).

An assessment of the potential risk for shallow water flow for future wells is generally performed with conventional 3D seismic data as described by Berger et al. (1998). High-resolution 3D data provide even more detail for evaluating the risk of shallow water flow as described by McConnell and Campbell (1999). The high-resolution 3D data helps define the geometry of potential channel or turbidity flow units where sand prone deposits may produce shallow water flow conditions. Thus, the proposed location of the well may be moved or a well casing and mud program may be designed to address the depth intervals where shallow water flow deposits may be encountered.

12 Site Assessment Risk Matrix

Selection of the final sites and foundation types for different project facilities means that the risks must be evaluated relative to their seafloor conditions, installation methods, and expected operating performance. Several site assessment factors may be used as a modified risk matrix as described by Young et al. (2009) to conduct the site assessment as shown in Table 5. The integrated design team can use all the data available in the 4D Geo-Site Model to evaluate each proposed foundation site as they lay out the seafloor field architecture. The site assessment risk matrix includes the following factors: 1) maturity of the foundation concept; 2) difficult soil conditions; 3) spatial soil variability; 4) type of seafloor strength profile; 5) foundation experience within the project area; 6) confidence in computed foundation capacity; and 7) seafloor topography.

Table 5. Site assessment risk matrix (SARM) (table modified after Young et al. 2009) © reproduced with permission of owner. Further reproduction prohibited without permission.

SITE FACTOR	RISK RATING					WEIGHTING FACTOR
	Low		Medium		High	
	1	2	3	4	5	
① Maturity of Foundation Concept	**1** Long History–Driven Piles		**3** Recent History–Gravity Anchors		**5** Novel Foundation Concept	3
② Difficult Soil Conditions	**1** Uniform Clay		**3** Weak over Strong Clay		**5** Carbonate Soil with Cemented Layers	3
③ Spatial Soil Variability	**1** Uniform, Layer-Cake Stratigraphy		**3** Sloping Soil Layers		**5** Highly Irregular	3
④ Type of Seafloor Strength Profile	**1** Normally Consolidated		**3** Stratified		**5** Overconsolidated	3
⑤ Foundation Experience in Area	**1** Foundation Previously Used		**3** Modest Use in Region		**5** No Foundation Use	2
⑥ Confidence in Computed Foundation Capacity	**1** High Safety Factor		3 Acceptable		**5** Low Safety Factor	2
⑦ Seafloor Topography	**1** Flat		3 Undulating		**5** Steep or Highly Irregular	2

The site assessment risk matrix is completed for each site factor by assigning a risk rating varying from 1 for those with the least risk to 5 for the highest level of concern for potential risks. Each rating for the site factors is multiplied times a weighting factor to assign the most critical factors of risk. The sum of all risk scores yields an overall site assessment risk rating. When the site risk rating is high (greater than 60), either a different foundation type should be selected, the foundation site moved, or additional work performed to demonstrate that the desired installation and foundation performance might be achieved.

12.1 Final Foundation Selection and Design

The principal risks in foundation design are associated with uncertainties in selection of design parameters, determination in foundation loads, and design method reliability. Each foundation type has a different level of reliability in terms of these foundation design uncertainties. Deepwater foundations are generally divided into two broad applications: 1) foundations (anchors) used for mooring and 2) foundations used to support seafloor facilities.

The most suitable foundation type is generally dependent upon:

1. understanding all the sediment properties;
2. satisfying the available installation procedures;
3. providing required capacity to resist the most critical loading conditions; and
4. limiting foundation movements to satisfy the structure tolerances.

Thus, the combined soil-foundation system must be designed to resist the maximum foundation loading applied during the facilities operating life without experiencing soil failure or excessive movement.

The challenge is to recognise the most crucial geologic features and understand their depositional nature and potential impact relative to the physical location of the proposed field architecture. Interpretation of the engineering properties surrounding a site is probably the most difficult task to be accomplished, bringing into focus the need for high quality site investigations to identity the spatial trends in the development area.

There are two types of uncertainty associated with acquiring data during an offshore site investigation. There is natural uncertainty about the random variability of the physical properties of the soil deposit that are called aleatory uncertainties. Epistemic uncertainties are defined as uncertainty due to lack of knowledge that can be reduced with additional data (Christian, 2003).

Our lack of knowledge of the spatial distribution of specific soil properties deposited in chaotic (i.e. high energy) conditions creates the epistemic uncertainty. Random errors in testing or sample disturbance can create much of the aleatory uncertainty, although some spatial variability in identified sediment trends are often considered as aleatory uncertainty.

Christian (2003) believes that geotechnical engineers generally face epistemic uncertainties. The acquisition of high quality geophysical and geotechnical data helps eliminate the epistemic uncertainty. Aleatory uncertainties associated with chaotic depositional processes such as debris flow deposits are much more difficult to define and should be avoided if possible. In summary, the 4D Geo-Site

Model allows geotechnical engineers to more accurately understand how different geologic processes impact the epistemic and aleatory uncertainties for the various soil profiles. It allows the preferred foundation type and site to be selected with more certainty and to avoid site conditions that pose high risks.

12.2 Ambiguous Regulatory Requirements

API, ISO, and BSEE have previously published a number of regulations and guidelines that describe the requirements for conducting deepwater geophysical/geotechnical investigations. Since publication of many of these standards, numerous advances have been made in site investigation technology (geophysical and geotechnical field methods) that have improved the quality of data used to construct the 4D Geo-Site Model.

In recent years, practicing geotechnical engineers working on deepwater offshore projects have found that establishing the scope of an offshore site investigation is challenging. The difficulty lies in the ambiguity and conflict in the regulations leading to a lack of consensus between the regulators and practicing geotechnical engineers as to what constitutes the best practices.

An example of a regulation governing the foundation design for floating moored structures in the Gulf of Mexico that has caused much confusion is presented in Section 250.915b published by the Minerals Management Service (MMS) in 2005 (Title 30-Mineral Resources, 2005). The regulation states that a boring must be taken at the most heavily loaded anchor location and at anchor points approximately 120° and 240° around the anchor pattern from the boring, and as necessary to establish a suitable soil profile. These regulations 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.

In addition, some regulators have assigned to date a very limiting definition to the term “boring” meaning a borehole advanced by rotary methods from a drillship. *In situ* testing with a CPT or long cores apparently do not satisfy their requirement of a “boring.” Compounding the difficulty, the traditional methods of drilling soil borings with a deepwater drillship are often very time consuming and expensive, which tends to minimise soil data collection. This may represent the greatest potential risk to overall foundation reliability. In addition, some regulators do not appear to appreciate the benefit of conducting an integrated 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. The geophysical data provides comprehensive coverage of the entire development area allowing extrapolation of soil stratigraphy and properties.

A panel of industry experts recently conducted a study (Young et al. 2013) to provide an independent review of the current US regulations including their historical development. The objective was to ensure that the regulations reflect the latest improved methods for conducting deepwater geophysical and geotechnical investigations. The panel recommended that changes in the regulation language be implemented to provide the practicing engineer more flexibility and to avoid ambiguity among regulators. It was the opinion of the panel members 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.

In lieu of the prescriptive requirement of the standards, the panel of experts recommended that different wording as stated in ISO/DIS 19901-4 should be adopted for worldwide application:

> *Geotechnical and Foundations Design Considerations*
> *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.*

In 1962 Dr. Ralph Peck emphasised 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 for achieving 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 geotechnical engineer now has an outstanding set of tools for developing engineering parameters for a myriad of geologic conditions so that he/she can confidently and economically design anchors and foundations around the world. This expert panel study emphasised 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. In summary, regulations should not be written to be overly prescriptive. Realizing the potential of the integrated approach means that stakeholders can focus on methods for acquiring data that will be most informative or have the greatest impact on project-specific decisions.

13 Risk and Design Reliability

Installation of permanent production systems in deepwater regions around the world always poses an element of risk. Risk is commonly represented by the probability of occurrence and consequence of a loss. Consequences can include human safety, environmental, and economic losses.

In order to mitigate foundation risk, operators and regulators must acquire an appropriate quantity, quality, and type of subsurface data. Geophysical data provides the greatest coverage of a project area and is quite useful for deducing the geologic conditions and spatial soil variability in the area. Thus, it helps set the scope of the geotechnical investigation to ground-truth the geophysical data.

A common decision point in offshore design is whether or not additional data are needed or would be beneficial enough to justify the cost, effort, and time to acquire the data. The value of additional data depends on how much those data are expected to reduce design conservatism and improve foundation design and control risk. Maximizing the value of information entails finding the optimal combination of design information and conservatism, such that the combination will minimise the total expected cost and maintain the requisite reliability.

The reliability of a foundation depends on the following factors, as summarised by Clukey et al. (2013):

- uncertainty in establishing geotechnical properties for design (e.g., a design profile of undrained shear strength versus depth) due to limited site-specific data;
- uncertainty in the actual capacity of a foundation compared to the capacity predicted with the design method; and
- uncertainty in the loads that will be applied to the foundation over its service life.

It is important to consider that uncertainty in geotechnical properties is not necessarily the largest determinant of the performance of a foundation and that eliminating this source of uncertainty does not eliminate the risk of a foundation failure. We must remember that most of the foundation design methods are empirical and need to be correlated to the same reference strengths as measured in the experimental testing. Mr. McClelland highlighted the importance of this factor as stated:

LESSON 5: Rely on experimental testing and case studies to calibrate the empirical foundation design methods.

Most foundation design methods are correlated to empirical tests where high quality samples or *in situ* testing was performed to establish the reference strengths. Thus, it is important that the methods described in this paper be used to select the design strength profile in the future to improve the reliability in foundation design.

Reliability analyses, such as described by Gilbert et al. (2010), provide guidance in establishing the value of various geophysical and geotechnical investigation methods in reducing the uncertainty in soil properties for foundation design. An integrated study provides all the data needed within the framework of the 4D Geo-Site Model to provide more certainty in interpreting the geotechnical properties and improving the design reliability.

14 Realizing the Full Potential of 4D Geoscience Study

The full potential of an integrated geoscience study is not fully appreciated by many professionals working in the offshore industry. Some believe that an integrated study is only needed when the geology is extremely complex and fraught with geohazards (risks that they do not understand). The author believes that all offshore geoscience studies should be conducted using the integrated approach no matter how mundane site conditions may appear. The beauty of the integrated study is that the level of work can be tailored to fit the complexity of the site conditions and foundation elements. The desk study provides an initial 3D Geo-Site Model that generally defines the complexity of the regional site conditions and potential constraints that must be addressed. Thus, the scope of the geophysical investigation can be carefully planned to address specific constraints and confirm that data coverage is adequate for the planned seafloor architecture.

Part of the problem is that our technical disciplines remain isolated by departments in setting up their university courses and research work. Thus, it may be difficult for a student in geotechnical engineering to take a course in marine geology, and vice versa. In fact, students in one discipline may not realise the value of understanding related disciplines. The inability of each professional on an integrated team to understand and appreciate the other technical disciplines, therefore, is the primary reason that the integrated approach is critical to understand all factors that may influence the site development.

One of my favorite clients (Mr. Horace F. House) once remarked to me:

> *You do a great job of investigating and measuring the soil properties within a 9-in borehole, but I still do not know how the soil conditions vary around that borehole.*

Even though Mr. House made this statement over 30 years ago when integrated studies were not practiced, he fully appreciated the need. An early pioneer in geotechnical engineering, Dr. Ralph Peck (1962) previously made these enlightening statements:

> *Subsurface engineering is an art; soil mechanics is an engineering science. This distinction, often expressed but seldom fully appreciated, must be understood if we are to achieve progress and proficiency in both fields of endeavor.*
>
> *Whether we realise it or not, every interpretation of the results of a test boring and every interpolation between two borings is an exercise in geology.*

All these statements highlight why the offshore industry should remember Lesson No. *6* from Mr. McClelland:

LESSON 6: Develop an integrated geologic/geotechnical model to assess risks and define constraints to site development.

An integrated geoscience study allows one to develop criteria for evaluating geo-constraints in terms of risk acceptance, risk avoidance, and risk mitigation. The full potential of an integrated study also allows one to achieve real economic benefit associated with eliminating future risks to the development. This means that all risks have been characterised and evaluated in a consistent manner. Its full potential is realised as illustrated in Figure 50 when the integrated team can quantify the frequency and magnitude of each geo-constraint event upon the impact on all planned seafloor infrastructure.

As described by Jeanjean et al. (2003), the evaluation of risk requires two important considerations: 1) the annual probability of occurrence and 2) a measure of the consequences of all risks in terms of damage to health, environment, capital investment, and company reputation.

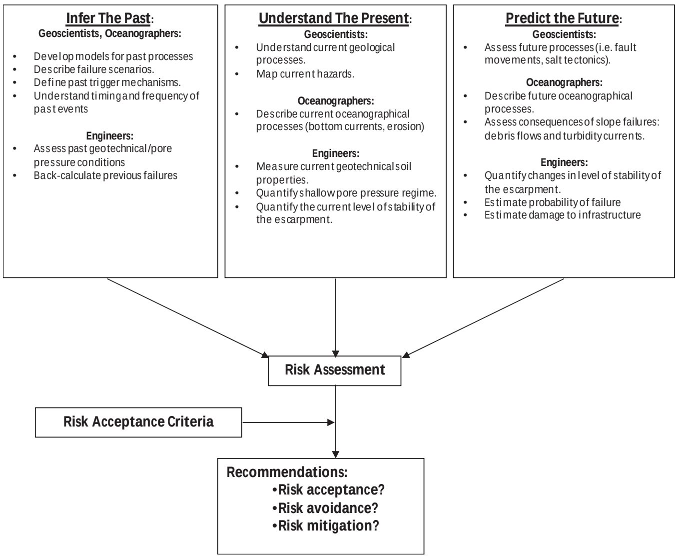


Figure 50: Risk Assessment Criteria (figure provided courtesy of BP, further reproduction prohibited without permission)

The full potential of an integrated study requires the combined experience of all team professionals and coordination of their work activities in executing and meeting project requirements. The full potential is achieved providing a myriad of benefits if one recognises the key to success as stated by Jeanjean et al. (2005):

> *The key to a successful integrated study might reside in gathering outstanding high-resolution geophysical and geotechnical data early in the project, but not too early, hire world-class technical specialists, give them as much time and space as possible, and ensure that they communicate and interact appropriately.*

In summary, there have been many integrated studies conducted over the last 20 years as illustrated by the case studies in this paper that *demonstrate* the potential technical benefits that may be achieved. There is a common misconception that the cost of an integrated study is necessarily more expensive than a more conventional site study and the benefits do not often justify the additional expense. Paradoxically an integrated study on the other hand offers the potential to reduce the overall cost by reducing the scope of the geotechnical investigation and the need to perform additional work if the field architecture is adjusted during the design phase of the project. The ability to confidently extrapolate soil conditions is a benefit that many offshore owner/operators do not fully appreciate because they do not **understand the full potential of an integrated geoscience study.**

15 Summary and Conclusions

Technological improvements over several decades have dramatically changed the way geophysical surveys and geotechnical investigations are conducted or at least should be 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 hence not used in a mutually supportive way to fully understand the subsurface geologic conditions and variability in sediment properties in a cost-effective manner.

A goal of this paper has been to change our way of looking at the seafloor and subsurface conditions. In the past the geotechnical engineers have looked at each site individually and concentrated on defining engineering properties for foundation design relying upon a combination of widely scattered *in situ* and laboratory test data. The marine geologists have focused on mapping "geohazards" and identifying seafloor constraints that might impact the placement of seafloor facilities or the drilling of exploration and/or development wells. When we look together at the seafloor and subsurface condition with a different approach, then we may find that 4D Geo-Site Model will portray many things that we never observed to wit:

> *If you change the way you look at things, the*
> *things you look at change.*
> *Anonymous*

Conducting an integrated study collectively with a team of experts allows one to construct a 4D Geo-Site Model using all geophysical, geotechnical, and geologic data. 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 4D Geo-Site Model provides an important opportunity to identify and define the potential geo-constraints, geologic conditions, and geotechnical engineering properties throughout the project development in a cost-effective manner. The author hopes that the case studies and the processes described in this paper will help the reader understand the full potential of an integrated study by:

> *Integrating the science of geology and*
> *geotechnics to master the art of seafloor*
> *engineering*

The objective of my paper has been to focus on the important interactions needed by the team conducting an integrated study. Each technical expert must understand his role and be capable of explaining the critical factors to other team members. Close collaboration is needed to make sure that all constraints and risks are identified and investigated during each appropriate phase.

Marine geologists and geophysicists need to improve their understanding of the general principles of geotechnical engineering. Geotechnical engineers need to teach themselves more geology in order to appreciate the critical role that geology plays in defining the spatial distribution and variability of soil properties. Both groups of experts need to understand that the CPT and sub-bottom profiler provide the two most important data sets needed to understand the stress history and depositional character of the sediments. Correlation of the two data sets allows stratigraphic definition to be fully interpreted and mapped throughout the full volume of the cube representing the 4D Geo-Site Model. Age dating will then constrain the timing of different depositional systems, establish sedimentation rates, and determine the timing and frequency of past geologic events. The age control is needed to verify that all risks have been characterised and evaluated to allow the field infrastructure to be adapted for the seafloor and subsurface conditions.

The author believes that the geotechnical community needs to change their thinking and break away from traditional practice for conducting a geotechnical site investigation. We should work closely with the marine geologists to maximise the use of the geophysical data to reduce the scope of the geotechnical investigation. We should conduct more CPT testing and less sampling and testing on samples from a soil boring. Frankly, in most cases the continuous CPT sounding will portray a more realistic definition of the depositional character, stress history, and strength gradient than more widely scattered laboratory test data. The use of more innovative geotechnical systems and tools as described previously will reduce the time to conduct the field investigation and provide more reliable and consistent data.

It is my opinion, the CPT and SHANSEP testing provides an improved method for establishing the design strength profiles than drawing lines through widely scatter laboratory test data. Case studies in the Gulf of Mexico and other offshore regions show that an average N_{kt} value of 17.5 will correlate closely with the DSS test results. The N_{kt} value provides very consistent results for normally consolidated clays, but more work is needed to establish the appropriate values for overconsolidated clays.

The author wants to emphasise that regulations should not be too prescriptive allowing experienced engineers and geologists to serve their critical role in planning the scope of the site investigation. Their experience and judgment are critical to understanding the geologic variability and establishing the amount and type of data needed to be informative for the design process and to have the greatest impact on project-specific decisions. The integrated study will reduce uncertainty in the overall design process and provide many benefits in terms of identifying potential constraints and the criteria for evaluating the potential impact of future events during the lifetime of the development.

In closing, the author applauds the vision that Mr. McClelland and other pioneering experts played in identifying the building blocks for conducting an integrated geoscience study. They identified the need for close collaboration between geologists and geotechnical engineers before equipment was available to acquire the high-quality data that can be acquired today. Mr. McClelland taught me six important technical lessons that I have shared in this paper. I dedicate this paper to him. He was a very special mentor and friend. I was so very fortunate to have had the opportunity to work with the first pioneer in offshore geotechnical engineering.

16 Acknowledgement

It is a distinct honor to be selected by the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) to give the Fourth Bramlette McClelland Lecture since Bram was a friend and mentor for over 40 years. The opportunity to work at his company, McClelland Engineers, with his team of outstanding geotechnical engineering experts was a highlight of my professional career. I am indebted to his company for allowing me to work on some very challenging offshore projects around the world.

I also dedicate this paper to my wife, Melinda, who supported my career for the last 46 years. Her dedication to me while teaching kindergarten and rearing three sons, Russell, Matthew, and Samuel, was a tremendous sacrifice that has allowed me to achieve a very enjoyable and fulfilling life.

A number of close friends and mentors supported me in preparation of this paper. Ms. Jill Rivette helped me stay motivated, and her assistance with the text, figures, references, and other details were critical to its successful completion. I also want to thank a group of mentors for reviewing and helping to edit the text. The assistance of Dr. Don Murff, Dr. Philippe Jeanjean, Dr. Niall Slowey, Dr. Bernie Bernard, and Mr. Earl Doyle was very beneficial in preparing this paper.

A number of other friends supported me throughout my career that I would like to acknowledge. This group of professionals who helped advance the state of practice of integrated geoscience studies wrote numerous papers as shown in the reference list. The group includes Dr. Ed Clukey, Dr. Eric Liedtke, and Mr. Dan Spikula with BP; Mr. Chris Hadley and Dr. Craig Shipp with Shell; Mr. Rob Little and Mr. Clarence Ehlers with Chevron; Mr. Mike Kaluza, Mr. Vernon Kasch, Mr. Bill Berger, Mr. Dan Lanier, Dr. John Brand, Ms. Dianne Phu, Ms. Laura Johnson Ms. Oluwayomi Oyedele, all formerly with GEMS; Mr. Steve Garmon with C&C Technologies; Mr. Bob Bruce; Dr. Bernie Bernard and Dr. Jim Brooks; and Mr. Kerry Campbell and Mr. Bill Quirós with Fugro-McClelland Marine Geosciences.

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