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"CPT Stinger" - An Innovative Method to Obtain CPT Data for Integrated Geoscience Studies

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Abstract

A new deepwater static cone penetrometer system, "CPT Stinger", was used to investigate subsurface conditions at a number of production sites in the deepwater Gulf of Mexico. Same site high-resolution geophysical data and long cores obtained with a Jumbo Piston Core (JPC) system illustrate the excellent correlation obtained with continuous geotechnical and geophysical data for defining the spatial variation in soil properties.

The high cost of drilling deepwater borings and sampling at widely spaced intervals imposes a significant constraint on obtaining a sufficient quantity of high quality soils data. Thus, improved methods are desirable for more quickly assessing requisite soil properties without sacrificing accuracy. The "CPT Stinger" system is a new tool that can fill this role.

This new system allows the same general suite of JPC coring equipment to be modified for CPT testing and can be deployed from an oilfield supply vessel. By simply replacing the standard piston core liner with a CPT system containing thrusting rods, a power/control module, and CPT data logging system, the field operation can quickly be converted from sampling to in situ testing mode. The results show that the new system provides continuous soundings with centimeter-depth accuracy and stratigraphic consistency. In addition to the acquisition of high-quality static CPT data, the sampling rate of the CPT logger allows the acquisition of dynamic CPT data during free fall that can be adjusted for velocity differences to emulate static data

A particularly effective way to use the system is in conjunction with nearby, continuous sampling with JPC cores and subbottom seismic profiles. This allows the correlation of the CPT results with strengths from continuous samples over a significant depth of overlap and with the geophysical cross sections. Correlations are presented in the paper for undrained shear strength data from long cores with *in situ* CPT data. Following the premise that more information acquired for a given budget tends to reduce the risks associated with foundation design and installation planning, the economic benefits of rapidly acquiring the geotechnical data from a lower cost vessel are also illustrated.

Introduction

The high cost of deepwater oil and gas developments has focused much attention on fast tracking these projects from discovery to production. An integrated geologic/geotechnical study including the "CPT Stinger" system provides an opportunity to characterize subsurface conditions in a cost effective manner. In contrast, the high cost of drilling deepwater rotary borings that sample at widely spaced intervals tends to limit the opportunity to acquire a sufficient quantity of high quality soils data to fully understand the site.

Background

The importance of conducting integrated geoscience (geologic/geotechnical) studies for deepwater developments has been clearly described by Campbell et al. (1988)[1] and Young and Kasch (2011)[2]. The three-dimensional integrated geoscience (geologic/geotechnical) model must be defined early to serve as a basis for planning the architecture of production facilities. The model serves to better understand the constraints imposed by: (1) geologic conditions and geo-hazards, (2) subsurface stratigraphy and its spatial variability, and (3) variable soil profiles and geotechnical properties. The resulting goal of the integrated geoscience model is to select facility sites with favorable conditions such as those with uniform geologic/geotechnical conditions and those most conducive to safe operations of planned seafloor supported structures.

Data collection in deepwater is expensive and generally requires coverage of a very large seafloor area. The high cost and broad coverage demand that all data be fully exploited while proper data quality and coverage is maintained to achieve the reliability expected by the owner and certification authorities.

This paper describes a significant improvement in geotechnical acquisition systems called the "CPT Stinger". For foundation concepts with depths on the order of 30.5 m *(100 ft)* or less the system offers many technical and economic benefits over conventional geotechnical drilling and sampling equipment currently used to conduct a deepwater geotechnical program.

Concept and Application

The "CPT Stinger" is a deepwater, static cone penetrometer testing (CPT) system that uses the same general suite of gear to perform CPT pushes that is used to acquire Jumbo Piston Cores (JPC) as described by Young et al. (2000)[3]. As with the JPC operation, the CPT system can be operated from an oilfield supply vessel. The "CPT Stinger" can acquire *in situ* CPT data up to 35 m *(115 ft)* below the seafloor that can be correlated with continuous core data obtained with the JPC.

In practice, the standard JPC core barrel and liner inside the barrel are replaced by the "CPT Stinger" system. The system consists of:

- cone rod assembly
- self-contained power and control module
- CPT cone and data logger module added to the rod assembly.

After insersion into the seabed, the embedded JPC barrel and weight-head serve as a reliable reaction for pushing the CPT cone. The system is capable of acquiring multiple static cone profiles per day without the expense and problems commonly associated with motion compensation using a geotechnical drillship.

This paper describes the "CPT Stinger" operations including: (1) equipment deployment, (2) triggering and free fall into the seafloor, (3) CPT data acquisition, (4) retrieval of equipment back to the vessel, and (5) data upload and analysis. In addition, the paper presents data from case studies showing the benefits of correlating CPT and JPC data with high-resolution subbottom profiler records. The data confirm the close correlation that exists between continuous geotechnical data and geophysical data leading to increased confidence in defining the spatial variation in soil properties. These data also verify the consistency of the cone response from replicate tests, including a comparison of dynamic versus static tip resistance, showing the centimeter accuracy in stratigraphic consistency of the different data sets.

Operating Procedures

The "CPT Stinger" operating procedures are very similar in many ways to the JPC operations. The benefit of using the "CPT Stinger" is to penetrate a cone system into the seabed to gather static and dynamic CPT data from the seafloor to 35-m *(115-ft)* depth. Thus, the system provides an effective way to correlate CPT data with nearby continuous sampling by JPC cores and subbottom seismic profiles.

The "CPT Stinger" is installed in the JPC weight-head. It is deployed and triggered allowing it to free-fall and penetrate into the sediment like a JPC. Once fully embedded in the seafloor, it provides a reaction force of typically 2,680 to over 3,570 kN *(12,000 to 16,000 lbs)*. The "CPT Stinger" is programmed to then extend its thrusting rod and cone deeper into the formation (like a stinger) at the standard ASTM[4] push rate of 2 cm/sec.

The CPT is designed to operate as a standard cone as described by Lunne et al. (1997)[5] to measure tip resistance, sleeve friction, and pore pressure using ASTM[4] specified methods. The CPT-Stinger includes a Piezocone with an internal memory cone that stores all the CPT data during the dynamic penetration and the standard static push. The Piezocone can be a standard non-compensted design or the new compensated cone as described by Boggess and Robertson (2010)[6]. The new Piezocone compensates for the large hydrostatic pressure at the seabed by filling the inside with oil and connecting the inner oil pressure with the ambient seawater pressure outside the cone. This ambient seawater pressure connection is sealed off just prior to penetration.

Figure 1 shows a schematic illustration of the "CPT Stinger" system. The deployed system is comprised of:

- the weight-head assembly
- the barrel assembly
- the push rod assembly
- the CPT cone and logger
- the power/control module
- the trigger system

The weight-head assembly is made up of a lead-filled weight-head with an inserted flange-barrel and coupling for attaching lengths of barrel in 3-m *(10-ft)* sections. A USBL transponder is mounted into the top of the weight-head for monitoring the deployed system's lateral position and depth. The weight-head has a lifting assembly that attaches to a trigger system. The weight of the core head can be adjusted by adding lead ingots. The trigger assembly is made up of the trigger arm, pendant clamp, trigger weight, trigger wire, and trigger wire connecting system, identical to that of the JPC.

On vessels with a back deck length of 22 m *(72 ft)*, the 14-cm *(5.5-in.)* OD barrel housing the push rods can be assembled in lengths up to 17.7 m *(58 ft)*. Upon barrel insertion the push rod assembly can push the cone up to 15.2 m *(50 ft)* deeper into the soil, from a starting point (after free fall) at about 19.2-m *(63-ft)* BML.

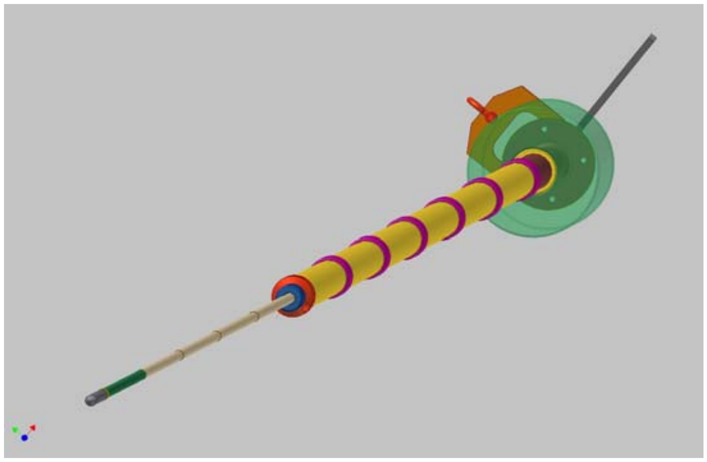

Figure 1. Schematic illustration of the "CPT Stinger" system

Figure 2 is a photo of the "CPT Stinger" system outfitted for deployment in a short-push mode, using a 11.6-m *(38-ft)* long barrel set. With the rod retracted and the cone assembly mounted at the bottom, the total length of the tool is 13.2 m *(43.25 ft)*. The total length is 23.3 m *(73.25 ft)* with the rods extended. A long-push system uses a 17.7-m *(58-ft)* long barrel with a total rod-retracted length of 19.3 m *(63.25 ft)* and rod extended length of 34.6 m *(113.35 ft)*.

Current best practice is to program the "CPT Stinger" to stop such that the weight-head protrudes 0.30 to 0.90 m *(1 to 3 ft)* above the seabed. This position produces a clear mudline indication of the weight head for confirmation of insertion depth. Techniques are used for processing the vertical accelerometer data to confirm the Stinger embedment depth and CPT cone push depth with accuracy of a few centimeters. The horizontal accelerometers report the rig's inclination during its free fall and its push.

Figure 2. "CPT-Stinger" with a 11.6-m *(38-ft)* barrel equipped for short push

Total penetration into the formation (the sum of free-fall insertion and subsequent cone push) is a function of barrel length as shown in Table 1.

Table 1. Penetration Ranges of "CPT Stinger" versus Barrel Length

Barrel Length, m *(ft)*	Insertion Depth BML, m *(ft)*	Push Rod Penetration, m *(ft)*	Total Penetration, m *(ft)*
8.5 *(28)*	9.1-10.1 *(30-33)*	6.1 *(20)* more	15.2- 16.2 *(50-53)*
11.6 *(38)*	12.2-13.1 *(40-43)*	9.1 *(30)* more	21.3-22.2 *(70-73)*
14.6 *(48)*	15.2-16.1 *(50-53)*	12.2 *(40)* more	27.4-28.3 (90-93)
17.7 *(58)*	18.3 19.2 *(60-63)*	15.2 (*50*) more	33.5- 34.4 *(110-113)*

The tool can be assembled into in 1.5-m *(5-ft)* length increments in order to perform CPT testing at various intervals below the seafloor. A back deck longer than 22 m allows even longer lengths than those of Table 1.

Figure 3 shows the stern deployment of the tool with the cone assembly attached to the end of the tool. The stern A-frame is used for deploying and retrieving the "CPT Stinger" system. In addition to the deployed hardware, several assemblies are mounted on the vessel working deck to manage the deployment and retrieval of the rig. These assemblies include: (1) track/bucket assembly, (2) main sheave from the stern A-frame, and (3) weight-head and tugger winches with their hydraulic power pack.

Figure 3. Deployment of the "CPT Stinger" from vessel stern

During deployment, as the rig nears the seabed during its water column descent, the winch payout speed is slowed and final position measured with the USBL logger at the instant of release. As the weight is released from the trigger arm, the trigger arm begins to rise with respect to the rig triggering release. The system is released to free fall down into the seabed. At this triggering point, the cone tip is 0.3 to 0.6 m *(1 to 2 ft)* above the seabed.

An efficient method for acquiring continuous geotechnical data is to obtain a JPC and then perform one or two "CPT Stinger" pushes at the same site. This method for performing a combined JPC, short-push CPT, and long-push CPT at a site is illustrated in Figure 4. For example, the JPC with a 19.5-m *(64-ft)* barrel is used to retrieve as much as 18.9 m *(62 ft)* of sediment core. Then "CPT Stinger" with a 17.7-m *(58-ft)* long barrel is used to make a 15.2-m *(50-ft)* cone push (long push) down to about 35.0-m *(115-ft)* BML. This long-push deployment also gathers dynamic (free fall) CPT cone data from seabed to about 19.2-m *(63-ft)* BML. The "CPT Stinger" can then optionally be equipped to make a short push by using an 11.6-m *(38-ft)* long barrel to obtain 9.1 m (30 ft) of continuous CPT data below the bottom of the embedded barrel. The short-push procedure records dynamic (free fall) CPT cone data from the seabed to about 11.6-m *(38-ft)* BML. This is followed by a push to gather static CPT cone data from 11.6-m *(38-ft)* depth down to about 22.9-m *(75-ft)* BML. Thus the tool can be configured to probe a range of depths to generate overlapping data, depending on the data needs of the project.

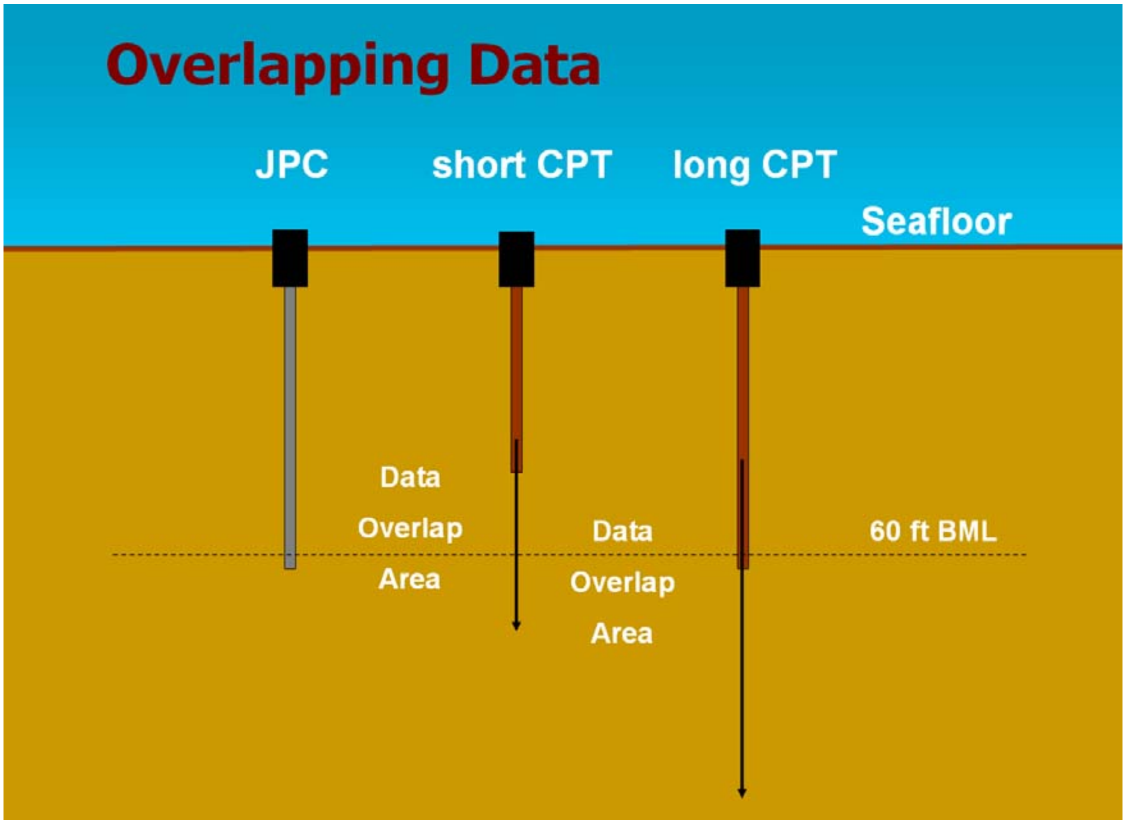

Figure 4. Illustration of JPC and "CPT Stinger" long push and short push at a site

Data Retrieval and Analysis

After the "CPT Stinger" is retrieved to the vessel deck, the CPT cone assembly is removed and brought into the lab for data retrieval and processing. A USB cable connects the cone's data logger to a laptop computer to upload the raw data file. A "CPT Stinger" program processes the data into an ASCII format (*COR* file) compatible with the commonly used *CPeT-IT* program by GeoLogismiki Geotechnical Software as detailed below.

After opening the raw data file, the user examines the plotted data to specify some event-points, including the Freefall Trigger Point, Seabed Insertion Point, and Post-FreeFall At-Rest Point. Figure 5 illustrates a time-plot of vertical acceleration and tip resistance during the 3-sec freefall from a typical long-push CPT deployment, with these three events annotated.

The program then determines the accelerometer baseline from data logged after the rig comes to rest in the soil, and then integrates the acceleration values with respect to time from the FreeFall Trigger Point to the Post-FreeFall At-Rest Point. This integration represents a very accurate velocity profile through this specific time interval. This velocity profile is used in processing the dynamic cone data. The program then integrates the velocity values over the same interval. The velocity profile integration represents the time-profile of distance travelled by the rig during free fall. In this manner, a very accurate measure is derived of cone freefall distance in the water and cone freefall insertion into the soil. Accurately determining the depth of penetration of the cone before it starts its static push is important for matching the resulting cone data with corresponding sub-bottom profiling data.

The program calculates the conventional baseline for tip resistance, friction sleeve resistance and pore pressure, as well as cone push duration, cone push rate, and push distance. The program then produces a so-called COR file, which is formatted suitably for use with the CPeIT software. This file includes the baseline-corrected "static" measurements of tip resistance, sleeve friction, and pore pressure for the duration of the cone push into the soil. The program also produces a Freefall-COR file that includes dynamic data for tip resistance, sleeve friction, and pore pressure during freefall. In this Freefall-COR file, each of the cone measurements is individually corrected for the velocity affect on the cone readings by calibrating (overlaying) the dynamic data with existing static data at the same or nearby site. These data can provide very important information for interpreting soil properties that will be described in the next section.

Once the site's raw data file has been successfully processed and determined to be acceptable, the system is prepared for the next deployment. The raw data file is erased from the tool's memory, the power/control module is serviced and the tool readied, typically in less than one hour, making multiple deepwater deployments per day feasible.

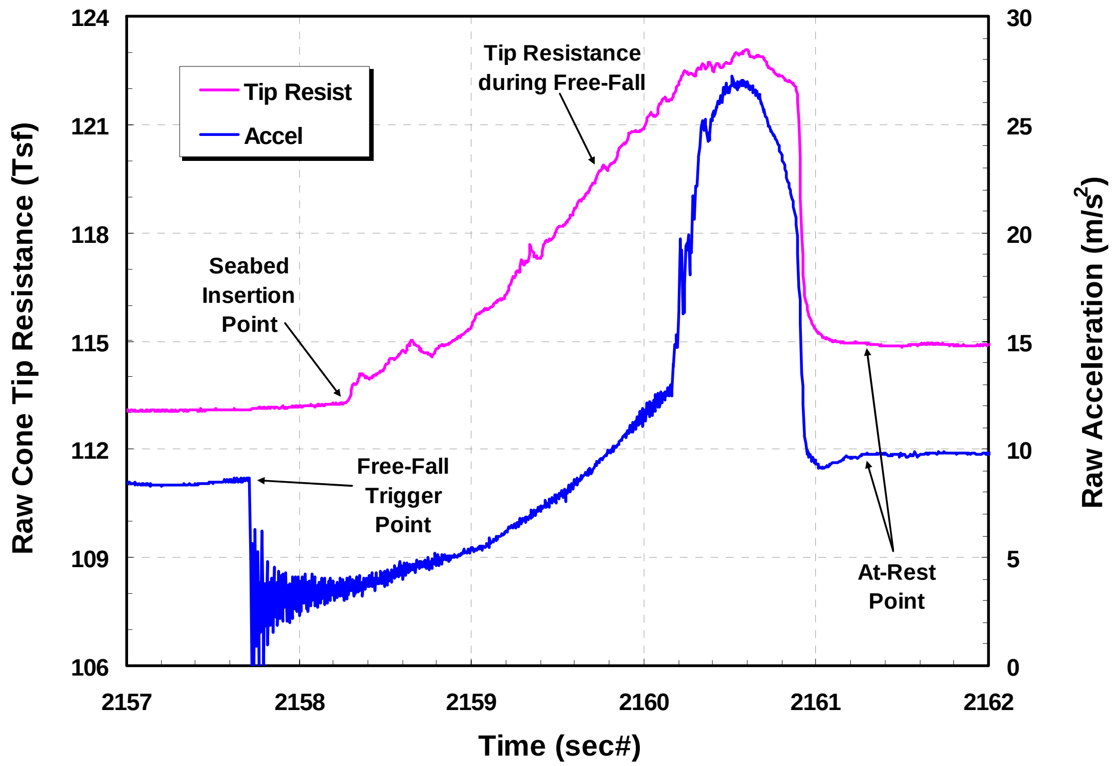

Figure 5. Plot of raw vertical acceleration and tip resistance for the 3 seconds of rig free fall into the sediment.

Dynamic Penetration Data

In addition to the acquisition of high-quality static CPT data during the cone push after insertion, the sampling rate of the CPT logger allows the acquisition of dynamic CPT data for the 3 seconds during free fall insertion of the tool into the sediment. Data are logged during the tool's free fall penetration at depth intervals no larger than 5 cm even at cone velocities approaching 9 m/sec.

The dynamic cone data can be adjusted to emulate static data by calibrating them with the corresponding strength data derived from JPC sections, and also by tying them to actual overlapping static CPT data acquired at the same site. Comparisons between the static CPT measurements pushed at 2 cm/sec with the velocity-corrected dynamic CPT data are remarkably good at all sites, indicating the potential of this technique.

Empirical data show that tip resistance is amplified by about 10% for each ten-fold increase in velocity above the standard 2 cm/sec rate (Lunne et al, 1997)[5]. Thus, the baseline-corrected cone load cell readings can be adjusted for this velocity affect. Adjustments can be made to the dynamic data by using the static data at the same site and iteratively changing the percentage required to force agreement between the static and dynamic profiles. The dynamic data are adjusted using the $\log_{10}$ of each velocity measurement with user-entered discounting factors from 0 to 20%. The dynamic values of sleeve friction and pore pressure measurements are adjusted independently for the velocity effects.

An example is shown in Figure 6 showing the static tip resistance data from long and short pushes at a site, and also showing the unadjusted and adjusted dynamic CPT tip resistance results. The figure illustrates the excellent fit of overlapping static data between the long and short pushes. If the static data from the short push reconcile with those of the long push, the short push static data may also be used to calibrate the dynamic data from the long push. In this example, the raw dynamic data have been velocity-discounted using a factor of 10.5% to force the resulting data to fit with the overlain static data. The JPC soil strength data could also be used for this calibration. Once the velocity-discount factor is determined for an area, it can be used to velocity-correct the dynamic data from nearby sites.

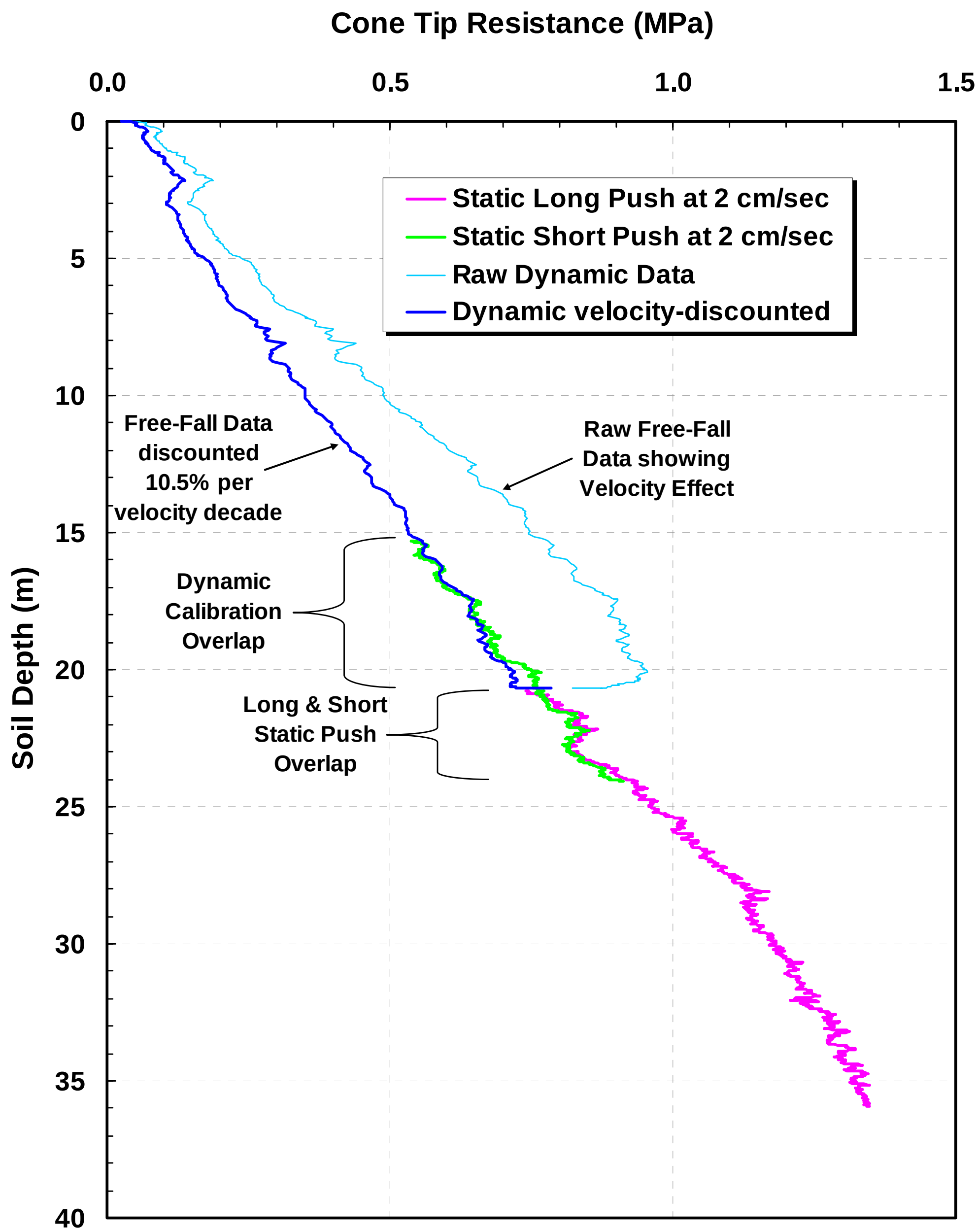

Figure 6. Dynamic and Static CPT data obtained with "CPT Stinger" system

Examples of "CPT Stinger" Data

The "CPT Stinger" was used to investigate subsurface soil conditions at a number of sites for planning deepwater developments. For one deepwater development a total of 8 JPCs were obtained that were accompanied by companion CPT pushes made using the "CPT Stinger" system. A short-push profile and a long-push profile of CPT data were made at all 8 sites to a depth of 35 m *(115 ft)* below the seafloor. The CPT results for all eight sites as subdivided by the four anchor clusters are shown on the four plots in Figure 7. Two JPC's and a companion CPT push for each JPC were obtained at each end of the four anchor clusters. The results show the very close consistency that exits in subsurface soil conditions and the strength data obtained at each test/sample site.

The measured profile of cone tip resistance was converted to and undrained shear strength profile using a N_{kt} value of 17.5 as proposed by Young and Kasch (2011)[3]. A number of earlier studies (Aas et. al., 1986)[7] and (Penetration Testing, 1988)[8] have shown this value is reasonable for strength interpretation in the near normally consolidated clays at deepwater Gulf of Mexico sites. The laboratory test results obtained on continuous samples from the JPCs are also shown in Figure 7 to a depth of about 18 m *(60 ft)* below the seafloor.

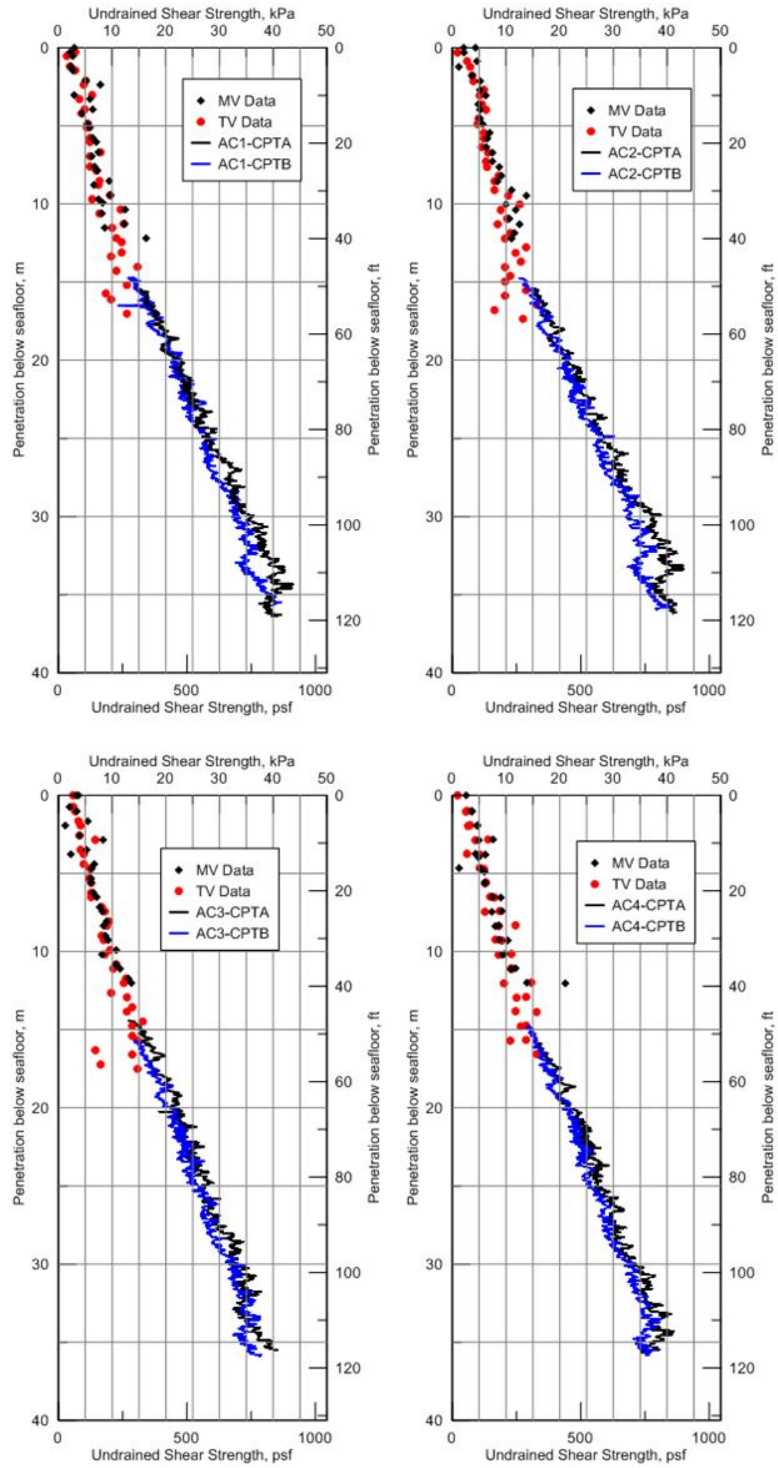

Figure 7: Profiles of Laboratory and CPT Strength Data at Four Anchor Cluster Locations

The foregoing results of the CPT strength data and the laboratory strength data are shown plotted together in Figure 8. This plot illustrates the excellent correlation that exists within the zone of overlap of the two data types. The results also reflect the close correlation that exists for all eight sites. All CPT strength data fall within a 10% band of the best estimate strength profile.

The tight correlation is consistent with the geophysical subbottom records confirming that "layer cake" stratigraphy exists throughout the project area shown in Figure 9. The yellow soil horizon encountered at about 14-m *(45-ft)* depth reveals an increase in the slope of the measured strength profiles above and below the yellow horizon as illustrated in Figure 9. The subbottom profiler data confirms the consistent depth of the yellow horizon throughout the site as was also verified by the CPT data and the strength data obtained from the JPC samples.

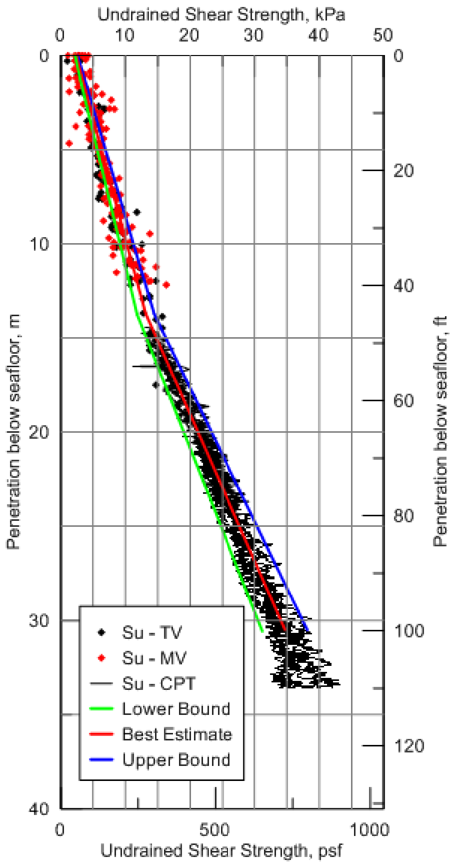

Figure 8: Plot of Laboratory and CPT Strength Data for 8 Test Sites (4 anchor clusters)

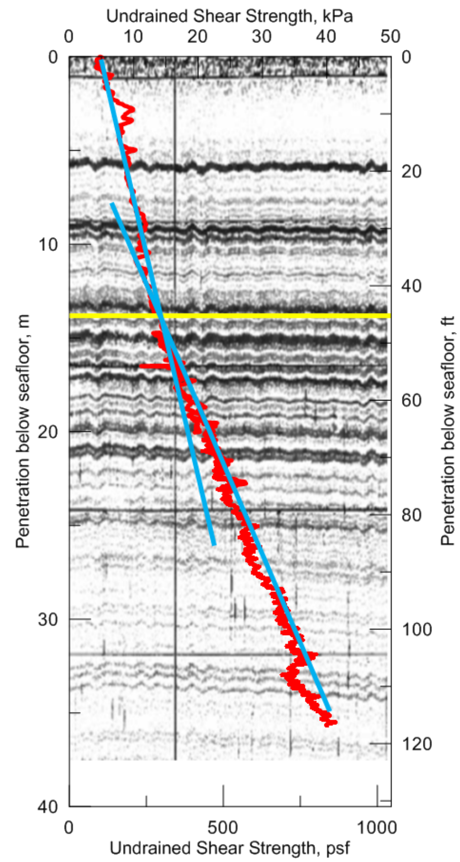

Figure 9: "CPT Stringer" results correlated with Subbottom profiler record

Conclusions

A new static cone penetrometer system, the "CPT Stinger", has been developed and used to investigate subsurface conditions at a number of deepwater production sites. The tool can acquire *in situ* CPT data up to 35 m *(115 ft)* below the seafloor that can be correlated with continuous cores obtained with the JPC. The "CPT Stinger" can be assembled into a number of different length tools in order to perform CPT testing at various intervals below the seafloor depending on project needs.

This data collection system is ideally suited for providing the soil stratigraphy and engineering properties needed to design suction piles as described by API RPI 2SK (2008)[9] that are routinely used to moor floating platforms. Since suction piles are typically embedded 30.5 m *(100 ft)* or less, the foundation zone of interest is generally limited to about 30.5 36.6 m *(100 to 120 ft)* below the seafloor. The system is also ideal for use for other types of shallow foundations used for support of various on-bottom deepwater production facilities. The JPC sampling and CPT testing methods as described for the "CPT Stinger" system in conjunction with the SHANSEP strength parameters (Ladd and Foott, 1974)[10] provide geotechnical engineers with a more effective set of tools for conducting deepwater site investigations.

The approach of obtaining continuous CPT data to correlate with JPC samples provides a number of advantages over the intermittent nature of sampling in a rotary boring such as the following:

- The new "CPT Stinger" system allows the same general suite of geotechnical JPC coring equipment to be modified for CPT testing while at sea.
- The results of CPT and laboratory strength data confirm excellent correlation that exists for the zone of overlap of the two data types.
- The dynamic cone data can be calibrated with the static CPT data and the corresponding strength data derived from JPC sections acquired at the same sites.
- The results from case studies clearly demonstrate the technical benefits of obtaining continuous samples and *in situ* CPT data to correlate with subbottom seismic profiles.
- The "CPT Stinger" can be operated from an oilfield supply vessel that is far less expensive than a drillship which is required for rotary borings.

In summary, the authors believe the new "CPT Stinger" system when used with JPC sampling provides significant economic benefits for acquiring geotechnical data, as well as improvements in data quality. This improved efficiency may also allow more geotechnical data to be acquired with the commensurate gain in foundation reliability.

Acknowledgements

Development of the new CPT-Stinger system required much dedicated effort from many individuals with TDI-Brooks International Inc., Detail Design, Inc. and Geoscience Earth & Marine Services. We are grateful for their commitment to make the Stinger a safe, operational tool for challenging deepwater environments.

The efforts of Dr. Peter Robertson, Mr. Tim Morgan, and Mr. Ron Boggess with Gregg Drilling were instrumentental in developing the PCPT capability required for the "CPT Stinger" system. Their support allowed us to acquire high quality PCPT data with the accuracy needed to make use of the dynamic PCPT data.

We appreciate the technical review and support of Dr. James D. Murff in preparing the paper. Dr. Murff and Dr. Chuck Aubeny with Texas A&M University provided very helpful feedback on the approriateness of the data to meet the requirements for foundation design of suction piles.

We appreciate the opportunity provided by a number of clients to use the CPT-Stinger at their offshore sites.

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