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A Case History in the Fraser River Basin on Different Liquefaction Triggering Assessments and Considerations for their Use

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ABSTRACT

Geotechnical engineers often need to complete geotechnical site investigations with one of the outputs being the completion of liquefaction triggering assessments. To complete liquefaction triggering assessments, geotechnical engineers typically rely on empirical procedures that have been developed from seismic case history data and use of various in-situ test methods. These in-situ methods include the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Shear Wave Velocity (V_s) measurement with the latter collected through a seismic CPT (SCPT), a Downhole Shear wave Test (DST) or other small strain methods. The numerous investigation methods each have their own different considerations for their use such as the application of correction factors or their own suite of test specific correlations. In a perfect world, the liquefaction triggering conducted by the different assessment methods would yield the same level of liquefaction susceptibility for the same soil unit. Unfortunately, differences between the outputs of the triggering procedures and other epistemic uncertainties often occur leading to inconsistencies. Additionally, depending on the use of the data there may be a need to consider the output traditionally developed through a single test method, such as the use of $(N_1)_{60}$, in non-linear constitutive numerical models, and correlation between other data sources may be necessary.

This paper presents a case study from a recent project in the lower mainland reviewing different liquefaction triggering correlations and their interaction; providing commentary on the application of existing empirical correlations and corrections; providing commentary on data collection methods; and reviewing Cyclic Direct Simple Shear (cyDSS) tests conducted on undisturbed samples and their comparison to empirical triggering methods.

Keywords: Liquefaction Triggering, Case Study, Standard Penetration Test, Cone Penetration Test, Shear Wave Velocity.

INTRODUCTION

As part of a recent geotechnical exploration program for a linear infrastructure project in the Fraser River Basin in the lower mainland of British Columbia subsurface information was obtained through different geotechnical drilling and in-situ testing methods. The exploration program included boreholes advanced using solid stem augers, mud rotary, and sonic drilling methods with in-situ tests including Nilcon Shear Vanes, Standard Penetration Tests (SPTs), Cone Penetration Tests (CPTs), Seismic CPTs (SCPTs), and Downhole Shear wave Tests (DSTs). In addition to the in-situ tests, disturbed and undisturbed samples were collected for subsequent laboratory testing following the exploration program.

As part of the scope of work, given the regional seismicity and encountered soils, liquefaction triggering assessments were conducted. To evaluate the soil's susceptibility to liquefaction various empirical triggering relationships were reviewed including those for the SPT, CPT, and Shear Wave Velocity (V_s). In addition to the in-situ testing, undisturbed samples obtained during the exploration program underwent dynamic laboratory testing in the form of Cyclic Direct Simple Shear (cyDSS) tests.

In several locations within the project limit, boreholes with SPT and collection of undisturbed samples were advanced and paired with CPT, SCPT and/or DST in close proximity. Given the close proximity of the tests there is a unique opportunity to review the differences between the common triggering methods.

This paper presents a case study reviewing different liquefaction triggering correlations and their interaction; providing commentary on the application of existing empirical correlations and corrections; providing commentary on data collection methods; and reviewing Cyclic Direct Simple Shear (cyDSS) tests conducted on undisturbed samples and their comparison to empirical triggering methods.

GEOLOGICAL SETTING

The project included in this study is located in Fraser River Basin in the lower mainland of British Columbia. The surficial geology map developed by the Geological Survey of Canada illustrates the surficial geology in the project area. The surficial geology is primarily composed of Quaternary Postglacial Lacustrine Deposits (SAq) throughout the alignment [1].

- Lacustrine Deposits (SAg): silt to clay, normally less than 5 m thick, in places overlying additional Lacustrine Deposits (SAr) or Fraser River Sediments (Fe).
    - Lacustrine Deposits (SAr): sand to sandy loam, up to 5 m thick also overlying Fraser River Sediments (Fe).
    - Fraser River Sediments (Fe): channel fill and floodplain deposits, overlying and cutting estuarine sediments and commonly overlain by overbank sediments. Estuarine fine sand to clayey silt, in places fossiliferous and probably underlying extensive areas in the Sumas and Matsqui valleys with thicknesses from 10 m to 150 m.

A series of geotechnical exploration programs were conducted to characterize the stratigraphy within the project alignment. Based on the results of the geotechnical exploration programs, the project site is interpreted to consist of eight main soil layers, of which the upper granular layers are the focus of the liquefaction triggering assessment. For the purpose of this paper, the granular soil units that are considered susceptible to liquefaction consist of a upper sand unit underlain by a mixture of sand, silty sand and silt. The SPTs performed in the upper sand indicate the material is compact and potentially liquefiable under the design earthquake loading. Below the upper sand, the granular soils become silty and transition into interbedded sand, silty sand, and silt. Fines content in the sand and silt interbeds layer varied between 3% and 78%.

SEISMIC SETTING

In southwestern British Columbia seismicity is generally related to the offshore subduction of the Juan de Fuca Plate beneath the North American plate [2]. The complicated tectonic regime results in three different earthquake source types in the project area: shallow crustal earthquakes, deep in-slab earthquakes, and interface subduction earthquakes [2]. As a result of the proximity of the project area to the multiple seismic sources the 2% probability of exceedance code based firm ground spectra considering a time averaged shear wave velocity in the top 30 m (Vs_{30}) of 450 m/s results in a Peak Ground Acceleration (PGA) of 0.38g when using the 6th Generation Canadian Seismic Hazard Model [3]. It should be noted, the site Vs_{30} was less than 450 m/s and the PGA is included as a reference of a firm ground condition to demonstrate the site's seismicity.

LIQUEFACTION TRIGGERING METHODS

The basis of liquefaction triggering relies on the ratio between a seismic event's cyclic demand, the cyclic stress ratio (CSR), to the soil's cyclic resistance, the cyclic resistance ratio (CRR). When the soil's CRR is less than the earthquake induced CSR the soil is anticipated to liquefy. It is important to note that not all soils are susceptible to liquefaction, typically granular soils such as sands, non-plastic to low plastic silts, and gravels are considered susceptible [4]. Additionally, for liquefaction to occur the soil must be saturated. With clean sands, sands with fines contents less than 10-15%, and gravelly soils, undisturbed sampling and testing is largely impractical and as such the ability to sample and test site specific samples in a laboratory setting is not possible for most projects. As a result, the soil's susceptibility to liquefaction is typically evaluated through liquefaction triggering methods from in-situ test data in these soils. For non-plastic silts, low plastic silts, and silt sand mixtures, undisturbed sampling through the use of thin walled piston/Shelby tubes carefully advanced during the geotechnical drilling program can be collected and undergo laboratory testing of the soil's resistance to liquefaction.

There are several methods that exist to correlate in situ test data to predict a soil's susceptibility to liquefaction based on empirical case history data from previous seismic events. These methods typically aim to predict whether the soil will liquefy and are commonly referred to as liquefaction triggering methods. It is important to recognize that the triggering methods do not aim to predict the strength of the soil following liquefaction, the soil's residual strength, but rather assess the soil's susceptibility to liquefaction. Further correlative models have been proposed by researchers to evaluate the residual strength of the liquefied soil (e.g. Idriss & Boulanger, 2008; Boulanger & Idriss, 2014), however these models are outside the scope of this paper and not discussed herein.

Soil liquefaction triggering models have been proposed for the SPT, CPT, and Shear Wave Velocity measurements. Table 1 provides a high-level summary of some of the considerations for different in-situ test methods as they pertain to liquefaction triggering.

Table 1: Summary of in-situ Test Methods Relating to Liquefaction Triggering

	SPT	CPT	Vs
ASTM Standard	ASTM D1586	ASTM D5778	ASTM D7400
Operator and Equipment Variability	Variable based on equipment	Independent of operator provided standard followed	Slight variability depending on test method if data collected by downhole or surficial inversion methods
Post Data Collection Corrections for Equipment	Several corrections to account for differences in test apparatus (Liner, energy, rod length, and hole diameter corrections).	Limited due to standardization of test. Corrections possible for thin layers which may influence the tip pressure.	Corrections may be applied to surficial methods baselined on downhole data. Limited correction for downhole data.
Overburden Correction	Yes	Yes	Yes
Strain Level	High Strain	Medium Strain	Low Strain
Select Common Published Triggering Models	Idriss & Boulanger, 2008; Boulanger & Idriss, 2014	Robertson & Wride, 1998; Idriss & Boulanger, 2008; Boulanger & Idriss, 2014	Andrus & Stokoe, 2000; Kayen, et al., 2013

COMPARISON OF LIQUEFACTION TRIGGERING METHODS

In a perfect world, the liquefaction triggering conducted by the different assessment methods would yield the same level of liquefaction susceptibility for the same soil unit. Unfortunately, differences between the outputs of the triggering procedures and other epistemic uncertainties often occur leading to inconsistencies. As part of the geotechnical exploration program the following borehole advancement techniques and in-situ tests were conducted:

- Three mud rotary boreholes including SPTs paired with CPT
- Two mud rotary boreholes including SPTs paired with SCPT
- One mud rotary borehole including SPTs paired with CPT and DST
- Two mud rotary boreholes including SPTs paired with SCPT and DST
- Three sonic boreholes including SPTs paired with SCPT
- One sonic borehole including SPTs paired with CPT

In addition to the in-situ tests, two Shelby tube samples of silty sand were obtained during the geotechnical exploration program and later underwent CyDSS testing at two CSR levels each. The samples had fines contents of 24% and 16%. The Shelby tubes underwent gamma-ray scans to provide visual evaluation of sample disturbance for specimen selection. The CyDSS tests were performed under stress-controlled and constant volume conditions following the general procedures outlined in ASTM D8296.

To demonstrate the comparison between the different triggering methods the two Mud Rotary boreholes paired with SCPT and DST Vs measurements were considered and are presented below. The soil stratigraphy varies slightly between the boreholes given their locations within the project alignment. The SPT and CPT triggering methods proposed by Boulanger & Idriss were considered [5]. The Vs based liquefaction triggering method proposed by Andrus & Stokoe was considered for comparison [6]. For the CRR values presented, an earthquake magnitude of 6.7 corresponding to the inslab seismic hazard was considered.

For the SPTs conducted within the geotechnical exploration program, liners were not used and there was a space for liners with an inner diameter of the SPT of 35 mm (1.375 in). The SPT triggering points presented within Figure 1 do not consider the liner correction as within this study area it did not appear to coincide with the data when reviewing the other triggering methods.

Energy measurements were collected before the outset of the program on the same equipment assembly as was used for the exploration program and were not collected or available for each of the borings.

The predicted CRR for the soil for each of the triggering methods is shown in Figure 1.

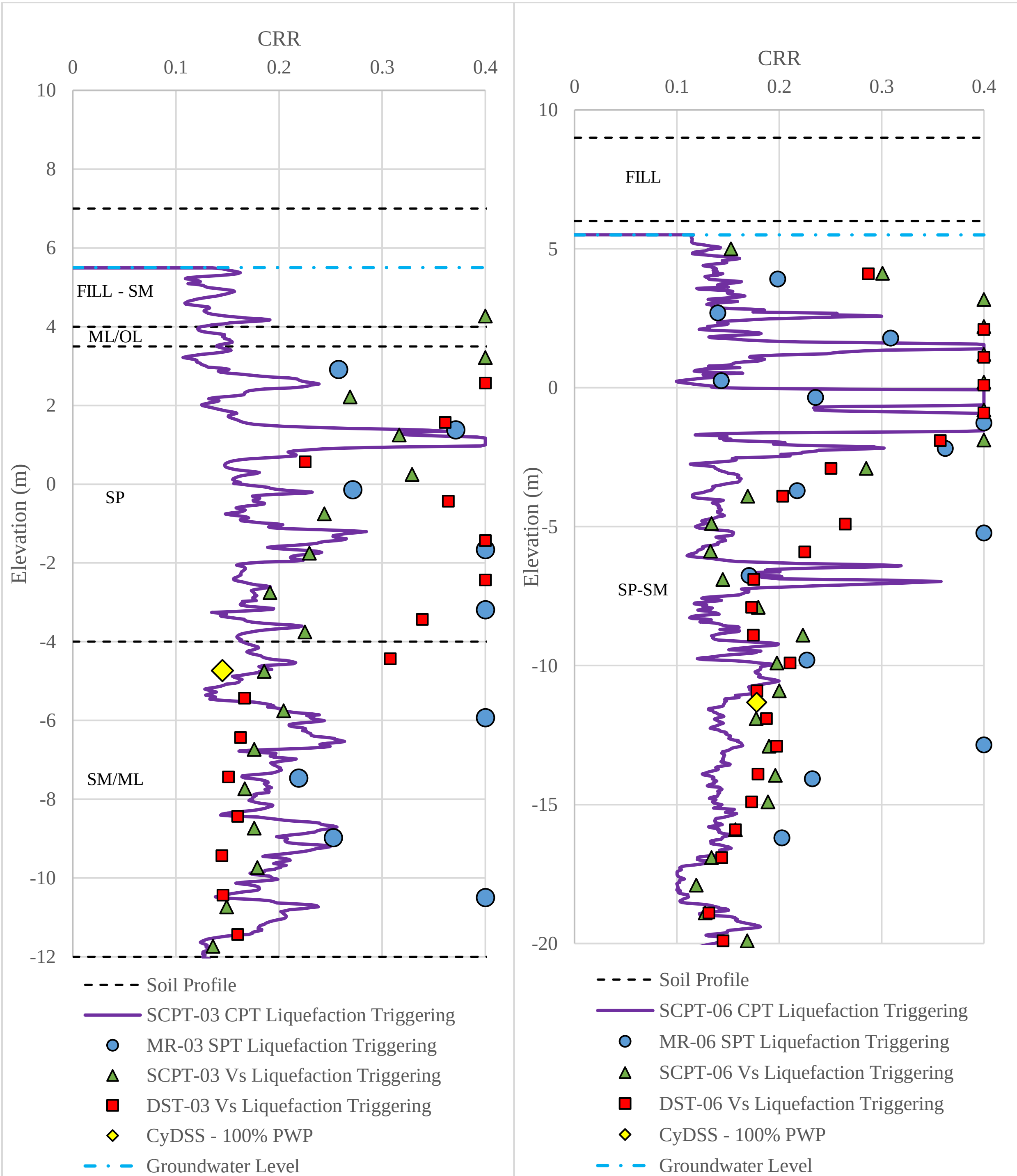

Figure 1: Comparison of Liquefaction Triggering Methods in Two Paired Mud Rotary Boreholes

In this study area, the SPT and CPT liquefaction triggering relationships proposed by Boulanger and Idriss appear to generally coincide in the borehole MR-06 shown on the right side in Figure 1. Within borehole MR-03 on the left side of Figure 1, the SPT predicted CRR generally was higher than the CPT CRR. The Vs Liquefaction triggering relationships generally appear to coincide with the SPT and CPT triggering methods, however there are areas of deviation in both boreholes within Figure 1.

There is also some scatter in Vs Triggering relationships in both holes between the Vs Data obtained by the SCPT conducted about 5 m away from the Mud Rotary boreholes, but generally the Vs data was similar between the different collection methods. In the case of the CyDSS tests, they were found to generally align with the CRR values from the CPT when considering 100% excess pore water pressure or 5% single amplitude strain for 10 cycles corresponding to a 6.75 Mw [7].

COMPARISON OF SONIC VS MUD ROTARY SPTS

In one of the locations a sonic borehole was advanced with SPT and paired with a SCPT. The initial intent was to advance this hole with a mud rotary drilling rig, but due to equipment availability the borehole was advanced with a sonic drilling rig instead. The sonic borehole was advanced approximately 175 m away from MR-06 presented within Figure 1. The same liquefaction triggering relationships and considerations were applied as those discussed above. Given the depositional environment the soil stratigraphy was similar between the two locations. The predicted CRR for the soil for each of the triggering methods for the sonic borehole is shown in Figure 2.

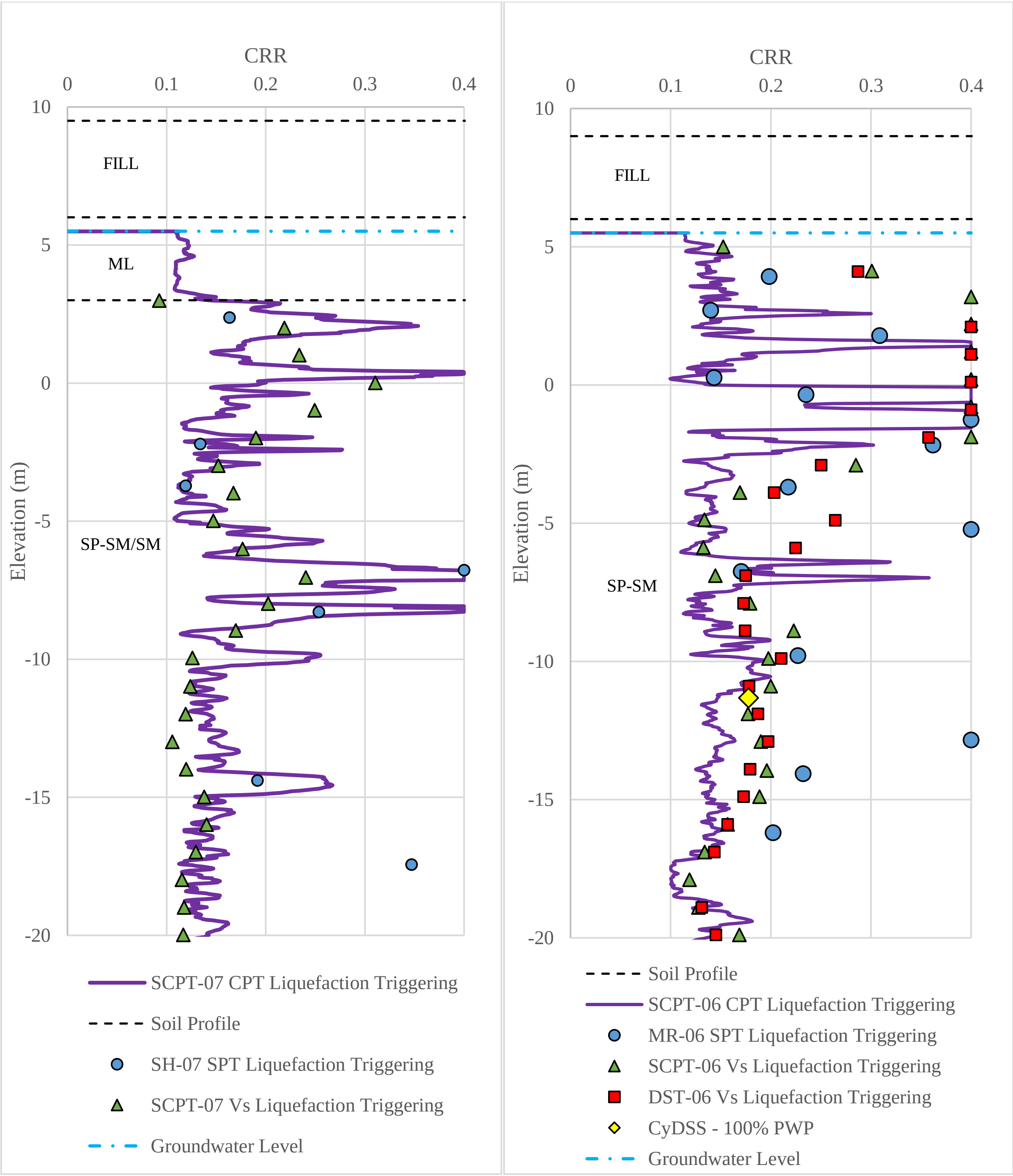

Figure 2: Comparison of Liquefaction Triggering Methods in Sonic (left) and Mud Rotary (right) Boreholes

Within Figure 2 it can be seen that the SPT correlated CRR for the Mud Rotary generally appear to coincide with the CPT correlated CRR. The general consensus is that the energy and vibration associated with sonic drilling potentially disturb the soils and affect the penetration resistance. In this case, the CRR correlated values from SPTs advanced within the sonic borehole are reasonably consistent throughout the tested profile as shown on Figure 2. The SPT data obtained from a sonic-drilled hole should be valid if the drilling was performed with care.

CORRELATION BETWEEN CPT AND SPT

A common issue for geotechnical engineers when they use constitutive models is the inputs to the model may be limited to a type of test. The SPT N value is one of the input parameters in two commonly used constitutive models, UBCSAND and PM4Sand, to capture pore pressure generation during dynamic analyses. These models are implemented in numerical modelling software packages, such as FLAC or PLAXIS, which geotechnical engineers use to aim to estimate the response to seismic events. Researchers have proposed relationships to correlate CPT obtained tip resistance values (qt) to N_{60} values. The use of two relationships were explored to review the fit with the obtained data from the exploration program. The relationship reviewed was proposed by Robertson in 2012 with the form below in Eq. 1 [8].

$$\frac{(q_t/p_a)}{N_{60}} = 10^{(1.1268\,-\,0.2817 I_c)} \qquad (1)$$

The second relationship considered was a piecewise function based on the soil's behaviour type index, I_c, following review of Soil Behaviour Type (SBT) ratio between qc and N_{60} considering the ranges published by Robertson et al in 1986 and the I_c bounds proposed Robertson and Wride [9, 10]. The ratio for the I_c ranges were adjusted to fit the data across the paired holes within the project until it was deemed through review that the ratio had an acceptable fit for engineering purposes. An important note for the application of the piecewise values used in this study was the primary area of interest was in granular soils with I_c values up to 2.6. However, a complete set of values including fine-grained soils was also added to the table for completeness.

The ratio between q_c/p_a and N_{60} considered based on the project data are shown in Table 2.

Table 2: Soil Behaviour Index (I_c) to N_{60} Ratio Considered

Soil Type(1)	**I_c Range**	**q_c/p_a to N_{60} Ratio**
Gravelly Sands and Sands	< 2.05	5.9
Sand Mixtures	2.05 to 2.60	2.6
Silts	2.60 to 2.95	2.6
Clays	2.95 to 3.60	2.0
Clays – Organic Soil	> 3.60	Not Evaluated in Project Area

1) Soil Behaviour Type Index, I_c from Robertson & Wride, 1998.

The relationship shown in Equation 1 and the piecewise values in Table 2 were applied to correlate CPT tip resistance with SPT values. The SPT and correlated SPT values are shown normalized for one atmosphere of overburden pressure ($(N_1)_{60}$) within Figure 3 below. Given the large scatter observed for the SPT values reported in sonic boreholes, the evaluation was performed using only the SPT values obtained in mud-rotary boreholes.

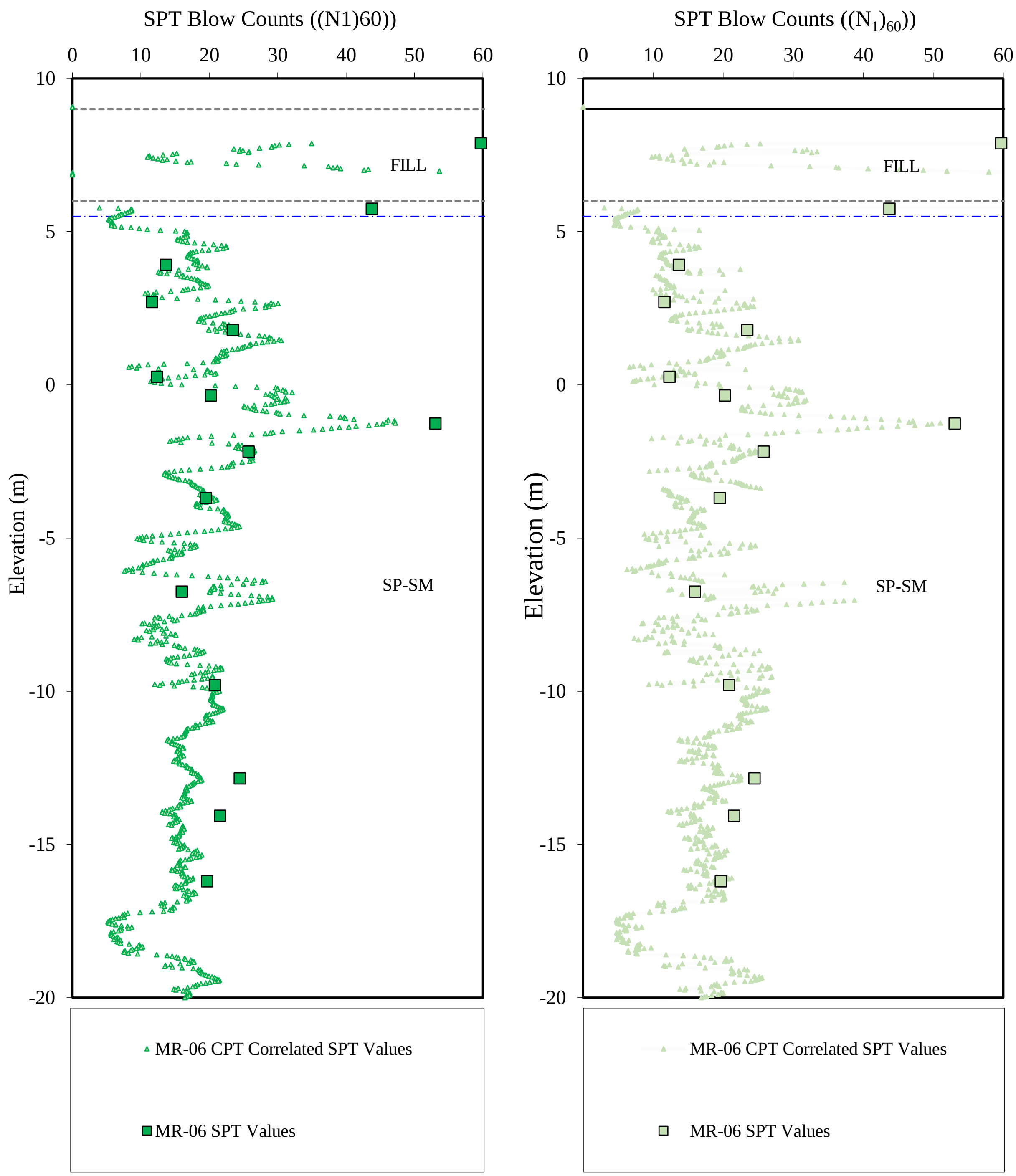

Figure 3: Comparison of CPT to SPT Correlation Approaches in MR-06. Robertson 2012 (left) Piecewise (right)

Within Figure 3, the relationship within Equation 1 generally appears to coincide with the SPT values in to an elevation of -10 m. Below -10 m, the relationship within Equation 1 appeared to show a minor underestimation of the SPT values within the information obtained in this exploration program. The piecewise ratios shown in Table 2 were adjusted specifically across the paired holes to obtain a project specific fit of the obtained SPT values.

CONSIDERATIONS FOR SITE EXPLORATION PROGRAMS AND CONCLUSIONS

When conducting geotechnical site exploration programs where liquefaction triggering assessments will be present, there are several elements that should be considered. The National Academies of Sciences, Engineering, and Medicine recommends where liquefaction is possible the soil's liquefaction resistance should use data from the CPT where feasible [4]. In addition, they go on to say site specific hammer energy measurements should be obtained if SPT is used for liquefaction triggering and the SPT setup should minimize the need for additional correction measures [4].

When considering the use of SPT, consideration should be given to the potential for disturbance from the drill method to the soil beneath the borehole. Within this project, SPT values obtained within Sonic advanced boreholes were generally found to be reasonably consistent with the CPT resistance. It should be noted the sonic drilling method has been observed by researchers to have a zone of disturbance beneath the tip of the sonic casing between 0.2 to 0.7 m [11]. As the zone of disturbance extends to within the area the SPT blow counts are contributing to the N value, the use of Sonic drilling obtained SPT N values should be used with caution when the values are being used for consistency values or as an input for correlative models developed on other methods of drilling.

In general, the SPT- and CPT-based liquefaction triggering assessment may underestimate the cyclic resistances of soils with high fines content. In high risk or high consequence projects and when there are uncertainties on the cyclic resistances in soil strata and/or additional non-linear coupled numerical models are required, there is value to conducting paired testing and laboratory testing in order to better understand site specific correlations or to evaluate existing correlations for their suitability to the project data. In particular, these correlated values can be used to provide input into further engineering analysis such as numerical model inputs requiring correlating from CPT tip resistance to SPT N for verification. A potential benefit of this approach comes from the continuous nature of the data obtained with a CPT offering the ability to review distributions of the correlated data to better inform parameter selection. However, the use of correlations should be applied with caution and engineering judgement.

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