Rate-Effect Correction Methods for Free-Fall CPT Data in Deepwater Gulf of Mexico - An Operator’s Perspective

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Abstract

A new geotechnical investigation tool called the “CPT Stinger” has recently been developed to cost effectively acquire geotechnical information at deepwater sites. Combining jumbo piston core (JPC) sampling with the “CPT Stinger” (deployed using the same rigging as the JPC) provides a full geotechnical profile at a given location down to a depth of 35 m below mudline. CPT data are collected during initial free-fall insertion of the “CPT Stinger” apparatus. These data could be used to provide a continuous stratigraphic profile from mudline down to the depth where conventional CPT data (push rate of 2cm/sec) are acquired, if a reliable and repeatable method for correcting the free-fall insertion data could be developed. Several methods have previously been proposed to correct soil shear strength for rate of loading effects. These methods are evaluated in this paper by comparing their results to data acquired in 2011 at a deepwater site in the Gulf of Mexico with an operator’s perspective on the potential of this technique.

1. Introduction

Deepwater Geotechnical acquisition is a cost intensive activity that causes operators to evaluate trade-offs between project economics and the relative value of the information being gathered. Operators are continuously evaluating more economical options for acquiring high quality data that can be used for design. Down-hole and wheel-drive CPT has been commonly and reliably used for many years to provide a continuous geotechnical profile in offshore applications. A new system was recently developed called the “CPT Stinger” that proposes to reduce geotechnical data acquisition costs by combining the traditional jumbo piston core (JPC) sampling technique with a CPT system that is deployed with the same equipment as the JPC.

The “CPT Stinger” essentially replaces the JPC core barrel and liner with the CPT cone, data logger, rod assembly and power and control modules (Young et al., 2011). After deployment, the system is lowered to a depth just above the seabed target location. Once triggered, the system is allowed to freefall into the sediment like a JPC with speeds approaching 10m/sec. The system uses the skin friction from the barrel and weight of the corehead as a reaction force to extend the rod and cone deeper into the soil at a standard push rate of 2cm/sec (ASTM, 2007). Interpretation and testing of the JPC soil samples and standard 2 cm/sec CPT push can be completed using standard geotechnical practice to provide a complete profile for the full 35m BML depth of evaluation.

Due to the high cost of deepwater geotechnical acquisition discussed previously, the authors sought to make use of all data collected, including data collected during free-fall insertion, rather than discarding the free-fall data and relying solely upon the results of the JPC laboratory testing program in the shallow stratigraphic region. The goal was to implement a technically defensible method to correct the free-fall data in order to replicate what would have been obtained if a standard 2 cm/sec push had been used in this zone. Due to the limited number of sites investigated during the acquisition program, the authors concluded that using previously proposed and peer reviewed methods of correction for rate effects should be the starting point. This paper presents the results of the evaluation of several methods that have been published and provides an operator’s perspective on the potential of the different methodologies in correcting free-fall CPT data based on the results of a recent survey using the “CPT Stinger” technique.

2. Background

Rate of loading effects on the shear strength of clays has been recognized since the early 1950's by Casagrande and Wilson (1951). In general, an increase in the rate of shear results in an increase in undrained shear strength. The problem has been addressed many times since for various applications and a wide range of rates. The following sections will highlight the most applicable previous work and proposed methods for correcting for rate effects. Literature review for these purposes was focused on studies that evaluated in situ rate correction; most commonly the vane shear test. Some statnamic and dynamic pile load studies (e.g. Randolph and Deeks 1992) could add value to this loading rate correction assessment and will be used to aid future analyses.

2.1. Logarithmic Method

The logarithmic method has been suggested for use in correcting pile capacity and CPT cone resistance (q_c) for rate effects by Bea and Audibert (1979) and Vivatrat (1978), respectively. A version of the proposed correction is shown in Equation 1.

$$s_u = s_{u.ref}\left[1+\alpha\log_{10}\left(\frac{v}{v_{ref}}\right)\right] \qquad (1)$$

where s_u = undrained shear strength at tested velocity, $s_{u.ref}$ = undrained shear strength at reference velocity, α = material constant, v = tested velocity, v_{ref} = reference velocity.

Lunne (1997) summarized Vivatrat's findings that q_c increased by 10% per log cycle increase in rate of penetration between 1 and 200 mm/sec in normally consolidated Boston Blue Clay (BBC) and EABPL clay. These findings were used as the basis for Young et al. (2011) suggestion that free-fall "CPT Stinger" data, including q_c, sleeve friction (f_s) and pore pressure (u_2), could individually be corrected for velocity effect using this method.

The method was further investigated using the results of several K_0 consolidated-undrained triaxial compression tests on resedimented BBC with an emphasis on the effect of OCR by Sheahan et al. (1996). The study found that for the high strain rate region, which would be more applicable for free-fall CPT penetration, the α value from Equation 1 is relatively constant at 9.5% ± 2%. For samples with an OCR of 1, the rate effects are most pronounced, as seen in Figure 1. Owing to the the trend of increasing rate effects with decreasing OCR, it would stand to reason that rate effects should be highest for underconsolidated clays, which are representative of most deepwater sites.

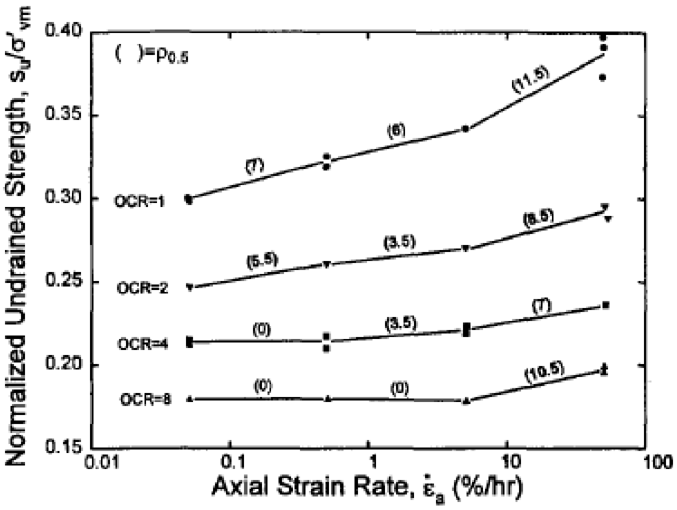

Figure 1: Normalized Shear Strength vs. Strain Rate (Reproduced from Sheahan, 1996)

As seen in Figure 2, Sheahan et al. (1996) found that the increase in shear strength for OCR 1 specimens was caused by the suppresion of the shear-induced pore pressure and an increase in the effective stress friction angle.

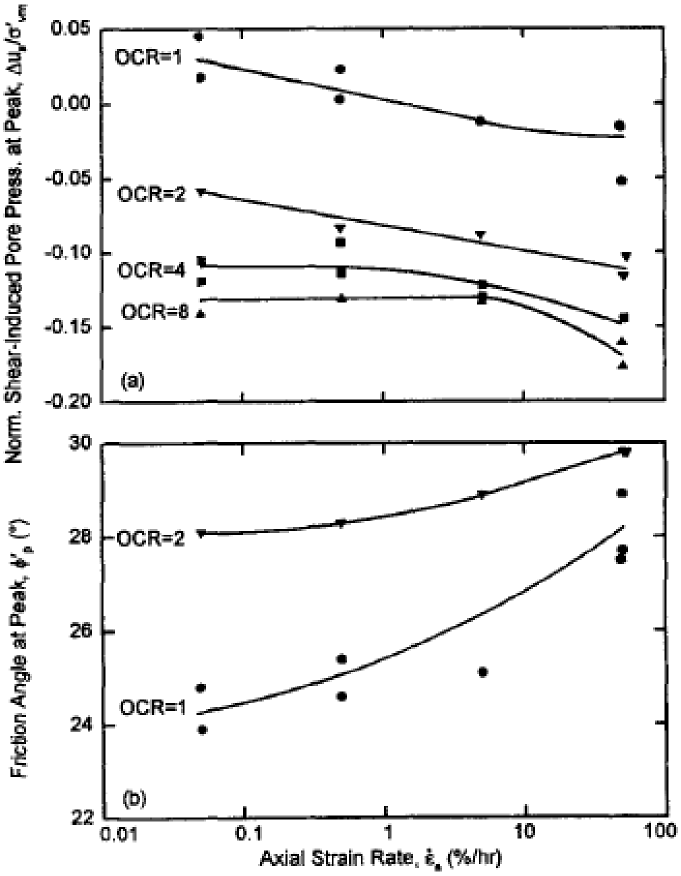

Figure 2: Summary Plots of Mechanism: (a) Normalized Shear-Induced Pore Pressure and (b) Friction Angle at Peak vs. Strain Rate (Reproduced from Sheahan, 1996)

2.2. Power Method

An alternative model was proposed by Riggins (1981), based on the results of large scale simple shear tests, that leads to a straight line on a log-log plot of shear strength vs. testing rate. This model is represented by Equation 2.

$$s_u = s_{u.ref}\left(\frac{v}{v_{ref}}\right)^{\beta} \tag{2}$$

where β = material constant.

Briaud and Garland (1984) expanded on this model to propose best-fit exponent values based on water content (*w*), plasticity index (PI) and liquidity index (LI).

The majority of laboratory and pile load test data evaluated by Briaud showed the β values to fall between 2% for hard clays and 8% for soft clays.

A large amount of work has been done since the 1950s to evaluate the rotation rate effect on vane shear testing. Biscontin and Pestana (1999) provided a good summary of the previous work and identified a gap in the analysis of rates of rotation that would be more representative of seismic or wave loading conditions. Much like for this paper, they evaluated the existing methods to determine which is most effective to account for rate effects based on their results. They found that the power method better estimated the increase in shear stength with increasing rate of shearing. The logarithmic method tended to underpredict the increase in shear strength at very high shearing rates, as shown in Figure 3.

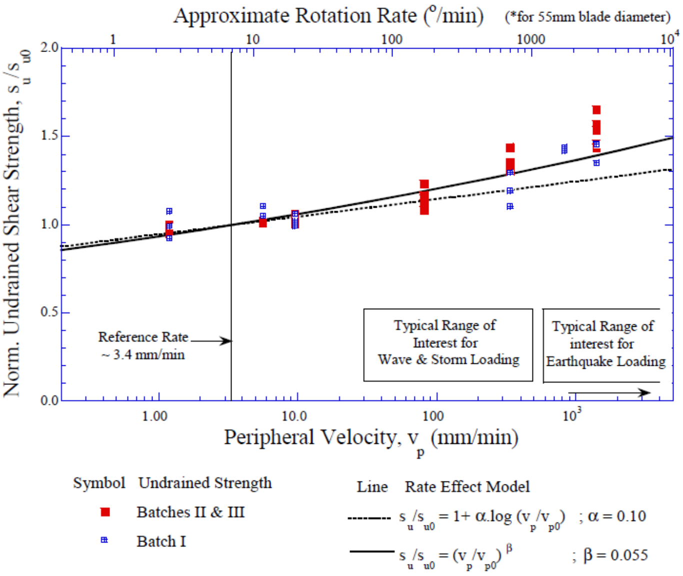

Figure 3: Summary of Peak Conditions for Shear Vane Tests (Reproduced from Biscontin and Pestana, 1999)

When the power method was used with β values between 5% and 10%, Biscontin and Pestana (1999) found that the method provided a better fit over the entire range of study. This agreement was significantly expanded by Peuchen and Mayne (2007). They presented shear strengths from a large collection of field and laboratory vane over nine orders of magnitude. A summary of these data is shown in Figure 4, from which it can be seen that, for a wide range of shearing rates and soil types, β values between 5% and 10% match the trends well and bound the majority of the data.

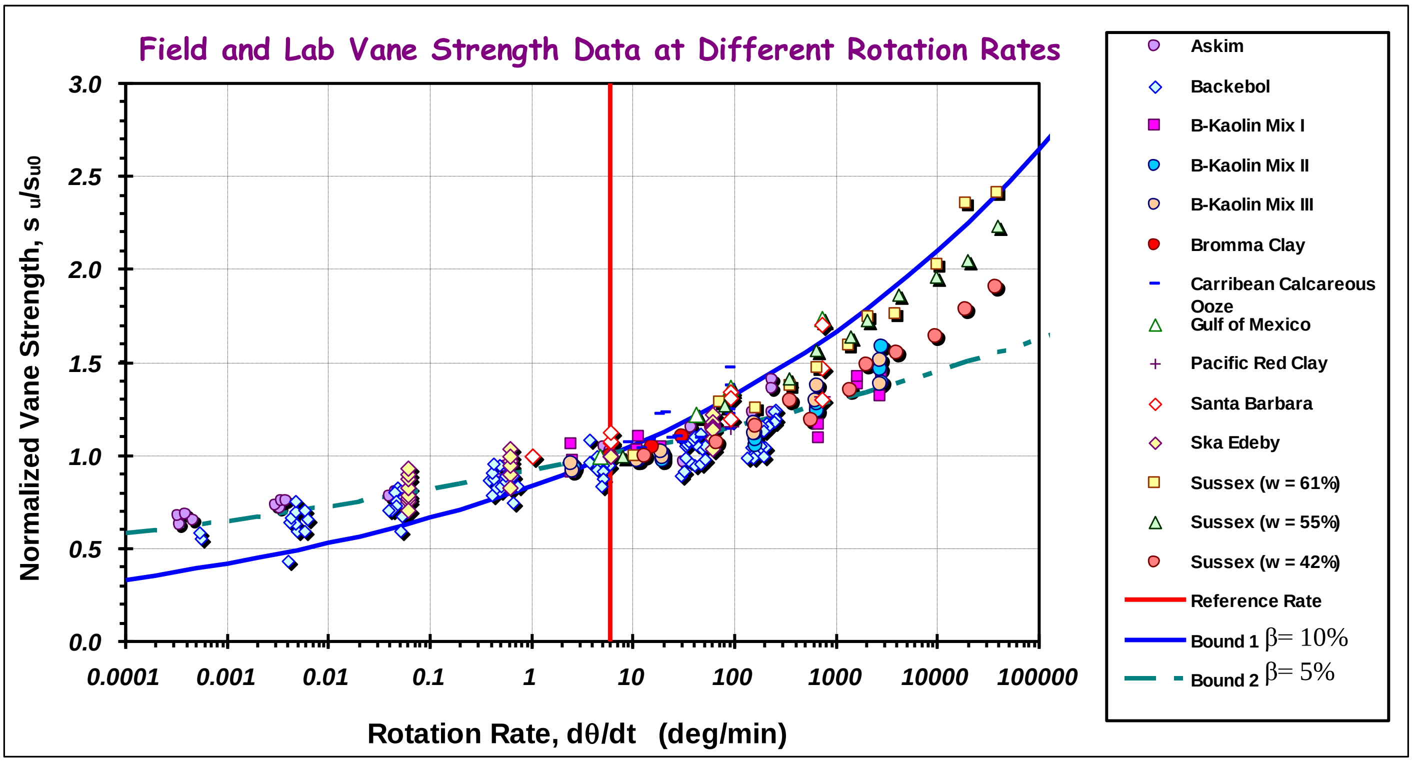

Figure 4: Normalized Vane Strengths vs. Rotation Rate (Reproduced from Peuchen and Mayne, 2007)

2.3. Square Root Method

A modified version of the power method was recently proposed by Abelev and Valent (2009) and is shown in Equation 3.

$$s_u = s_{u.ref}\left[1+\lambda\sqrt{\left(\frac{v}{v_{ref}}\right)}\right] \qquad (3)$$

Where λ = material constant.

While the data used to produce the logarithmic and power methods span many orders of magnitude, most data do not reach the high range of shear rates characteristic of marine dynamic penetration events (Abelev and Valent, 2009). This led to the goal of their study, which was to evaluate the rate of loading effects in the upper ranges that had not received much attention in previous studies.

They chose the vane test as the testing method and a soft Gulf of Mexico clay prepared at various water contents as the testing medium. The range of rates evaluated were 90 to 360,000deg/min or approximately one order of magnitude greater than the data range from Figure 3. The results showed that the logarithmic and power methods did not represent the best fits. In response, they developed what they called the “modified power function”. The modification called for two material constants including both an exponent and a coefficient. They recognized that adding a material constant may be an undesirable complexity, thus they fixed the exponent at 0.5, which worked well with the data set. The authors of this paper agreed that adding another variable is not desirable and as such refer to the method as the square root method (i.e., exponent of 0.5).

The results of Abelev and Valent’s study are presented in Figure 5. The plot compares the calculated shear strength values at various rates with the different rate correction methods. As can be seen, the square root method provides a significantly better fit over the entire range of rates investigated. Unfortunately, values for the coefficient λ were not presented by Abelev and Valent (2009).

3. Deepwater Project Overview

The project site was located in the central Gulf of Mexico in approximately 2100m water depth. The intent of the program was to characterize the surficial material for the design of flowlines, subsea equipment, and temporary anchoring for mobile offshore drilling units (MODUs). The authors of this paper served as the Company representatives offshore with the dual purpose of monitoring quality control and determining the potential of this relatively new site investigation technology for future projects.

The site investigation program consisted of a combination of box cores, piston cores, JPCs and “CPT Stingers”. This paper will focus on the results of the JPCs and “CPT Stingers”. The remaining sections summarize the findings that would be of interest to the industry.

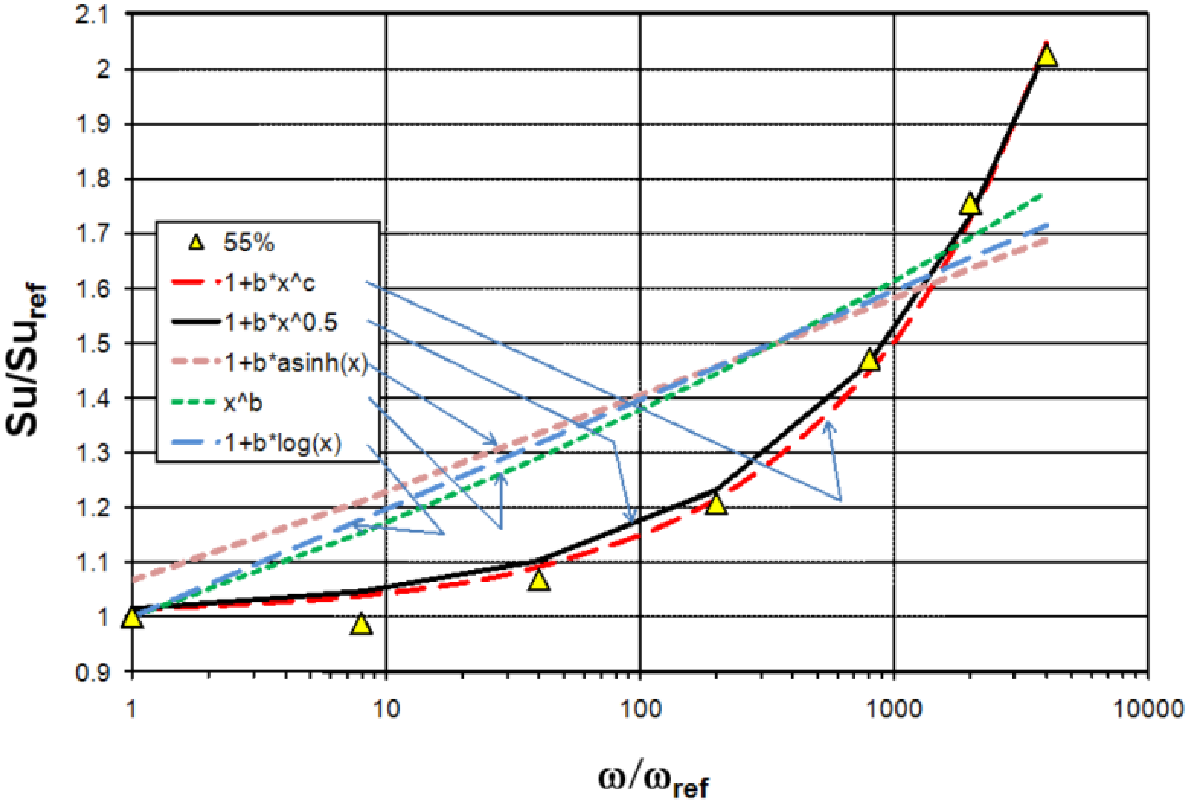

Figure 5: Normalized Shear Strength vs. Normalized Rotational Rate (Reproduced from Abelev and Valent, 2009)

3.1. Testing Program

A total of six locations were selected to acquire JPC and “CPT Stinger” combinations. The combination selected included one JPC, one *short* “CPT Stinger”, and one *long* “CPT Stinger”. The rationale was to provide a complete profile consisting of either JPC samples or standard (2cm/sec) CPT testing to the target depth of 35m. A summary of the average penetration, recovery and testing depths for the different acquisition types from this project are presented in Table 1. Young (2011) provides an eloquent summary of “CPT Stinger” operations, which will not be elaborated on in this paper.

Table 1: JPC & “CPT Stinger” Investigation Depths

	Sampling	**Free-Fall**	**Static Push**
JPC	0-19m	-	-
Short CPT	-	0-14m	14-24m
Long CPT	-	0-20m	20-36m

An extensive laboratory testing program was conducted on the JPC samples that included Multi Sensor Core Logging (MSCL), X-radiography, index testing (water content, unit weight, Atterberg limits, degree of saturation, specific gravity, hydrometer, carbonate content and salt content), torvane, minivane (undisturbed, remolded and thixotropy), UU triaxial compression, controlled rate of strain (CRS) consolidation, static, cyclic, creep and rapid direct simple shear (DSS), and K_0Triaxial compression and extension tests. A sample of the index properties results is included in Figure 8.

4. Results

4.1. Interpretation of Stratigraphic Profile

The undrained shear strength profile was interpreted through analysis of the field and laboratory vane, torvane, static direct simple shear tests, and standard push CPT. The results of the static DSS tests, when adjusted for sample disturbance through the SHANSEP method, were determined to be the best measure of undrained shear strength. The interpreted profile is summarised in Table 2.

Table 2: Interpreted Undrained Shear Strength Profile

Depth	**s_u (kPa)**
0-9m	1.92+0.177kPa*z
9-35m	9.09+0.622kPa*(z-9)

Most of the testing locations showed a significant variation in shear strength in both the laboratory testing and CPT data between 12-18m. This was verified using the interpretation of the subbottom profile, which indicated a mass transport complex in that range. A summary of the upper 25m of the subbottom profile showing key stratigraphic features used during interpretation is shown in Figure 6.

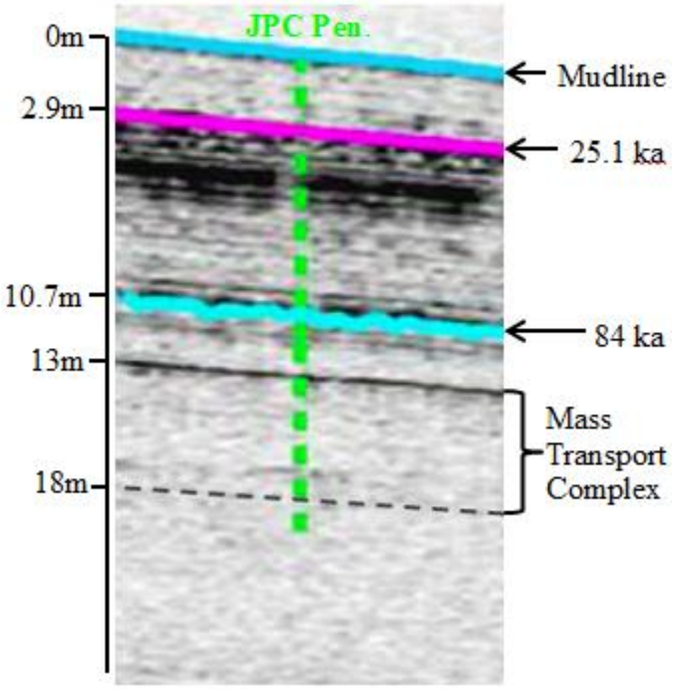

Figure 6: Interpreted Subbottom Profile

The sub-bottom profile images combined with the results of MSCL data, the moisture content profile, the undrained shear strength profile, and the preconsolidation stresses derived from the CRS consolidation tests indicate the soils are underconsolidated from mudline to approximately 25m BML, becoming normally consolidated below 25m. The preconsolidation pressures measured from the CRS consolidation tests using the Casagrande and Becker methods are shown in Figure 7, with the estimated in situ overburden stress and preconsolidation pressures.

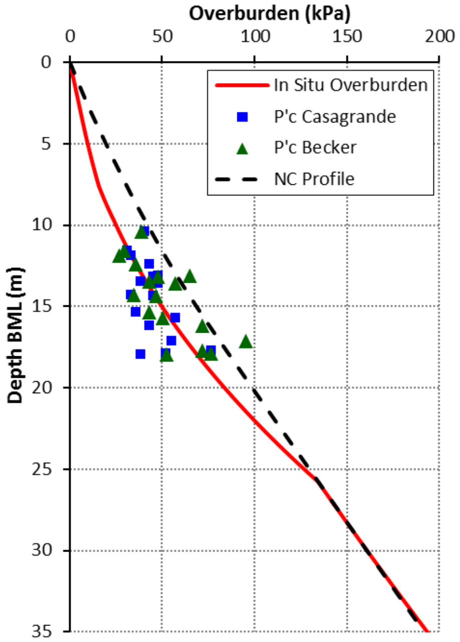

Figure 7: Estimated in situ overburden stress and preconsolidation pressure vs. depth

4.2. Free-fall CPT Correction Results

The author’s first step was to determine the rate correction on u_2 values, since this is an integral value in deriving corrected cone resistance (q_t). The authors consistently found that no correction on u_2 was needed to align the free-fall and static CPT data. This matched a common finding of several CPT rate correction studies (e.g., Lunne et al. 1997). The excellent fit of the free-fall data to static data is shown in Figure 8.

Once u_2 was determined to not be affected, the author's focus turned to the q_c correction. The paper by Young et al. (2011) showed that the logarithmic method to correct q_c provided good agreement with the static CPT overlap. Since this paper was directly applicable, analysis logically began using the same technique. The authors found similar performance in the deceleration zone of the free-fall CPT data that overlapped with the short static CPT push; however, using the method with the same material constant caused a notable overprediction of the shear strength in the upper sediments. Young et al. (2011) did not provide a derived and corrected s_u based on the logarithmic method for comparison to the available JPC data. Since the area of greatest interest to the authors was s_u in the zone between mudline and static CPT push (~0-14m), additional methods were evaluated to adjust the shear strength over-prediction.

The three methods discussed in section 2 were evaluated for each JPC/"CPT Stinger" combination using the material constants shown in Table 3 based on the recommendations of material constants from previous studies. The goal was to find a correction method that would make the corrected dynamic CPT data match the JPC laboratory testing results and standard push CPT. More simply, the correction should adjust the interpreted undrained shear strength from the free-fall CPT to align it with the interpreted shear strength profile from Table 2.

Table 3: Material Constant Values Used

Method	Variable	Value	Reference
Logarithmic	α	10.5%	Young 2011
Power	β	5% 10%	Peuchen and Mayne 2007
Square Root	λ	3%	Authors

A summary of the uncorrected and corrected shear strength values interpreted from the CPT using the Table 3 values are summarized in Figure 8. Only the "long" CPT correction is shown for clarity. Additionally the velocity profiles are shown for reference to the magnitude of the correction needed.

The square root method (λ=3%) and the power method (β=10%) provided a better fit with the shear strength profile based on the results of JPC laboratory testing. However, the relationship tends to diverge once the cone begins the rapid deceleration during the final stages of penetration. This is illustrated in Figure 8 from 14-20m. This corroborates the findings of Aubeny and Shi (2006). They postulated that this is the results of elastic rebound of the soil, which is not considered in the correction. On the other hand, the logarithmic (α=10.5%) and power (β=5%) laws more closely match the conventional (2cm/sec) CPT data from the Short CPT data, but significantly undercorrect q_c during the accelerating period of the free-fall.

All three methods show potential for repeatable use at different times during free-fall penetration. As more data are gathered at a range of sites and soil conditions, based on these findings, the authors see potential for a single method being developed to correct the full range of penetration rates.

5. Summary and Conclusions

This paper provides a summary of published methods for correcting for rate effects in geotechnical testing. These methods were then applied to 6 JPC/"CPT Stinger" combinations at a site in the deepwater Gulf of Mexico. The following conclusions can be drawn from this study:

1. The measured u_2 values during free-fall penetration do not need to be corrected for rate effects to obtain equivalent results that would be received during a standard push CPT.
2. The Square Root and Power Methods using conventional ranges show the most potential for correcting q_c for rate effects due to increased correction at the highest rates of penetration (~10m/s).
3. All three methods can correct the rapid deceleration period accurately; however, the material constants used to reach this agreement overpredict the shear strength in the under-consolidated zone encountered at this site.
4. No single existing method and material constant was identified that was able to accurately correct the **full** range of penetration rates at this site.

As more CPT data are collected using the free-fall technique, these correction methods show great potential for being improved and utilized to consistently correct the data to represent what would be recovered during a standard 2cm/sec push. The authors hope that this paper encourages collaboration from other operators that are using the same geotechnical acquisition techniques. An industry accepted method of using free-fall CPT data would provide a significant first step to gaining flexibility in site investigation programs.

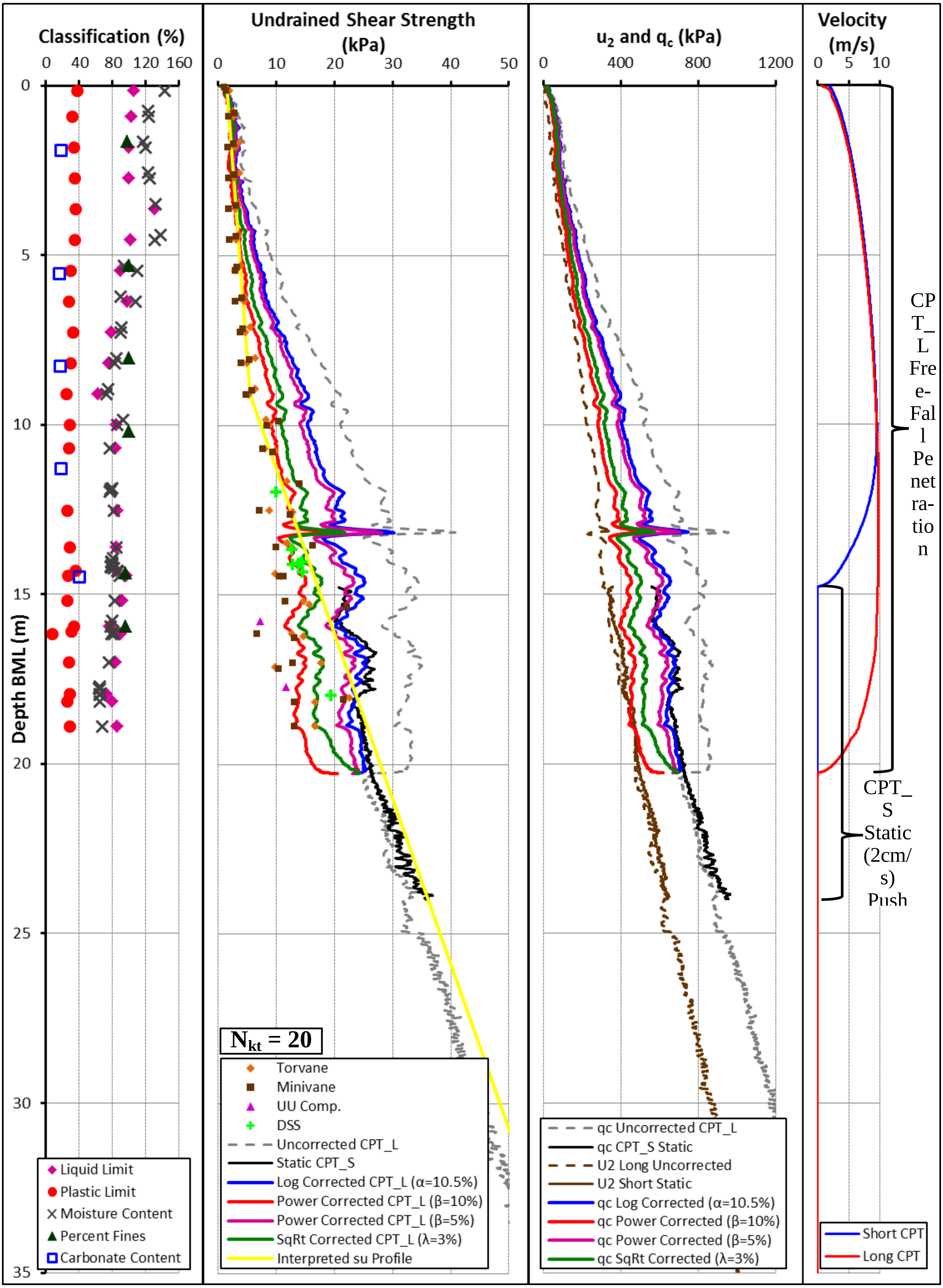

Figure 8: Comparison of Rate Effect Correction Methods

6. Acknowledgements

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