Evaluation of Shear Wave Velocity and Void Ratio in Mine Tailings using the Field Velocity Resistivity Probe

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ABSTRACT: The seismic cone penetration test (sCPT) is the most common in-situ testing technique utilized for determination of the shear wave velocity in soils. This technique yields results that are adequate in natural soils. However, sCPT has important limitations when used in mine tailing deposits because mine tailings can exhibit significant differences between the intact shear wave velocity and that measured by the sCPT. This paper describes the field velocity resistivity probe (FVRP) which is a recently developed tool that allows for improved accuracy in the determination of in-situ shear wave velocity when compared to sCPT. The paper presents the results of shear wave velocity measurements on two soundings side by side which illustrate the difference between the sCPT and the FVRP in the determination of shear wave velocities in mine tailings deposits.

1 INTRODUCTION

Measurement of the shear wave velocity in soils has become common practice in geotechnical engineering. The determination of the shear wave velocity in soils is important because it is directly related to small-strain mechanical behavior of soil. For example, the shear wave velocity can be converted to small-strain shear modulus using elasticity principles ($G_{max} = \rho V_s^2$). The shear modulus is an important parameter in advanced numerical modeling of soil behavior and engineered structures. Robertson (2016) also indicated that shear wave velocity can potentially identify micro-structure in soils. Shear wave velocity can also be used to identify liquefaction susceptibility in soil and determine the in-situ state parameter (Fear and Robertson, 1995; Schnaid et al., 2020).

In the laboratory, wave propagation and shear wave velocity of undisturbed specimens is measured using bender elements mounted at the platens of a triaxial cell. In the field, the most common in-situ testing technique is the seismic cone penetration test (sCPT). However, for materials that are recently deposited and very soft or loose, such as mine tailings, collection of undisturbed specimens for laboratory testing and determination of the shear wave velocity using the sCPT presents some important limitations, as described below. The field velocity resistivity probe (FVRP) is an in-situ testing tool that uses bender elements to more accurately measure the shear wave velocity of the intact material (Lee et al., 2010). The FVRP may overcome many of the limitations of the sCPT in mine tailings deposits by reducing the impact of soil disturbance around the probe and eliminating the errors due to aggregation. This paper presents a discussion of the limitations and over prediction of the shear wave velocity measured by the sCPT. A comparison of the measured shear wave velocity profiles from SCPT and FVRP soundings performed side-by-side through mine tailings deposit is also presented and discussed.

2 SCPT

The sCPT was introduced in the early 1980s when significant advances were made with the cone penetration test (CPT) and new sensors were experimentally added to the CPT. sCPT is a simple, reliable, and relatively inexpensive tool to determine the seismic wave profile of a soil deposit. The seismic wave velocity measurements are typically made at 1-meter intervals and can be combined with other CPT measurements to obtain a comprehensive soil profile characterization to use in design. Both compression waves (P-waves) and shear waves (S-waves) can be measured with sCPT.

The basic sCPT configuration consists of a wave source, trigger circuit, geophone in the penetrometer, and digital storage oscilloscope in addition to the standard CPT acquisition system. The wave source typically consists of a steel beam set on the ground surface parallel to the geophone axis that is acted upon by a normal force at the time of the test. The sCPT is pushed into the ground and penetration is stopped at the desired depth for measurements. The steel beam is hit by the hammer with a contact trigger, generating a front of waves that travel through the ground; the signal is picked up by the geophone and recorded in the digital storage device. Two hits of the steel beam are performed at each test depth to generate polarized wave traces, facilitating the interpretation of wave arrival times. Modern CPT trucks include built-in seismic beams utilized for shear and compression wave velocity determinations.

Engineers utilize the time of wave arrival and the distance from the shear beam to the geophone to compute the wave velocity. It is assumed that the travel path of the waves from the beam to the geophone is a straight line. Early sCPT versions used dual arrays with two receivers (geophones) separated by a set distance on the rods allowing for determination of the “true time” of wave arrival, defined as the time difference between both locations, as shown by Butcher, et al. (2005). Other sCPT units used a single receiver for determination of the “pseudo-time” of wave arrival, defined as the time difference of two readings at two test depths. However, Robertson, et al. (1986) found that the difference of the “true time” and the “pseudo-time” were very small with an error generally less than 2 percent.

Other automatic seismic sources, such as “auto-seis” (Mayne & McGillivray, 2005), which use a single hammer have been developed. Similarly, the “auto-seis” allows for wave recording at 10-centimeter intervals (Mayne, 2014). However, these devices are not extensively used in practice at the present time.

Measurement of shear wave velocity has evolved from a research technique into routine engineering practice due to the simplicity and repeatability of the measurements. In fact, sCPT is the most used tool for this determination. This is because it allows for different uses as follows: (1) direct measurement of soil stiffness for use in settlement calculation and numerical modelling, (2) estimate of soil parameters correlated to shear wave velocity, (3) evaluation of soil liquefaction susceptibility based on shear wave velocity, (4) determination of soil saturation based on compression wave velocity, and (5) identification of soils with micro-structure. These attributes make the sCPT a very powerful tool in geotechnical engineering. As a result, its use has been extended extensively in the characterization of natural soils.

2.1 *Limitations of sCPT*

In spite of the benefits of the sCPT to characterize soils, it presents some important limitations. Most notably, the measured arrival time and total travel distance of the signal represent the aggregated time and material travelled by the wave from the ground surface to the downhole receiver (geophone). To better illustrate this aspect, Figure 1 shows the geometry associated with the sCPT.

Figure 1 shows the typical arrangement of the sCPT which includes the axis of the sCPT, shear beam, and receiver (geophone). It can be seen in Figure 1 that the shear beam is located at a horizontal distance, X, from the axis of the sCPT. The receiver (geophone) is located in the axis line of the sCPT at depth, D, from the ground surface. Finally, the travel path of the seismic waves from the shear beam to the receiver (geophone) is a straight line, L. Figure 1 includes two positions at depths, D_1 and D_2, and their associated travel paths, L_1 and L_2.

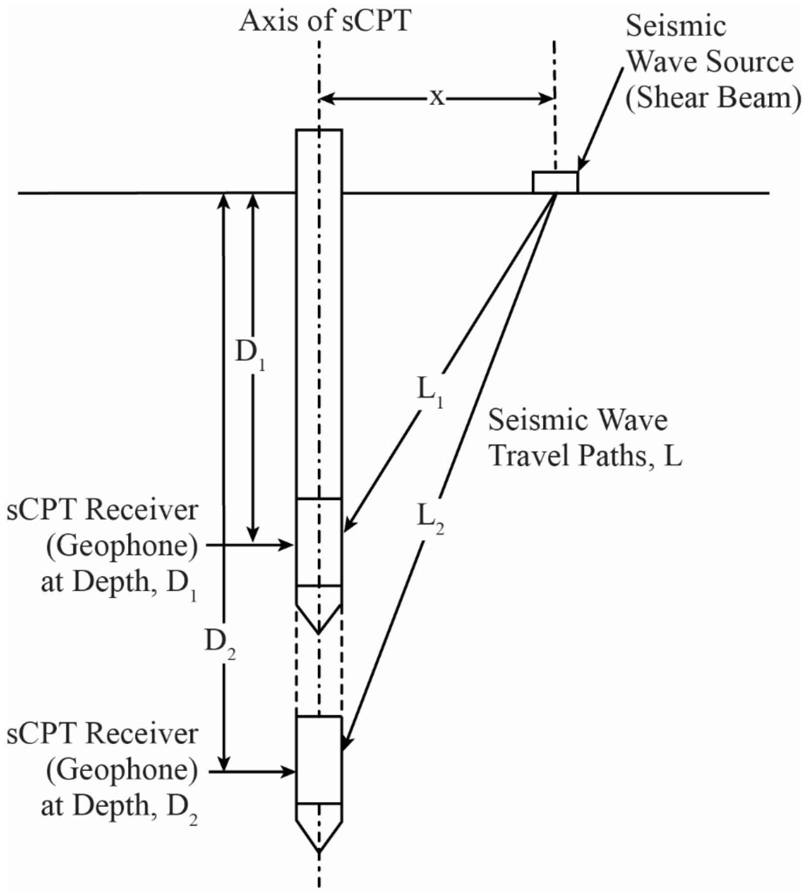

Figure 1. Typical Arrangement for sCPT Measurements (adapted from Butcher, et al., 2005)

In Figure 1, the arrival or travel time of the seismic waves associated with positions 1 and 2 are t_1 and t_2, respectively. The interval velocity in the segment between positions 1 and 2, typically one (1) meter, is computed using Equation (1) as follows:

$$V_s = \frac{(L_2 - L_1)}{(t_2 - t_1)} \tag{1}$$

It is clear from Figure 1 and Equation 1 that a significant limitation of the sCPT is the fact that the measured arrival time and total travel distance of the signal represent the aggregated time and material travelled by the wave from the ground surface to the downhole receiver (geophone). The numerator in Equation 1 represents the difference between two hypotenuses of two right triangles. The denominator represents the incremental arrival time, Δt, between positions 1 and 2. As a result, there is not a direct measurement of the arrival time at the interval distance. Therefore, the wave velocity calculated by Equation 1 represents an aggregate value, which works relatively well in most soils because of their relatively higher seismic velocity . However, in very soft or loose soils, such as mine tailings, this aggregation may not provide an accurate measurement of the actual seismic wave velocity of the in-situ material because with their much lower seismic wave velocities the errors may be more impactful.

3 FVRP

The FVRP is an in-situ tool that uses bender elements to more accurately measure the seismic wave velocity profiles of the intact soil and was initially introduced by Lee, et al. (2008) and Yoon, et al. (2008) with subsequent improvements by the same team of researchers (Lee, et al., 2010; Yoon, et al., 2010). FVRP provides a direct measurement of seismic wave velocities of nearly undisturbed soil at discrete locations without the distortion from aggregation. It generally consists of two tines with bender elements and other sensors connected to a stem and an adapter to drill rods as shown in Figure 2. The distance between the tines is approximately 88 mm, and the distance between the source and receiver bender elements mounted on the inside of the tines is approximately 68 mm. As such, the material between the tines is nearly undisturbed. One set of bender elements is used for measuring the shear wave, and another set of bender elements is used for measuring the compression wave. A triangular fin is welded at the end of the tines to minimize soil abrasion and protect the bender elements during penetration. Additional sensors, such as electrical resistivity and temperature, are installed within the leading edge of the polymer blade at the base of the tines.

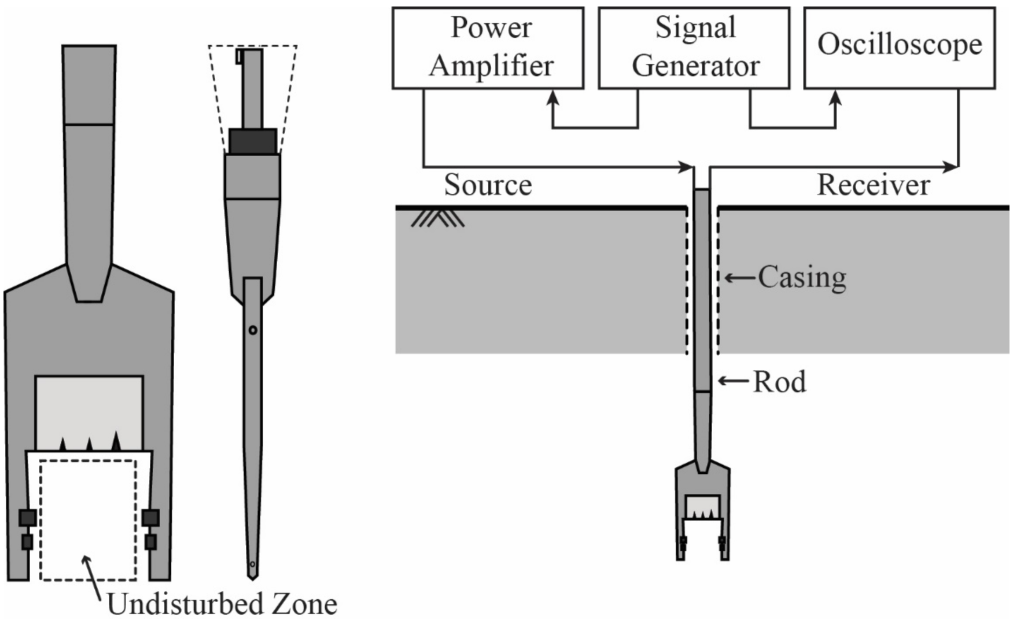

Figure 2. Schematic and Arrangement of FVRP Apparatus (adapted from Jung, et al., 2008)

The source and receiver bender elements are mounted facing each other so that the signal travels through the nearly undisturbed soil. The signals are generated at the surface using a waveform generator with power amplifier and are applied to the source bender element. Subsequently, the signal is read by the receiver bender element, which transmits the signal to an oscilloscope at the surface as shown in Figure 2. The signals generated by the waveform generator are also sent directly to the oscilloscope for comparison of the signal arrival time. The automatically generated signals are stacked to increase the signal-to-noise ratio producing higher quality signals. Because of the configuration of the FVRP and the location of the source and receiver bender elements, the measurements of seismic waves are essentially oriented in the horizontal direction. In addition to the seismic wave velocities, the FVRP is also equipped with electrodes to determine the electrical resistivity of the in-situ material.

In practice, the FVRP is advanced in the borehole to the desired test depth using direct-push methods. At the desired test depth, the signals are generated and the arrival times are measured. By knowing the distance between bender elements and the arrival times, the seismic wave velocities are calculated. Electrical resistivity and temperature measurements are also made at each test depth. Then, the FVRP is advanced to the next desired depth for each subsequent test and the procedure is repeated. For practical purposes, there is no minimum depth interval between subsequent tests, although depth intervals less than 10 cm may become overly time-consuming.

The main benefits of the FVRP are: (1) the measurement of seismic wave velocity is representative of the nearly undisturbed soil, (2) the measurements can be performed as often with depth as desired which can be used to develop a more dense data profile through the soil column, and (3) automatic signal generation reduces manual labor and allows for increased stacking that results in higher quality signals. Further, Jung, et al. (2008) demonstrated in a laboratory chamber that the FVRP provides accurate measurements of nearly undisturbed soil. This validation was performed by setting two instrumented rods with source and receiving bender elements, similar to an in-situ cross-hole seismic test, to measure the seismic wave velocity in the soil column. The FVRP was then inserted between the two instrumented rods to measure the seismic wave velocity profile once again. Comparison of the seismic wave velocity profiles were nearly identical demonstrating that the FVRP causes minimal disturbance and measures seismic waves of intact material. Robertson (2016) highlighted the challenge of using sCPT for seismic wave velocity in the determination of the parameter K_G^* to identify soils with microstructure. This is due to the fact CPT generates nearly continuous profiles of tip resistance, sleeve resistance, and dynamic pore-water pressure with measurement at 10- to 50-mm intervals, whereas the sCPT provides seismic wave velocity profiles with 1-m intervals, as typically implemented.

4 IMPORTANCE IN MINE TAILINGS DEPOSITS

Obtaining accurate measurements of seismic wave velocities is very important in mine tailings deposits because of the following unique characteristics of these materials: (1) mine tailings are very soft or loose materials due to their recent deposition history and high water content during deposition, and thus low shear wave velocity as compared to natural soils, (2) mine tailings are frequently layered with combinations of materials having different gradations which can be missed by the sCPT due to its aggregated seismic wave values at relatively large intervals, and (3) aggregation of the seismic wave velocities by the sCPT tend to skew the actual seismic wave velocity of the undisturbed material. As a result, the FVRP has many advantages in tailings characterization with seismic wave velocities when compared to sCPT.

5 COMPARISON OF SEISMIC WAVE VELOCITIES FROM SCPT AND FVRP

The authors were involved in a field campaign that utilized the FVRP in a tailings basin. As part of this field campaign, two soundings (sCPT and FVRP) were performed side-by-side with the purpose of evaluating the accuracy of the seismic wave velocity measurements from both systems. Figure 3 shows the results of the sCPT and FVRP. The upper 9 m were pre-drilled due to the presence of an overlying dense tailings layer. Layered tailings are present in the depth interval between 9 and 17.5 m. In the depth interval between 17.5 and 24.3 m, the deposit consists of uniform tailings. Native soils exist below a depth of 24.3 m. The profile described above is interpreted from the sCPT sounding profiles of tip and sleeve resistance in Figure 3.

The shear wave velocity from the sCPT is plotted in Figure 3 as segments in approximately 1-m intervals, whereas the shear wave velocity from the FVRP is plotted as markers in approximately 0.3-m intervals. It can be seen from Figure 3 that the shear wave velocity from the sCPT is usually larger than the shear wave velocity from the FVRP. In many instances the difference is 50 percent or more. This difference is attributed to the fact that the FVRP makes a direct measurement of the nearly undisturbed material at discrete depths, whereas the sCPT makes an aggregate measurement as previously described. While the difference in shear wave velocity by the sCPT and FVRP may not be relevant or significantly important in natural soils, this significant difference is very important and relevant in mine tailings due to their soft or loose nature and significant impact on interpreted properties.

Figure 3 shows how the FVRP measurements better capture the layered nature of the mine tailings deposit, as compared to the sCPT which obscures the layering due to aggregation. The FVRP also provides a profile of the compression wave velocity, electrical resistivity, and temperature as shown in Figure 3. The compression wave velocity is associated with the water compression and can be used to identify the saturated nature of the deposit. The electrical resistivity can be used in the estimation of void ratio.

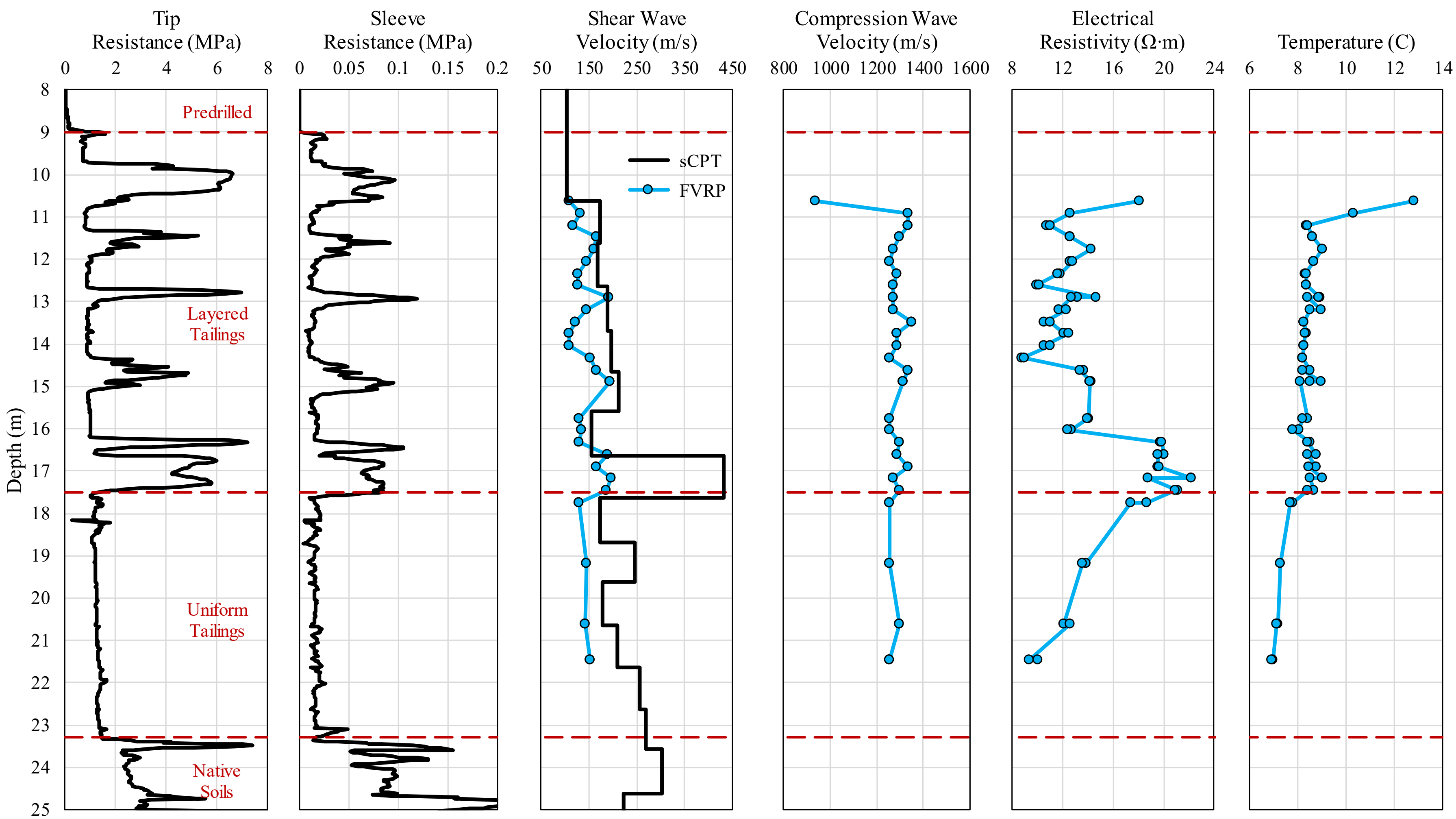

Figure 3. Comparison of Data from Seismic Cone Penetration Testing (sCPT) and Field Velocity Resistivity Probe (FVRP)

The importance of accurate and closely spaced shear wave velocity, in conjunction with electrical resistivity measurements, can be seen when performing calculations to estimate the void ratio profile of the tailings deposit. The in-situ void ratio is an important element in evaluating the liquefaction susceptibility and the post-liquefaction shear strength of the tailings deposit when assessing within the critical state soil mechanics (CSSM) framework. Numerous correlations are available to estimate the in-situ void ratio or state parameter (ψ) based on in-situ moisture content, standard penetration test (SPT), and CPT among others. The benefit of the FVRP is that the void ratio can be measured in-situ with greater accuracy and at relatively close intervals throughout the tailings profile. Figure 4 shows the application of the FVRP to estimate the in-situ void ratio and state parameter (ψ) for use in comparison of the laboratory measured critical state line (CSL) for three representative tailings types encountered at the CPT and FVRP sounding location shown in Figure 3. Further development of this approach is in progress and will be presented in subsequent publications.

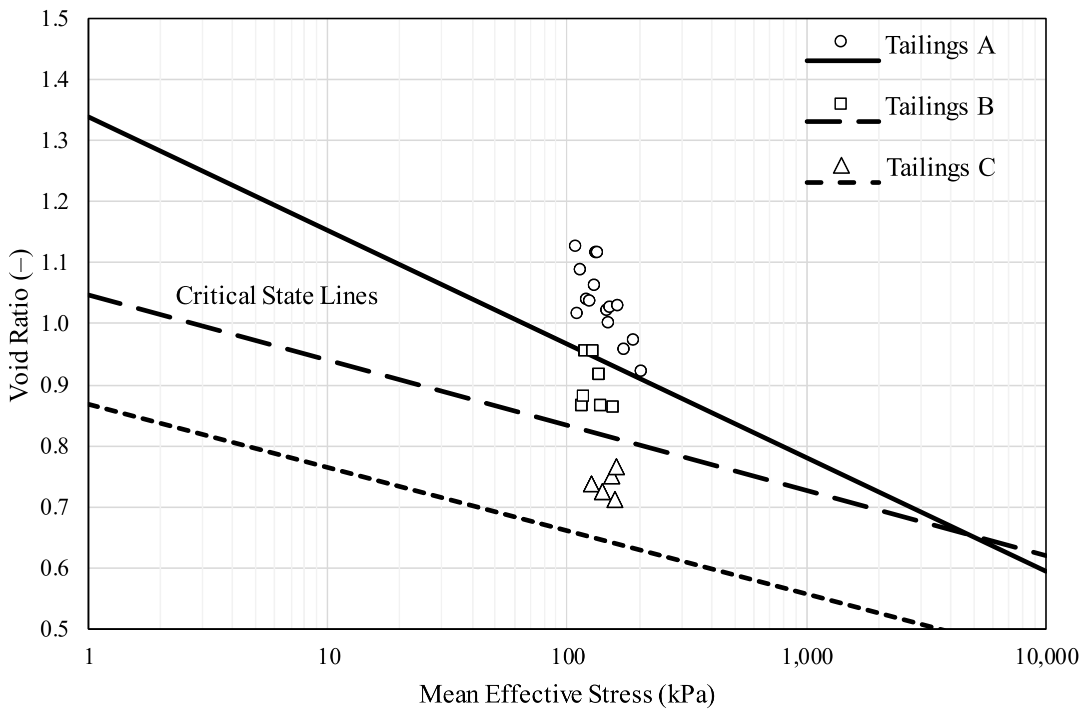

Figure 4. Application of FVRP to Critical State Soil Mechanics Approach to Liquefaction Assessment

6 SUMMARY AND CONCLUSIONS

The most common in-situ testing technique in geotechnical engineering to determine the seismic wave velocities is the sCPT. While this technique generally provides acceptable results in natural soils, it may have some limitations in its application to mine tailing deposits. This is because mine tailings are high water content materials that were recently deposited and thus very soft or loose. As a result, the aggregation of the seismic wave velocities from the sCPT can fail to characterize the low seismic wave velocity nature of the in-situ material and its layering. Therefore, the FVRP may provide an improvement in the accuracy and definition of seismic wave velocity measurements.

Data from a mine tailings deposit where side-by-side soundings of sCPT and FVRP were performed are presented. It is shown that the shear wave velocity from the FVRP is consistently lower than the aggregated value obtained from the sCPT. Additionally, the aggregation produced by the sCPT does not allow for identification of the variations in seismic wave velocity profile of the in-situ material generated by the layered nature of the tailings deposit, as compared to the FVRP.

These important differences and limitations of the sCPT suggest that the FVRP is a better specialty tool to determine the shear wave velocity in mine tailings deposits. The difference in shear wave velocity from the sCPT and FVRP may be up to 50 percent or more. This significant difference is very important when using the shear wave velocity results to compute geotechnical parameters. As a result, the authors support the further use of the FVRP over the sCPT in mine tailings deposits because FVRP provides a more accurate direct measurement of the in-situ shear wave velocity of the tailings material. FVRP also captures the layered nature of mine tailings deposits better than the sCPT, and thus can be used for more accurate determination of geotechnical parameters. In this regard, the authors are currently assessing the use of the FVRP to estimate the in-situ void ratio with the purpose of determining the state parameter (ψ) for use in liquefaction assessment and slope stability analysis within the CSSM framework. This aspect of the seismic wave interpretation from FVRP will be the subject of a separate future publication.

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