Proceedings Tailings and Mine Waste 2011
Vancouver, BC, November 6 to 9, 2011

SPT – CPT Correlations for Oilsands Tailings Sand

Mahmoud Elbanna & Joseph Quinn

Klohn Crippen Berger Ltd., Canada

Scott Martens

Shell Canada Energy, Canada

Abstract

Two commonly used in-situ tests for assessing the density and flow liquefaction susceptibility of sandy soils are the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT). A rich case history database exists that relates observed performance during liquefaction events to SPT blow count data that was obtained prior to the widespread implementation of CPT testing. Issues with SPT reliability and productivity have however reduced confidence in this test method. The CPT has proven to be a more reliable and cost effective tool for various applications in geotechnical engineering and can be utilized as a more effective tool for the assessment of flow liquefaction susceptibility. This paper presents a review of SPT-CPT correlations that enable the direct use of CPT data in flow liquefaction assessments. A site-specific $q_{t1}/(N_1)_{60}$ ratio of 0.45 is presented that can be useful for the geotechnical engineering community of the oilsands in northern Alberta.

Introduction

The assessment of liquefaction susceptibility is usually undertaken by comparing a measure of a soil's in-situ density state (e.g. penetration resistance (SPT or CPT), or shear wave velocity (v_s)) with test values that were either measured or inferred from case histories of failures. The majority of flow liquefaction case histories have field data in the form of SPT measurements. Consequently, a rich case history database exists that relates observed performance during liquefaction events to SPT blowcount data, which predates the widespread implementation of CPT testing. Performance case histories have more recently been formulated in terms of the CPT (e.g. Olson and Stark, 2003; Robertson, 2010), however, there remains value in correlating CPT and SPT data so that CPT results can be evaluated in terms of the full performance case history database. Various correlations have been published between the CPT and SPT, however, these correlations encompass a wide range of soil types and are not universally applicable, but depend on the soil characteristics and specifics of the SPT hammer and testing assembly.

Density testing is routinely performed at oilsands tailings dams to confirm that the dyke construction meets the design specifications. Density testing at Shell Canada Energy´s (SCE´s) Muskeg River Mine (MRM) has mostly been made using CPT. At a subset of the MRM test locations, a parallel series of SPTs were performed to obtain soil samples, compare the results of the two test methods and establish a site-specific correlation. From these test results, published SPT-CPT correlations were evaluated for the MRM tailings sand, and suitable correlations were selected that allow equivalent SPT blowcounts to be predicted reasonably from the CPT. This paper summarizes the correlations between the CPT and SPT for the MRM tailings sand, and provides an indication of the accuracy of the correlations. Correlations with average grain size (D_{50}), and a comparison with published measurements at other oilsands tailings facilities (namely, the Syncrude Mildered Lake and J-Pit sites) are also discussed.

Background

Site and Material Description

The MRM is an oilsand mine located in northern Alberta, approximately 70 km north of Ft. McMurray. The test measurements discussed in this paper were made at the MRM External Tailings Facility (ETF). The measurements concentrated on the beaches at the regions of the ETF that have been constructed using the upstream method. The material deposited in these regions of the dyke typically comprises Coarse Sand Tailings (CST) that is overboarded from a single point discharge.

The tailings deposited below the pond level form Beach Below Water (BBW) tailings, and the remaining tailings form Beach Above Water (BAW) tailings. BBW tailings are generally looser than BAW tailings and are subsequently more susceptible to flow liquefaction. The tests reported in this paper were pushed through the BAW tailings; however, since the construction method involves ‘stepping’ subsequent raises out on top of former beaches, the tests penetrated both BBW and BAW tailings (see Figure 1).

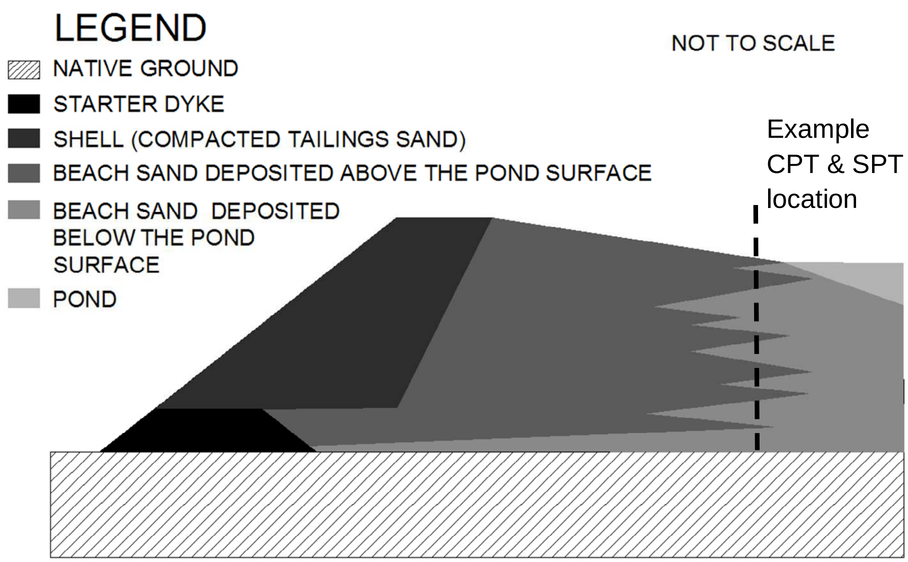


Figure 1: Schematic Illustration of an Upstream Tailings Dyke

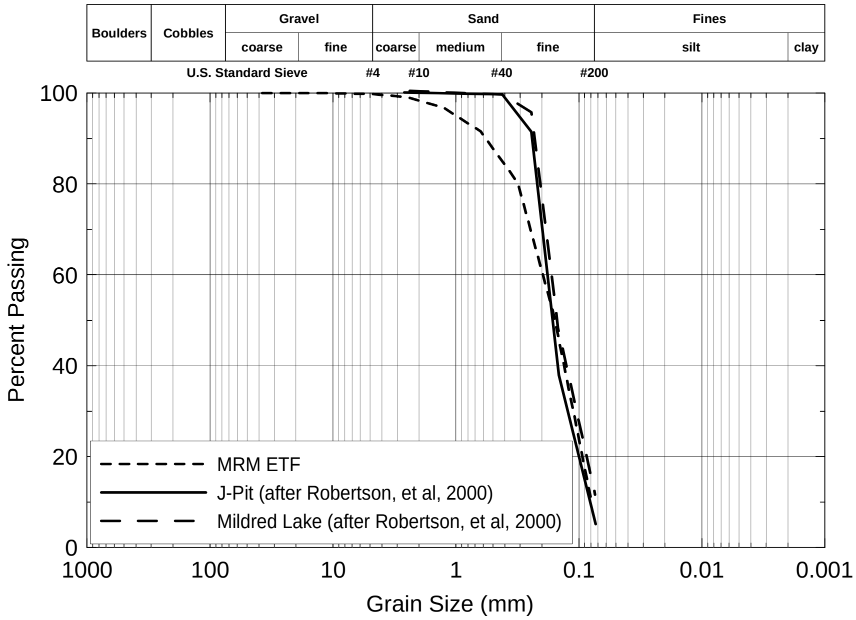


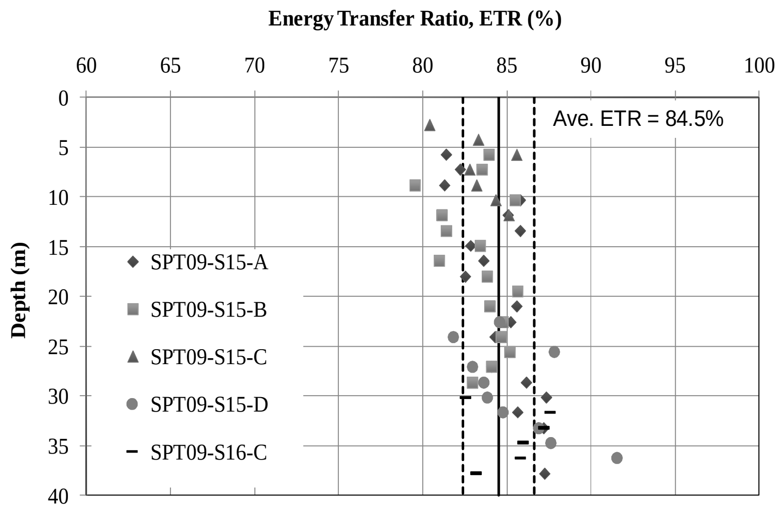
Figure 2: Oilsands Tailings Gradations

The gradation of the tailings deposits from the three sites considered in this study is generally similar with fines contents ranging between approximately 10 % and 20 %. A typical MRM ETF tailings gradation is shown in Figure 2 together with typical tailings gradations at the Mildered Lake and J-Pit facilities.

D_{50} values for the three deposits considered during this paper are 0.19 (standard deviation of 0.09), 0.16 and 0.17 for MRM, Mildred Lake and J-pit respectively (Robertson, et al, 2000).

Description of Equipment

The SPTs were carried out through 98 mm diameter boreholes that were advanced using a track mounted, mud-rotary drill rig. These test measurements were made in general accordance with the ASTM D 1586-08 standard. In accordance with the recommendations of Wride, et al (2000), and to enable the standardization of results, the SPT measurements also included Energy Transfer Ratio (ETR) hammer energy measurements that were made in general accordance with the ASTM D 4633-05 standard. The Force-Velocity (FV) method (Sy and Campenella, 1991) was used in the ETR calculations. Results of the ETR calculations are shown in Figure 3.



	Energy Transfer Ratio (ETR) (%)	
	Mean	Standard Deviation
SPT09-S15-A	84.8	2.0
SPT09-S15-B	83.4	1.8
SPT09-S15-C	83.5	1.7
SPT09-S15-D	85.5	2.9
SPT09-S16-C	85.3	2.1

Figure 3: ETR Results

The CPT soundings were advanced using a 25 ton track mounted rig with an electrical cone penetrometer that had a cross sectional area of 15 cm^2 and a cell capacity of 20 tons. Measurements of dynamic pore water pressure (u), tip resistance (q_t) and sleeve friction (f_s) were made at 10 mm depth increments. The test procedures were carried out in accordance with the ASTM D 5778-07 standard.

Published SPT-CPT Correlations

The published literature includes several correlations between CPT and SPT that use the D_{50} of the soil. Example relationships from Robertson, et al (1983), Kulhawy and Mayne (1990) and Stark and Olson (1995) are illustrated later in this paper together with the data from this study in Figure 6.

A potential difficulty with using the correlations involving D_{50} is their dependence on laboratory derived gradation data, which may not be available at an initial screening stage. Consequently, Jefferies and Davies (1993), and Lunne, et al (1997) suggested the following correlations that require only CPT data:

Jefferies and Davies (1993):

$$\frac{Q_c}{N_{60}} = 0.85\left(1 - \frac{I_c}{4.75}\right)$$ **(1),** where:

$$I_c = \sqrt{\{3 - log[Q(1 - B_q)]\}^2 + [1.5 + 1.3(\log F)]^2}$$ **(2)**

Lunne, et al (1997):

$$\frac{(q_c/P_a)}{N_{60}} = 8.5\left(1 - \frac{I_c}{4.6}\right)$$ **(3),** where:

$$I_c = \left((3.47 - log\ Q_t)^2 + (log\ F_r + 1.22)^2\right)^{0.5}$$ **(4)**

The Lunne, et al (1997) relationship was assessed during the CANLEX experiment (Wride, et al, 2000), which found that the equation generally predicted the SPT results well, although it occasionally produced overestimates. Jefferies and Davies (1993) found that their procedure also produced equivalent SPT N_{60} values that closely matched the actual SPT results. The repeatability cited by Jefferies and Davies for their procedure was greater than that produced by the SPT itself.

The Lunne, et al (1997) method has been used for comparison with the $q_{t1}/(N_1)_{60}$ ratio calculated during this study. As part of this comparison, the N_{60} calculated from Equation 1 was converted to $(N_1)_{60}$ using Equation 5 in accordance with the recommendations of Youd and Idriss (2001).

$(N_1)_{60} = N_{60} \times C_N$ **(5)**, where:

$C_N = (P_a/\sigma'_{vo})^{0.5}$ **(6)**

Liquefaction Criteria

In this study the equivalent $(N_1)_{60}$ values calculated from CPT data were compared against the Fear and Robertson (1995) contractant-dilatant boundary line, as represented by Olson and Stark (2003). An equivalent assessment was also undertaken using the actual SPT $(N_1)_{60}$ values to identify the effect that using SPT rather than CPT would have on the calculated percentages of liquefiable material identified at a sounding location.

The Olson and Stark (2003) criteria was chosen for this assessment since it is formulated in terms of SPT $(N_1)_{60}$ and therefore allows a direct comparison of the two methods of obtaining $(N_1)_{60}$ on liquefaction susceptibility.

The methodology for calculating the percentages of liquefiable material involved using a 1 m moving averaging window to search for any 1 m depth increments that contain less than 80 % non-liquefiable material. Any metre depth increment that failed the 80 % non-liquefiable criteria was designated as susceptible to liquefaction. Once the entire CPT or SPT had been assessed, the amount of liquefiable material was calculated as a percentage of the tailings column. This assessment method is illustrated in Figure 4. More details of the procedures illustrated in this figure are provided by Martens, et al (2009).

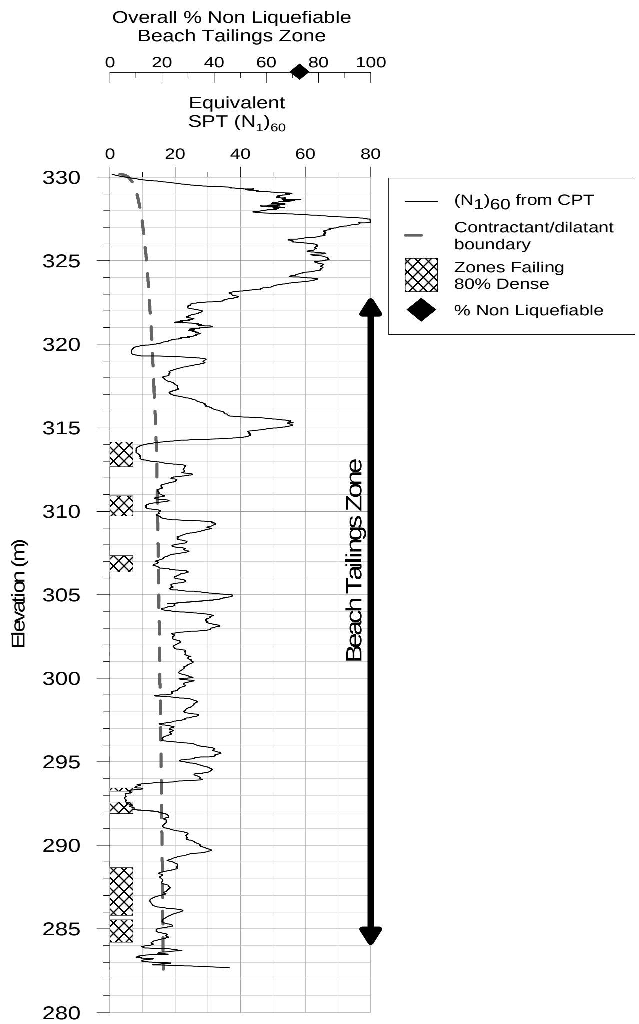


Figure 4: Liquefaction Susceptibility Assessment Method (after Martens et al. 2009)

Results

$q_{t1}/(N_1)_{60}$ Ratio

The average CPT q_{t1} measurements that were obtained over the 0.3 m depth increments that correspond to adjacent SPTs are plotted against the SPT $(N_1)_{60}$ values in Figure 5. Based on the comparison of 23 adjacent CPT and SPT tests, Figure 5 shows that a $q_{t1}/(N_1)_{60}$ ratio of 0.45 is appropriate for the MRM tailings. The standard deviation around the average $q_{t1}/(N_1)_{60}$ ratio (0.45) is 0.07. When the ratio calculated during this study is compared with the ratios calculated at the Mildred Lake and J-Pit, it can be seen to be very similar. The average ratios at Mildred Lake and J-Pit are 0.44 (with a standard deviation of 0.15) and 0.51 (with a standard deviation of 0.25) respectively (Wride, et al, 2000).

The oilsands $q_{t1}/(N_1)_{60}$ ratios are compared with various D_{50} based relationships in Figure 6. This figure shows that the three oilsands ratios considered all cluster together around the Robertson, et al (1983) and Stark and Olson (1995) relationships. These results would suggest that, in the absence of a site specific correlation, suitable SPT-CPT correlations for oilsands tailings are those of Robertson, et al (1983) and Stark and Olson (1995). However, these relationships require gradation data. If gradation data are not available then the $q_{t1}/(N_1)_{60}$ ratio of 0.45 calculated during this study would be suitable since it is similar to the values calculated at other oilsands tailings storage facilities.

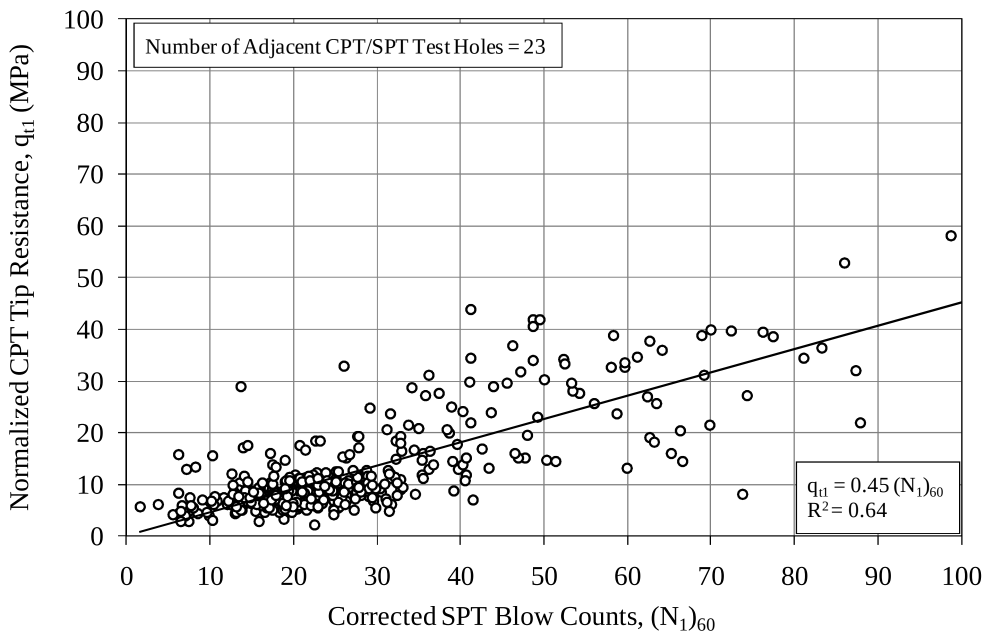


Figure 5: SPT-CPT Correlation

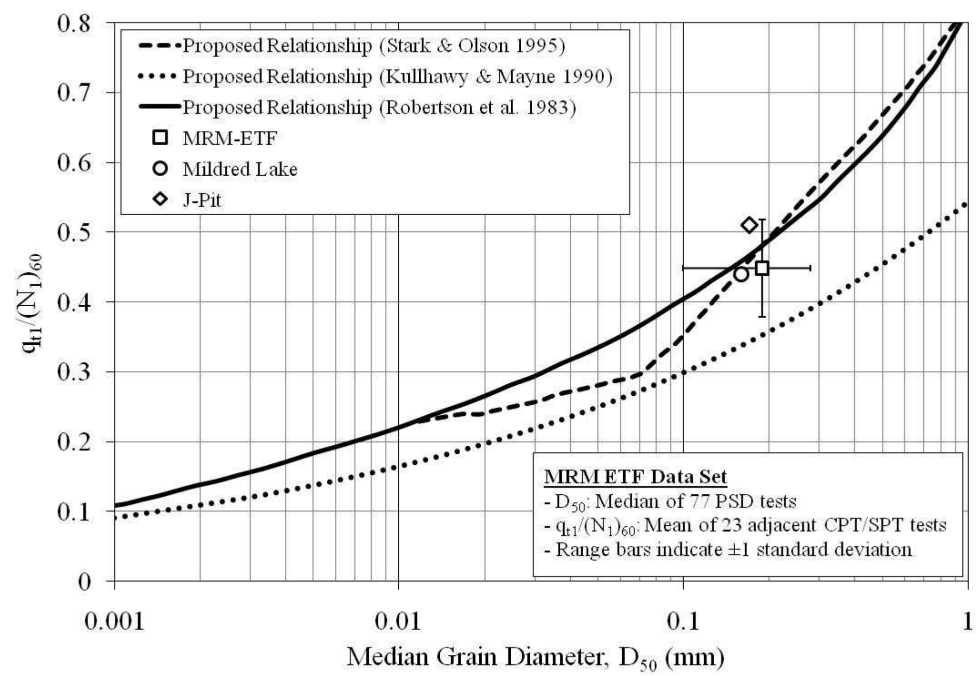


Figure 6: Comparison of $q_{t1}/(N_1)_{60}$ Ratios Calculated at Oilsands Mines with Standard Ratios

$(N_1)_{60}$ and CPT Equivalent $(N_1)_{60}$ Comparison

The equivalent SPT $(N_1)_{60}$ calculated using the 0.45 $q_{t1}/(N_1)_{60}$ ratio has been compared with the actual SPT results. The results for a selection of the test holes are presented in Figure 7.

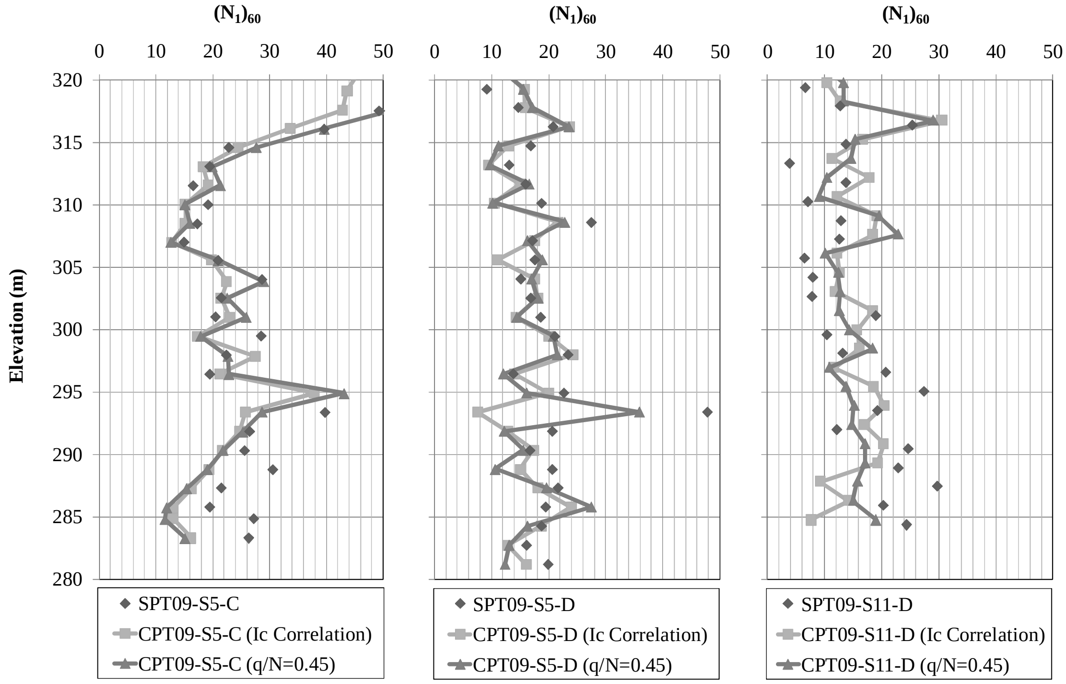


Figure 7: Comparison of $(N_1)_{60}$ Measurements with Equivalent $(N_1)_{60}$ Values

The SPT values that can be calculated using the Lunne, et al (1997) algorithm are also plotted on Figure 7. This figure shows, similarly to the findings of the CANLEX experiment, that the values derived from the Lunne, et al (1997) equation are generally close to the measured values. The results of the Lunne, et al (1997) equation generally plot very similarly to the results from the $q_{t1}/(N_1)_{60}$ ratio of 0.45.

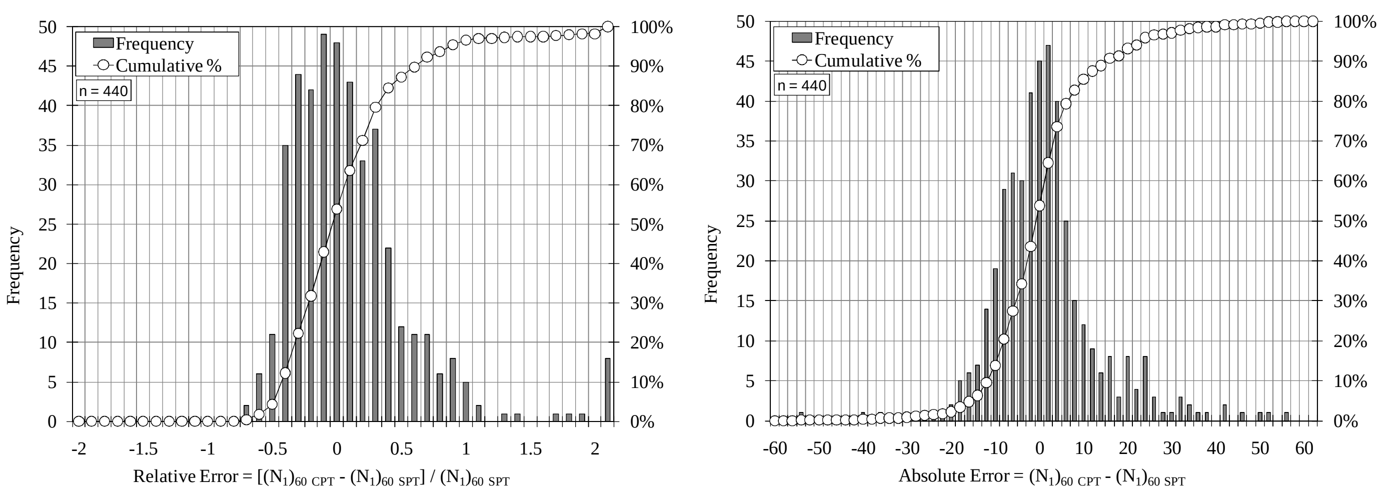


Figure 8: Comparison of $(N_1)_{60}$ Measurements with Equivalent $(N_1)_{60}$ Values

The accuracy of the equivalent $(N_1)_{60}$ values was assessed in terms of the absolute error (difference between calculated and measured $(N_1)_{60}$) and the relative error (ratio between the estimated and measured $(N_1)_{60}$ difference to the measured $(N_1)_{60}$). The results of this analysis are shown in Figure 8. The mean relative error is 0.36 (standard deviation of 0.52) and the mean absolute error is 8.41 (standard deviation of 9.00). In other words, out of 440 adjacent SPT and CPT tests, almost 75 % of the tests produced absolute error of less than ±8 blow counts and relative error less than ±0.4.

Potential Sources of Uncertainity in the SPT-CPT Correlation

A potential source of uncertainty in the SPT-CPT correlation is the accuracy of the depth measurement for both tests. The actual test elevation may differ from the presented elevation due to the inclination, which may change with depth. An advantage of the CPT method over the SPT is that the CPT allows inclination measurements which can be used to apply a depth correction, whereas, the SPT inclination cannot be measured. The accuracy of the CPT measurements is illustrated in Figure 9.

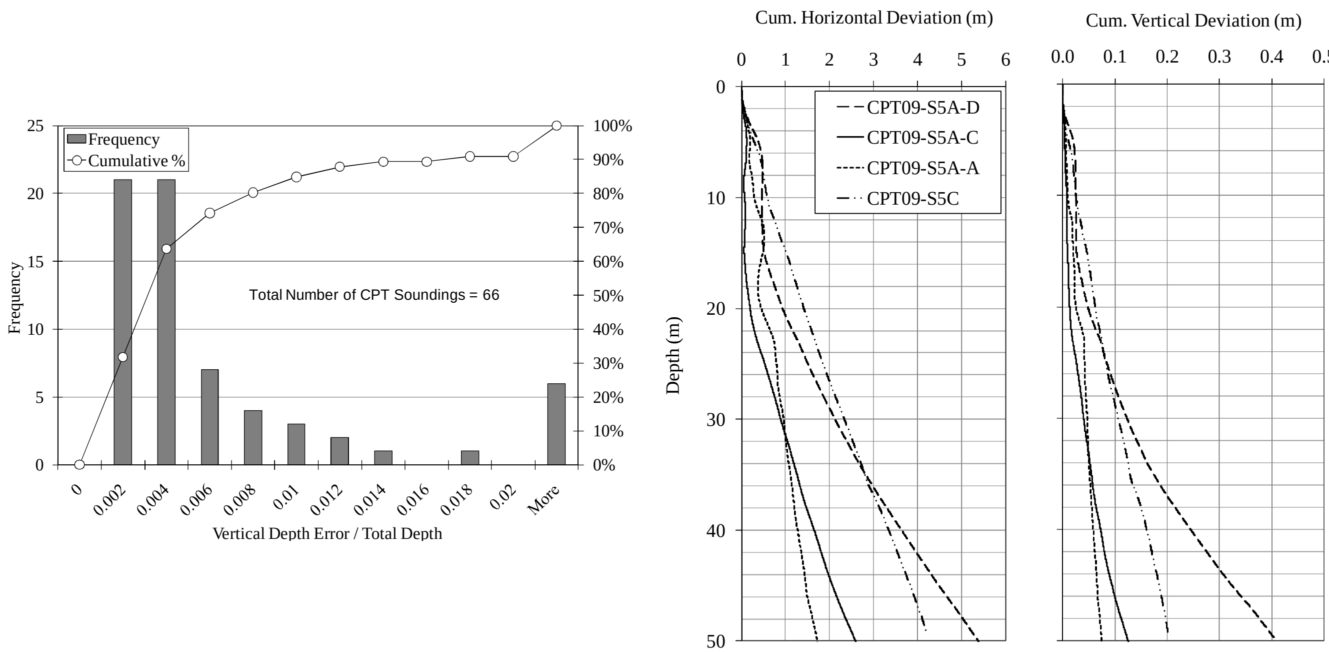


Figure 9: Plots of CPT Measurement Error

Figure 9 shows that the vertical deviation is significantly less than the horizontal deviation. The vertical deviation is generally less than 0.5 m and equates to less than 1.5 % of the total depth for 90 % of the measurements. These data suggest that at the bottom of a 50 m deep sounding the CPT measurements can confidently be thought of as being generally less than 0.5 m vertically apart from the SPT measurement, and within a maximum of approximately 5 m horizontaly. This error is sufficiently small to suggest that the SPT and CPT measurements were generally in very close proximity. During this study, this has been assumed to be the maximim deviation between the SPT and the CPT messurements, since the SPT hole was assumed to be perfectly straight. There are however no data to confirm this assumption, and any inclination in the SPT hole could result in the SPT and the CPT being either closer together or farther apart.

The error in the CPT measurements can be seen to increase with depth; however, this does not appear to have transferred to the $q_{t1}/(N_1)_{60}$ ratio since there is no strong trend in the $q_{t1}/(N_1)_{60}$ ratio error with depth.

Another potential source of error in the SPT-CPT correlation is the natural soil variation between adjacent SPT and CPT. MRM tailings are deposited from a single point discharge at the upstream edge of the dyke crest, which forms BAW and BBW that are sloped by 2% to 10%. Therefore, the depth error due to the beach slope may range between 0.1 m and 0.5 m for a horizontal offset of 5 m between SPT and CPT locations.

Impact on Liquefaction Susceptibility Assessments

The impact of using an $(N_1)_{60}$ calculated from the $q_{t1}/(N_1)_{60}$ ratio of 0.45 as opposed to using the measured $(N_1)_{60}$ during a liquefaction susceptibility assessment is illustrated in Figure 10. The calculation of the percent non-liquefiable in this figure is illustrated in Figure 4 and described in more detail by Martens, et al (2009). Figure 10 shows that the CPT approach calculates a greater quantity of liquefiable material than the SPT approach. This is considered to be a result of the near continuous CPT measurements (10 mm) capturing thin weak layers that were not identified by the more widely spaced (1500 mm to 2000 mm) SPT measurements.

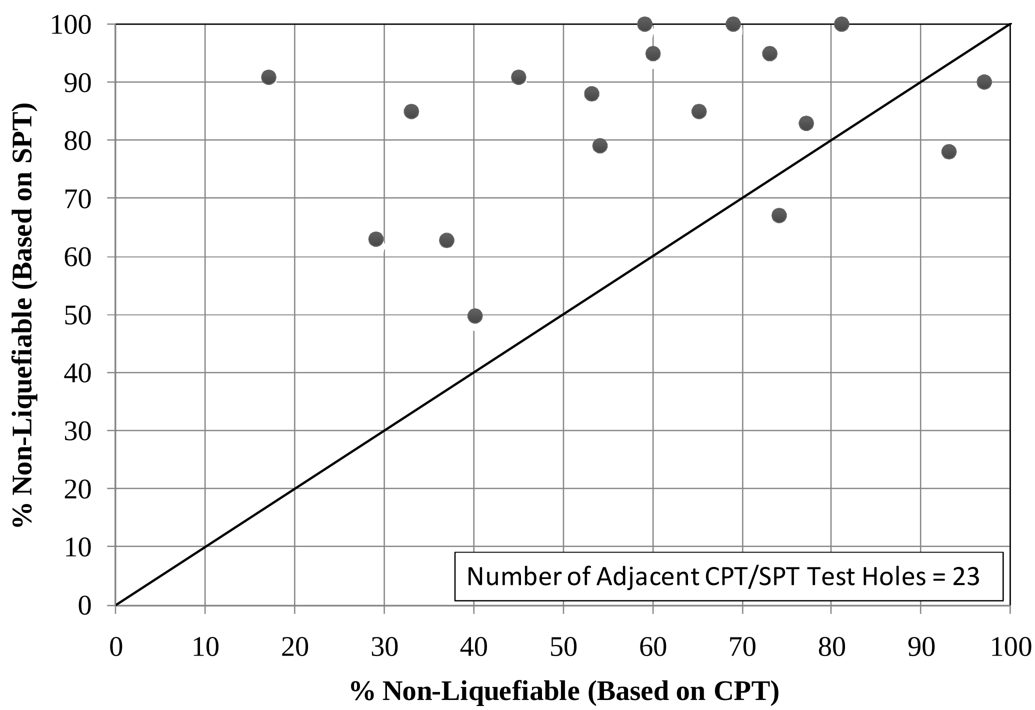


Figure 10: Effect of Non-Liquefiable Percentages Calculated using $(N_1)_{60}$ from SPT and using $(N_1)_{60}$ from CPT

Conclusions

This paper has assessed the correlation between SPT and CPT for tailings sand from three different oilsands tailings facilities and compared the effect of using either SPT or CPT measurements in liquefaction susceptibility assessments. Key findings from this study include the following:

- A $q_{t1}/(N_1)_{60}$ ratio of 0.45 is applicable for the MRM, which is similar to measurements made at other oilsands tailings storage facilities.
- There is significant scatter in the correlation but the mean value is robust and there is evidence (Jeffries and Been, 1993) that the scatter is mainly due to the poor repeatability of the SPT.

- All of the oilsands $q_{t1}/(N_1)_{60}$ ratios assessed during this study plot similarly to the relationships presented by Robertson, et al (1983) and Stark and Olson (1995).
- The $q_{t1}/(N_1)_{60}$ ratio produces equivalent $(N_1)_{60}$ values that differ from measured $(N_1)_{60}$ values by ±8 blow counts for almost 75 % of the 440 adjacent SPT/CPT carried out at the MRM ETF.
- When liquefaction susceptibility is assessed using an $(N_1)_{60}$ derived from CPT data, a greater quantity of liquefiable material is identified than when it is assessed using SPT data directly. This underestimate of liquefiable material from the SPT approach is considered to be due to the wide spacing of SPT measurements missing weak layers that are captured by the close spacing of CPT measurements.

In summary, $(N_1)_{60}$ can be well estimated at the MRM using a $q_{t1}/(N_1)_{60}$ ratio of 0.45. Using an $(N_1)_{60}$ derived from CPT data to assess liquefaction susceptibility is preferable to using SPT data directly since the discrete nature of SPT data tends to under-represent the quantity of liquefiable material, which could potentially lead to unsafe conclusions regarding liquefaction potential.

Acknowledgements

The authors gratefully acknowledge the permission of Shell Canada Energy to publish the data and findings of this paper.

References

ASTM D 1586-08. Standard Test Method for Standard Penetration Test (SPT) and Split Barrel Sampling of Soils. ASTM International.

ASTM D 4633-05. Standard Test Method for Energy Measurement for Dynamic Penetrometers. ASTM International.

ASTM D 5778-07. Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils. ASTM International.

Fear, C.E. and Robertson, P.K. 1995. "Estimating the Undrained Strength of Sand: A Theoretical Framework." *Canadian Geotechnical Journal*, 32 (4).

Jefferies, M. G., and Davies, M. P. 1993. "Use of CPTu to Estimate Equivalent SPT N_{60}." *Geotechnical Testing Journal*. 16 (4).

Kulhawy, F.H, and Mayne, P.W. 1990. *Manual on Estimating Soil Properties for Foundation Design*, Electric Power Research Institute, Palo Alto, CA.

Lunne, T., Robertson, P.K., and Powell, J.J.M. 1997. *Cone Penetration Testing in Geotechnical Practice*. Blackie Academic & Professional, London.

Martens, A., Lappin, T., and Eaton, T. 2009 "Zoned Strength Model for Oilsands Upstream Tailings Beach". Tailings and Mine Waste 09, Banf, Alberta.

Olson, S.M. and Stark, T.D. 2003. "Yield Strength Ratio and Liquefaction Analysis of Slopes and Embankments." *Journal of Geotechnical Engineering*. American Society of Civil Engineers. 129 (8). 727-737.

Robertson, P.K., Wride (Fear), C.E., List, B.R., Atukorala, U., Biggar, K.W., Byrne, P.M., Campanella, R.G., Cathro, D.C., Chan, D.H., Czajewski, K., Finn, W.D.L., Gu, W.H., Hammamji, Y., Hofmann, B.A., Howie, J.A., Hughes, J., Imrie, A.S., Konrad, J.-M., Küpper, A., Law, T., Lord, E.R.F., Monahan, P.A., Morgenstern, N.R., Phillips, R., Piché, P., Plewes, H.D., Scott, D., Sego, D.C., Sobkowicz, J., Stewart, R.A., Watts, B.D., Woeller, D.J., Youd, T.L., and Zavodni, Z. 2000. The CANLEX project: summary and conclusions. *Canadian Geotechnical Journal*, 37 (3), 563-591.

Robertson, P.K., Campanella, R.G., and Wightman, A. 1983. “SPT-CPT Correlations.” *Journal of Geotechnical Engineering*, American Society of Civil Engineers, 109 (11). 1449-1459.

Robertson, P.K. 2010. “Evaluation of Flow Liquefaction and Liquefied Strength Using the Cone Penetration Test.” *Journal of Geotechnical Engineering*. American Society of Civil Engineers. 136 (6), 842-853.

Stark, T.D. and Olson, S.M. 1995. “Liquefaction Resistance Using CPT and Field Case Histories.” Journal of Geotechnical Engineering. American Society of Civil Engineers. 121 (2). 856-869.

Sy, A and Campenella, R.G. 1991. “An Alternative Method for Measuring SPT Energy.” 2nd Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Paper 3.39, Vol 1 pp. 499-505.

Wride (Fear), C.E., Robertson, P.K., Biggar, K.W., Campanella, R.G., Hofmann, B.A., Hughes, J.M.O., Küpper, A., and Woeller, D.J. 2000. Interpretation of in situ test results from the CANLEX sites. *Canadian Geotechnical Journal*, 37 (3), 505-529

Youd, T.L., and Idriss, I.M. 2001. Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshop on Evaluation of Liquefaction Resistance of Soils. *Journal of Geotechnical and Geoenvironmental Engineering.* 127 (4), 297-313.