The use of seismic trace characterization to guide the analysis of DST results to obtain more accurate soil parameters

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ABSTRACT:

Downhole Seismic Testing (DST) is a very popular applied seismology site characterizing tool within geotechnical engineering. A challenging aspect of DST is to characterize the acquired seismic data sets to determine the analysis method that will result in the most accurate interval velocity values. BCE has invested considerable resources into developing Seismic Trace Characterization (STC), which uses various independent parameters of the acquired data at a particular depth. Initial work in this area resulted in the selection of the linearity estimate from the polarization analysis, the cross correlation coefficient of the full waveforms at the particular depth and the preceding depth and a uniquely developed parameter referred to as the signal shape parameter for this characterization. Subsequent analysis in STC identified two other parameters: the Signal-Noise-Ratio (SNR) and the Peak Symmetry Differential (PSD). The paper briefly describes these parameters and then outlines how they can guide the data analysis to derive more accurate results, especially near surface, which is especially important to assess the liquefaction potential in areas prone to earthquakes, such as California. The process will be illustrated with actual data from another area prone to earthquakes, namely New Zealand.

1. INTRODUCTION

The near surface characterization of low strain in-situ shear wave velocities (V_S) has proven critical for liquefaction assessment. Liquefaction is a phenomenon in which dynamic loading of saturated soil results in the material properties to change suddenly from a solid state to a liquefied state. V_S is an important parameter for evaluating liquefaction potential due to fact that it is influenced by many of the variables that influence liquefaction (e.g., void ratio, soil density, confining stress, stress history, and geologic age (Andrus et al., 1997)). Aki and Richards (2002) also outline that the amplitude of ground motion should depend on the density and shear wave velocity of near surface soils and rocks according to the theory of wave propagation. Since the change in density with the increase in depth is relative minor compared to that of the shear wave velocity, the latter is a very useful parameter to represent site conditions (Stewart et al., 1997). Bray (2014) and his colleagues carried out an extensive geotechnical analysis of the catastrophic liquefaction that occurred in Christchurch, New Zealand in 2010 and 2011 and found that near surface rather than deep liquefaction resulted in extensive foundation damage.

Downhole Seismic Testing (DST) has proven to be a very powerful technique for measuring in-situ near surface V_S values (ASTM, 2017) and thus a valuable tool for liquefaction assessment. The main goal in DST is to obtain arrival times as the source wave travels through the soil profile of interest, and from these arrival times the velocities are then calculated by taking into account proper source wave raypaths (Baziw, 2002; Baziw and Verbeek, 2012 and 2016). In a DST configuration a seismic source is used to generate a seismic wave train at the ground surface. One or more downhole seismic receivers are used to record the seismic wave train at predefined depth increments. The downhole receiver(s) may be positioned at selected test depths in a borehole or advanced as part of an instrumentation package as in the case of Seismic Cone Penetration Testing (SCPT). When triggered by the seismic source a data recording system records the response of the downhole receiver(s).

Near surface DST seismic data set can be particularly challenging to process compared to relatively deeper acquired traces as they are more effected by near surface measurement noise, "rod noise", near-field source waves, and reflections. Especially for those traces it is critical to have the ability to assess the quality of the DST seismic trace and to get guidance how to best analyze these traces.

BCE has invested considerable resources (Baziw and Verbeek, 2016a, 2016b, and 2017) into the characterization of acquired DST data sets and the guidance for data analysis that can be derived from this characterization. This paper summarizes that work and also describes proposed signal processing and post data analysis techniques for data sets with poor trace metrics.

2. THE STC PARAMETERS

Seismic Trace Chaacterization (STC) refers to quantifying the quality of the acquired DST seismic traces based upon independent seismic trace characteristics. This facilitates post data processing and provides a highly valuable quantification of the quality of the DST data set under analysis and subsequent interval velocity estimates. The analysis of numerous seismic data sets, many of which were recorded with triaxial seismic sensors, has resulted in a better understanding of how a seismic trace can be characterized. Typically, investigators have utilized the Cross-Correlation Coefficient (CCC), which gives an indication of the similarity between traces used in obtaining relative arrival times (Baziw, 1993), but this parameter has been proven to be an unreliable indicator due to the fact that measurement noise (random and systematic) can also be correlated and result in high CCC values. In order to overcome these limitations other parameters were added and over the years the number of parameters considered by the authors has increased to five. The five STC parameters are briefly outlined below due to length constraints on this paper, but the parameters are discussed in more detail in papers included in the References.

STC Trace Metric 1: Linearity (LIN) Estimates from the Polarization Analysis

Polarization Analysis (PA) refers to analyzing the source wave responses on multi-component seismic sensor packages (Kanasewich, 1981; Baziw and Verbeek, 2016b). A very important component of PA is obtaining linearity or rectilinearity estimates. Linearity values are obtained by diagonalizing the covariance matrix of the X(t), Y(t) and Z(t) recordings over the seismic event of interest and subsequently calculating the ratio of the principal axis of the diagonalized matrix. A measure of the rectilinearity is referred to as linearity and it is calculated as follows:

$$F(\lambda_1, \lambda_2) = 1 - \left({}^{\lambda_2}/_{\lambda_1} \right) \quad (1)$$

where λ_1 and λ_2 denote the largest eigenvalue and next largest eigenvalue of the diagonalized covariance matrix, respectively. The linearity approaches unity when the rectilinearity is high

(λ_1 » λ_2) and approaches zero when the rectilinearity is low ($\lambda_1 \approx \lambda_2$). Since linearity values nearing 1.0 identify seismic recordings that have highly correlated responses and strong directionality, the quality of the data set with a high linearity value can be considered good. Lower linearity values on the other hand indicate a lower quality trace (whether due to poor source generation, near-field waves, ambient noise that is not easily filtered out, source wave reflections, or differential probe coupling). Figure 1 illustrates an example X(t) and Y(t) source wave responses which have high linearity. In this case the peaks and troughs on the X(t) and Y(t) axis are aligned (Fig. 1(A)). This is also reflected in the hodogram (Fig. 1(B)) where the X(t) and Y(t) responses are plotted against one another and a least squares best fit straight line is applied. In Fig. 1(B) the plotted points have low deviation from the best fit least squares straight line.

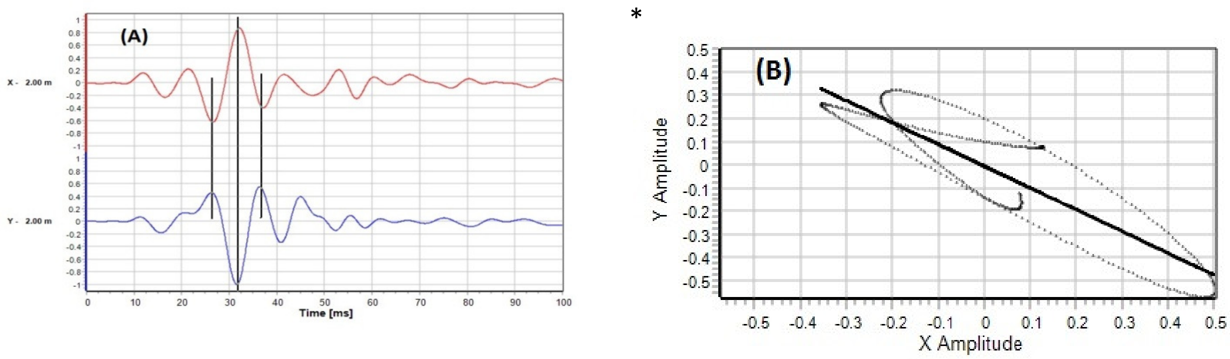

Figure 1: (A) DST X and Y axis seismic responses illustrating alignment of peaks and troughs. (B) Corresponding hodogram (light grey dots) and linear least squares best fit (dark black line) with a calculated linearity of 0.89

STC Trace Metric 2: Cross-Correlation Coefficient (CCC)

The cross-correlation between two time or distance offset seismograms is given as

$$\varphi_{xy}(\tau) = \sum_k X_k \, Y_{k+\tau} \tag{2}$$

Normalizing the cross-correlation of the zero mean seismic signals by their standard deviations gives the cross-correlation coefficient:

$$\rho_{xy}(\tau) = \sum_k X_k \, Y_{k+\tau} \Big/ \sqrt{\sum_k X_k^2} \, \sqrt{\sum_k Y_K^2} \tag{3}$$

The CCC between the two DST seismic traces gives an indication of the similarity between the two waves being correlated. CCC values approaching 1.0 indicate that the two waveforms are highly correlated. CCC values approaching 0 indicate very poor correlation (Baziw and Verbeek, 2016b).

STC Trace Metric 3: Signal Shape Parameter (SSP)

The SSP trace metric quantifies the deviation of the shape of the frequency spectrum from an ideal bell shape. Based upon frequency spectrum analysis of large sets of DST data it was determined that the shapes of high quality DST data sets had frequency spectrums closely resembling Gaussian bell-shape pdf curves (Baziw and Verbeek, 2016a), which can be described as follows:

$$p(f|\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(f-\mu)^2}{2\sigma^2}} \tag{4}$$

where μ denotes the mean or expectation of the distribution and σ denotes the standard deviation with variance σ^2. Based on this observation a STC parameter was developed which quantified the deviation of the shape of the frequency spectrum of the seismic trace under analysis from a bell-shaped pdf curve.

*STC Trace Metric **4**: Peak Symmetry Differential (PSD)*

The PSD trace metric facilitates the identification of traces whose peak source wave responses have been significantly skewed due to measurement noise or source wave reflection interference. Figure 2 illustrates this phenomenon. In Fig. 2(A) we have an ideal source wave recording where no interference is present. In this case the time difference between the two zero crossings bounding the peak response (A1) are identical (Δt1 = Δt2). In Fig. 2(B) we have a source wave recording with interference, resulting in skewing or time shifting of the peak source wave response. The "peak symmetry" error assessment is also carried out on the adjacent peaks and/or troughs if the amplitude exceeds 70 % of that for the peak response. Obviously traces with a lower PSD value are of a lesser quality and require more attention during analysis.

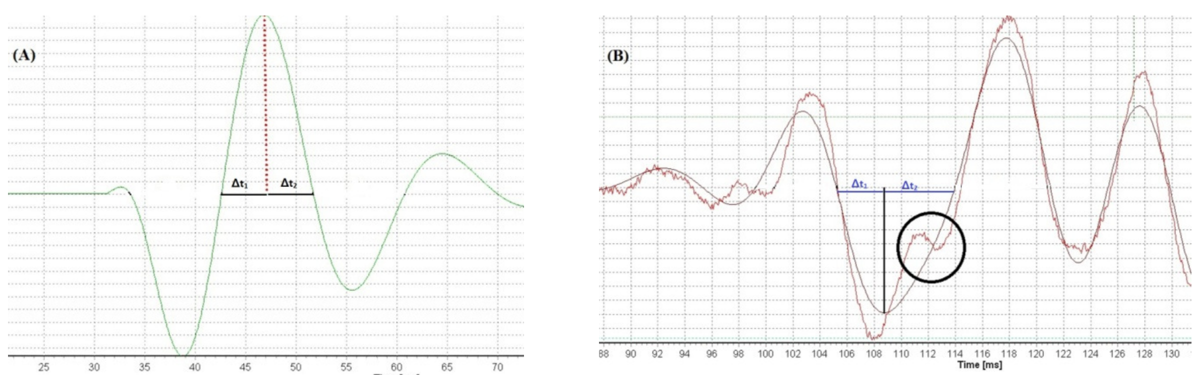

Figure 2. Source wave peak distortions due to measurement noise or source wave reflection interference. (A) Ideal source wave recording where no interference is present. (B) Source wave with interference resulting in skewing or time shifting of the peak source wave response. The black line is the unfiltered trace while the red line is the filtered trace where a low pass filter of 200 Hz was applied.

STC Trace Metric 5: Signal to Noise Ratio (SNR)

The SNR trace metric uses as input the as-recorded seismic trace and compares it with the filtered trace to quantify what portion of the spectral content of the recorded seismogram resides within the desired source frequency spectrum. While this parameter provides mainly insight in the quality of the data acquisition (such as gain settings, noise levels and testing environment) and does not really provide guidance for data analysis, it is nevertheless an important parameter. When during testing to establish SH interval velocities testing is performed from two sides, the SNR metric is very beneficial in selecting the outcome when there is a large spread between the two results.

It should be noted that it is possible for source wave distortions (such as near-field effects, reflections, refractions, and "dirty sources") to have spectral content which resides within the source wave frequency spectrum. Consequently the parameter value may imply a better quality trace than it really is.

3.0 RECOMMENDED DATA ANALYSIS and SIGNAL PROCESSING BASED on STC

All STC trace metrics vary from 0 to 1 where it is desired that they approach the optimal 1.0 value. Low LIN values are typically handled separately from SSP, CCC and PSD values. This is due to the fact that the LIN values directs the investigator on whether the full waveforms should be utilized for analysis or a preferential axis response, while the SSP, CCC and PSD trace metrics give indications of the quality of the seismic traces under analysis. Different seismic signal processing techniques are then applied based upon the SSP, CCC and PSD values.

3.1 Post Analysis and Signal Processing: Linearity Values

LIN estimates are derived from triaxial or biaxial seismic sensor configurations. For data analyses to obtain horizontally polarized shear wave (V_{SH}) velocity values the X- and Y-axis responses are of interest. LIN values for these responses approaching 1.0 are highly desirable and indicate that there is a preferred directionality of the source wave responses, and therefore the X- and Y-axis responses can be rotated on to the full wave form axis, which increases the signal-to-noise ratio. Generally, LIN values 0.8 or better indicate that the full waveforms can be utilized without any cause of concern, while lower values require corrective action as illustrated in the four test cases below.

3.1.1 Test Case LIN 1 – overall linearity values ≥ 0.8 with a few outliers due to poorly correlated source wave responses.

DST Data sets with these LIN values are typically of very good quality and the full wave forms can be used for data analysis. Generally, there are either dominant responses on the X axis and/or Y axis or highly correlated responses on the X and Y axis, but a few lower LIN values may need to be addressed. Figure 3 illustrates filtered (200Hz low pass) Vertical Seismic Profile (VSP). The filtered VSP illustrates X- and Y-axis responses with the dominant source wave responses on the Y axis. The corresponding LIN values are given in Table 1 and for most depths they exceed 0.8, in which case the full wave forms are utilized. However, lower LIN values occur at depths 1m, 2m and 9m.

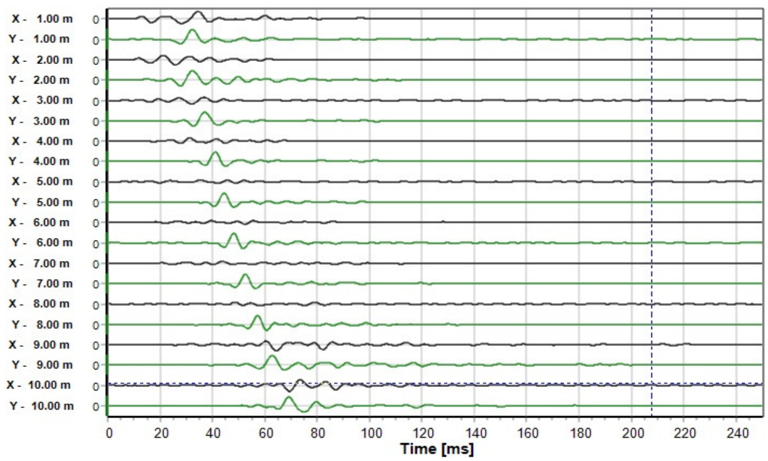

Figure 3. Filtered (200 Hz low pass) VSP [LIN 1]

Table 1. Linearity Values for [LIN 1]

Depth [m]	Linearity [0-1]
1	0.52
2	0.55
3	0.83
4	0.80
5	0.86
6	0.85
7	0.82
8	0.86
9	0.58
10	0.82

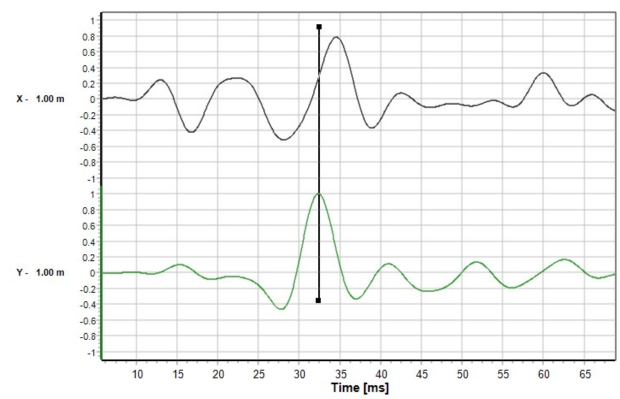

Figure 4. Filtered recorded traces at 1 m [LIN 1]

To overcome this the first step is to identify which axis shows the dominant response. If this is consistent with the full wave forms then the response on this axis can be used in the analysis. For example, the filtered VSP in Figure 3 clearly showed that the dominant responses reside on the Y axis. The filtered traces recorded at 1m are shown in Figure 4 and it is clear that the responses are not correlated (resulting in the low linearity value of 0.52 as shown in Table 1). It is also clear that there is a high quality Y-axis response recorded at this depth, which is in line with the dominant responses at the other depths. Therefore at 1 m the Y-axis response is utilized rather than the full wave form. This is also the case for the traces recorded at 2m and 9m which had associated low linearity values of 0.55 and 0.58, respectively.

3.1.2 Test Case LIN 2 – overall linearity values ≥ 0.8 with a few outliers due to low SNR

Data sets with these LIN values are typically of very good quality and the full wave forms can be used for post analysis. Generally, there are either dominant responses on the X axis and/or Y axis or highly correlated responses on the X and Y axis, but a few lower LIN values may need to be addressed. Figure 5 illustrates filtered (200Hz low pass) Vertical Seismic Profile (VSP) for test case LIN2. The filtered VSP in Figure 5 illustrates X and Y axis responses where there is no single axis that contains the dominant response at all depths. The corresponding and widely varying LIN values are given in Table 2.

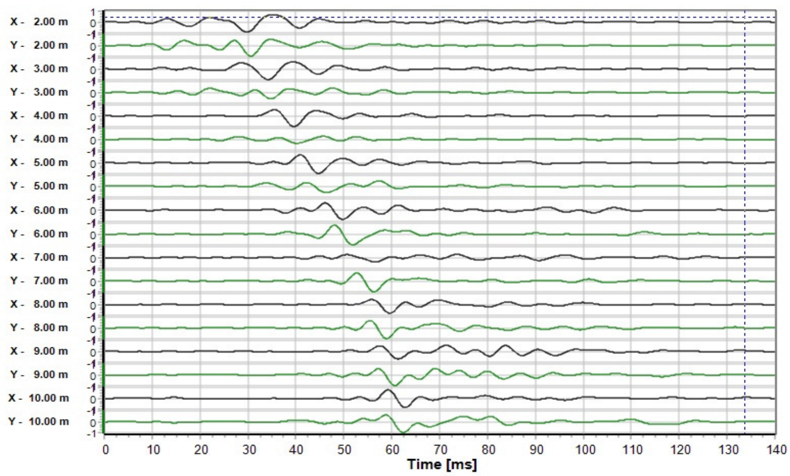

Figure 5. Filtered (200 Hz low pass) VSP [LIN 2]

Table 2. Linearity Values for [LIN2]

Depth [m]	Linearity [0-1]
2	0.58
3	0.70
4	0.84
5	0.62
6	0.30
7	0.80
8	0.81
9	0.48
10	0.81

Figure 6 illustrates the X- and Y-axis responses recorded at 10m, which demonstrates that the high linearity is due to correlated X and Y axis responses and not due to dominant responses on either the X or Y axis. This in turn means that the X and Y axis responses can be utilized in post analysis where poor linearity values occur due to noise responses and not poorly correlated source wave responses. Figure 7 illustrates the filtered X- and Y-axis responses at 2 m, where again the peaks and troughs of the source wave responses align, but the interference on the X axis (highlighted by the red circle) introduces such distortion on the X axis so that the LIN value is significantly reduced. For this case we can utilize the higher quality Y-axis response along with the full wave forms for other depths.

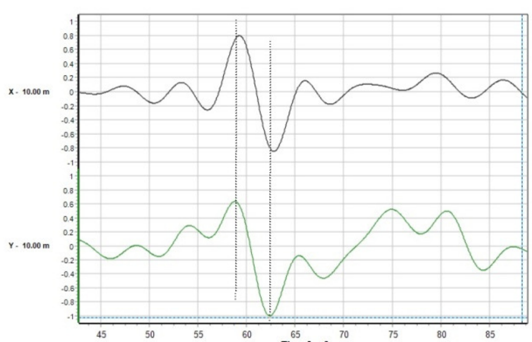

Figure 6. Recorded traces at 10 m [LIN 2]

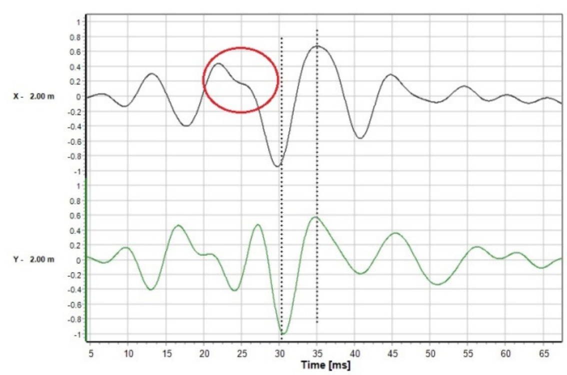

Figure 7. Recorded traces at 2 m [LIN 2]

3.1.3 Test Case LIN 3 – Overall low linearity values with poorly correlated X and Y axis responses, but with a dominant response at all depths on the same axis

For data sets with low LIN values we cannot utilize both X and Y axis responses in post analysis. The investigator must then select either the X or Y axis responses for data analysis and subsequently determine individual axis trace metrics values. Figure 8 illustrates filtered (200Hz low pass) Vertical Seismic Profile (VSP) for test case LIN3, where the Y-axis responses are clearly dominant and of higher quality. The corresponding LIN values are given in Table 3, suggesting very poorly correlated X- and Y-axis responses. In cases like this the investigator proceeds with the analysis using the higher quality responses, which in this case are obviously the Y axis responses.

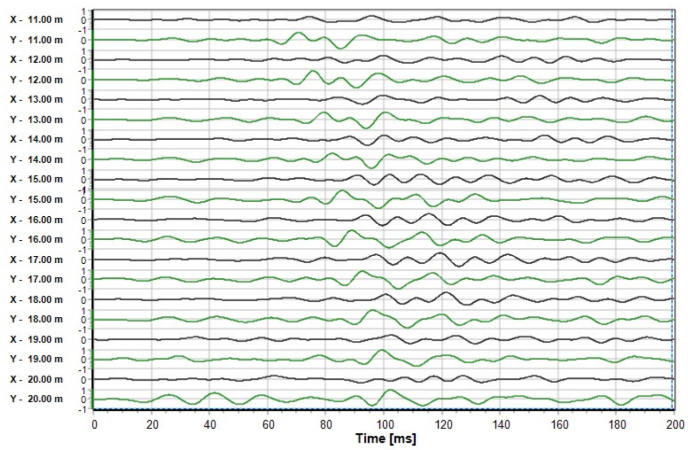

Figure 8. Filtered (200 Hz low pass) VSP [LIN 3]

Table 3. Linearity Values for [LIN3]

Depth [m]	Linearity [0-1]
11	0.76
12	0.80
13	0.72
14	0.69
15	0.65
16	0.61
17	0.57
18	0.67
19	0.75
20	0.67

3.1.4 Test Case LIN 4 – Overall low linearity values with poorly correlated X and Y axis responses and no dominant response on the same axis for all depths.

As mentioned before, for data sets with low LIN values the post-analysis cannot utilize X and Y axis responses randomly: the investigator must select either the X or the Y axis responses. But sometimes this is impossible and the X-axis responses have to be used for certain depth intervals and the Y-axis responses for others. In that case it is important that there is overlap when transitioning from X axis to Y axis responses and vice versa. For example, assume the investigator is going to use X axis responses for depths 1m to 6m and Y axis responses from 6m to 15m. In this case interval arrival times are obtained for traces between 1m and 6m utilizing the X-axis responses and a reference time for one of the depths between 1m to 6m. Next the Y axis responses for traces between 6m to 15m are utilized to obtain interval arrival times with the X axis arrival time for 6m as the reference time. The arrival time are then feed into an algorithm which takes into account raypath refraction when estimating interval velocities (Baziw, 2002; Baziw and Verbeek, 2012 and 2014).

3.2 Post Analysis and Signal Processing: CCC, SSP, and PSD Values

While the LIN value helps with the selection of the traces to be analyzed, the SSP, CCC and PSD trace metrics give indications of the quality of the seismic traces under analysis based upon the form and shape of the time series and corresponding spectral content. Several different combinations (high vs low) of SSP, PSD and CCC values can exist due to the fact that they address different characteristics of the acquired seismic trace. Based on the values of these parameters the most appropriate processing technique (batch signal decay, seismic feature decay and aggressive frequency filtering) is then selected as illustrated in the various test cases below, which assume threshold values for SSP, PSD and CCC of 0.6, 0.8 and 0.3, respectively.

3.2.1 Test Case SSP PSD CCC 1 – Good CCC and PSD values, but poor SSP values

Data sets with good CCC and PSD values but poor SSP values occur whenever there is source wave "ringing" as illustrated in the filtered (200 Hz low pass filter) VSP in Figure 9. Table 4 outlines the corresponding SSP, CCC, and PSD trace metric.

Table 4. SSP, CCC and PSD Values for [SSP PSD CCC 1]

Depth [m]	SSP [0-1]	CCC [0-1]	PSD [0-1]
20	0.547	0.9216	0.96
21	0.525	0.8266	0.48
22	0.379	0.8024	0.87
23	0.483	0.9151	0.65
24	0.556	0.9533	0.71
25	0.491	0.9671	0.79
26	0.51	0.9587	0.73
27	0.391	0.9379	0.96
28	0.428	0.9144	0.84
29	0.544	0.8841	0.61
30	0.363	0.8569	0.94

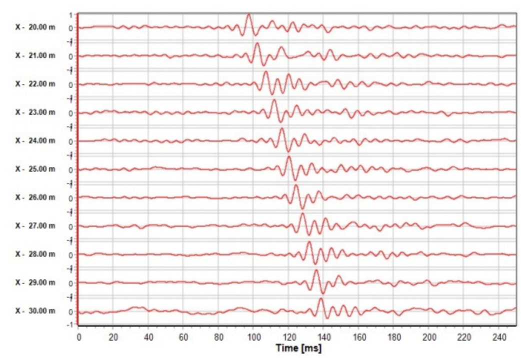

Figure 9. Filtered VSP [SSP PSD CCC 1]

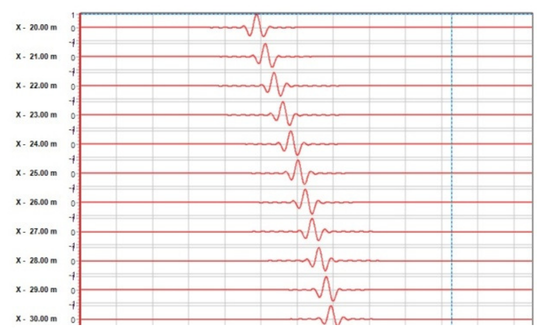

Figure 10. Filtered VSP after batch signal decay [SSP PSD CCC 1]

Clearly only the SSP values are cause of concern and this is readily addressed through batch signal decay (BSD), which applies a time window around the peak responses moving forward and backward in time by two crossovers. The implementation of BSD on this data set is shown in Figure 10.

3.2.2 Test Case SSP PSD CCC 2 – Good CCC values, but poor PSD and SSP values

Data sets with very low PSD values generally are affected by extensive source peak skewing. This is illustrated in the filtered (200Hz low pass) VSP in Figure 11, while the trace metrics values of SSP, CCC and PSD are given in Table 5 with low PSD values between 10m and 13 m and also between 17 m and 20 m. The black circles outline in Fig. 11 outline the extensive peak skewing. To address the low PSD values a consistent portion of the seismic source wave signature where there is minimal to no skewing is isolated throughout the profile (so-called Signal Feature Decay (SFD)). The seismic traces recorded between 12 m and 14 m shown in Fig. 12 clearly show that there is minimal first trough distortion, and therefore SDF is applied on this data set to isolate the first troughs. The results are illustrated in Figure 13.

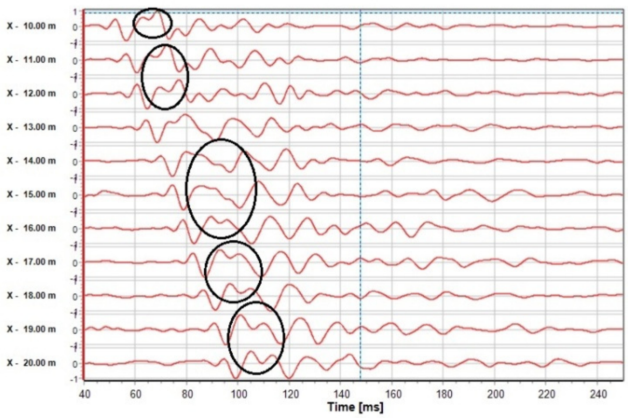

Figure 11. Filtered VSP with peak skewing areas highlighted [SSP PSD CCC 2]

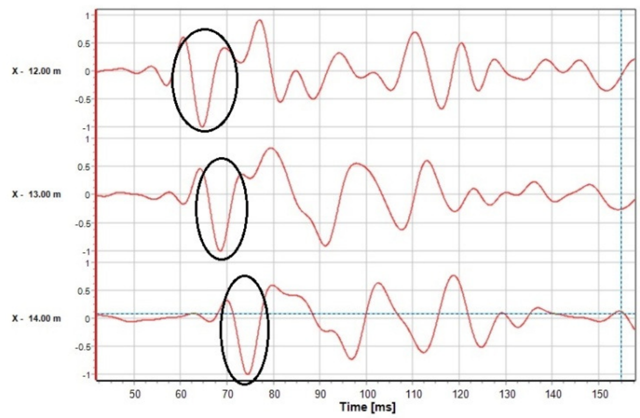

Figure 12. DST seismic traces between 12 m and 14 m [SSP PSD CCC 2] illustrating first trough responses.

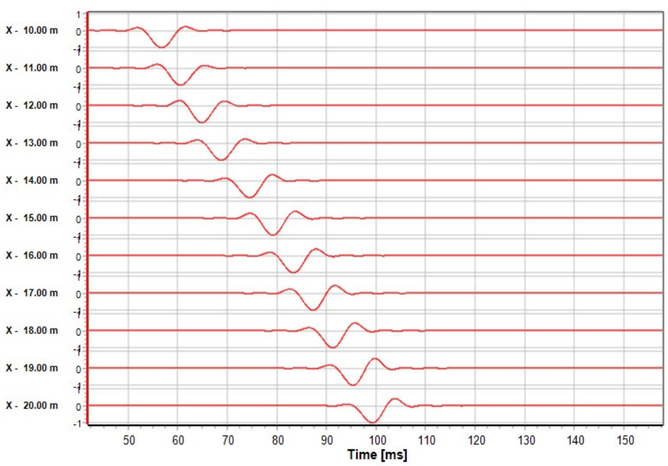

Figure 13. Filtered VSP after signal feature decay [SSP PSD CCC 2]

Table 5. SSP, CCC and PSD Values for [SSP PSD CCC 2]

Depth [m]	SSP [0-1]	CCC [0-1]	PSD [0-1]
10	0.49	0.9603	0.01
11	0.45	0.9239	0.01
12	0.39	0.9323	0.01
13	0.55	0.9144	0.01
14	0.47	0.8582	0.39
15	0.58	0.9283	0.96
16	0.53	0.9553	0.84
17	0.52	0.952	0.01
18	0.59	0.9884	0.01
19	0.56	0.9464	0.01
20	0.54	0.9814	0.01

3.2.3 Test Case SSP PSD CCC 3 – Good SSP and PSD values, but poor CCC values

If only the CCC values are low, SFD is again the suggested remedial action. In Fig. 14 a filtered (200Hz low pass) VSP is shown with the corresponding SSP, CCC and PSD trace metrics outlined in Table 6, which shows low CCC values between 3 m and 5 m with very good PSD values and SSP values very close to the desired 0.6 threshold except at a depth of 5 m. The dashed line in Fig. 14 clearly identifies the first trough responses in the entire VSP and Figure 15 then shows the VSP after isolating the first trough responses by SDF.

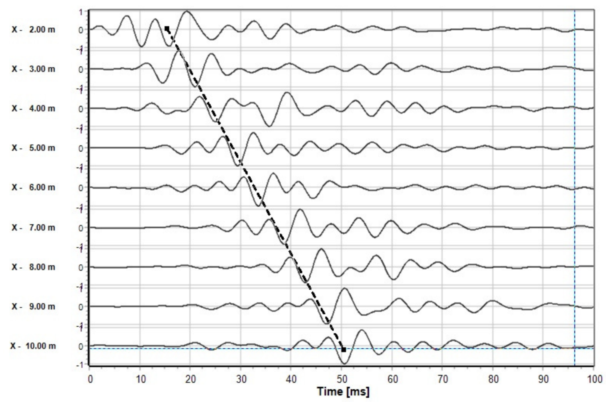

Figure 14. Filtered VSP with the first trough trend line [SSP PSD CCC 3].

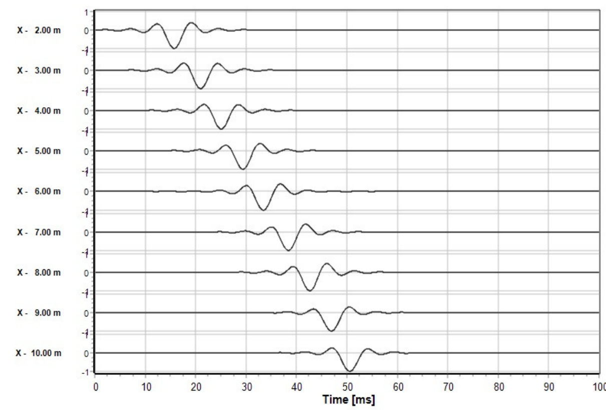

Figure 15. Filtered VSP after SDF applied [SSP PSD CCC 3]

Table 6. SSP, CCC and PSD Values for [SSP PSD CCC 3]

Depth [m]	SSP [0-1]	CCC [0-1]	PSD [0-1]
2	0.60	N/A	0.54
3	0.64	0.6497	0.69
4	0.59	0.5229	0.73
5	0.48	0.6394	0.75
6	0.46	0.8639	0.78
8	0.50	0.6862	0.85
9	0.59	0.8853	0.87
10	0.59	0.8558	0.83

Table 7. SSP, CCC and PSD Values for SSP PSD CCC 4

Depth [m]	SSP [0-1]	CCC [0-1]	PSD [0-1]
1	0.563	N/A	0.67
2	0.462	0.7526	0.07
3	0.45	0.6931	0.01
4	0.517	0.7264	0.37
5	0.75	0.833	0.99
6	0.6	0.9513	0.09

3.2.4 Test Case SSP PSD CCC 4 – Poor SSP, PSD and CCC values

In certain cases the entire VSP shows evidence of interference, resulting in poor SSP, PSD and CCC values. To address this type of data set an aggressive 120Hz low pass filter is applied so that the source wave interference is "smoothed". The "smoothed" responses then have SFD applied. This is illustrated on the filtered (200Hz low pass) VSP shown in Fig. 16, where there is evidence of significant source wave distortions throughout the source wave responses. Table 7 outlines the corresponding SSP, CCC and PSD trace metrics, while Figure 17 shows the data set after applying an aggressive 120Hz low pass filter and SDF on the "smoothed" second peak responses.

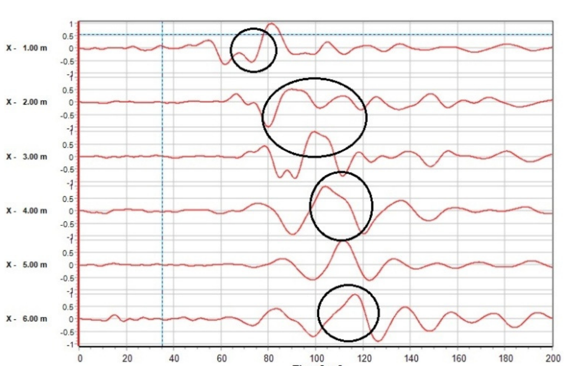

Figure 16. Filtered VSP with the evidence of interference at all depths [SSP PSD CCC 4]

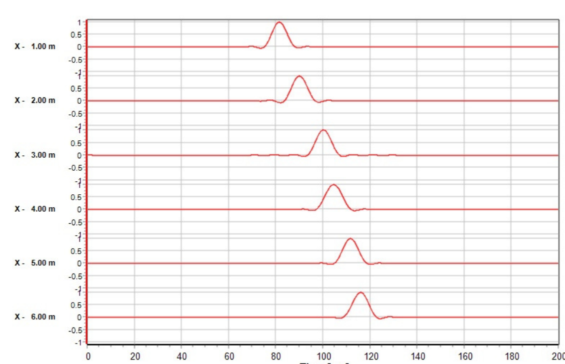

Figure 17. Aggressively filtered VSP after SDF [SSP PSD CCC 4]

3.3 Post Analysis and Signal Processing: SNR Values

When based on the LIN values the traces to be analyzed are selected, and based on the PSD, SSP and CCC values the most appropriate processing technique is determined, the SNR value can provide inside when there is a substantial difference between the outcome for the signals from the right side and the left side.

In Table 8 below the calculated interval velocities are shown for the right side and the left side, which reflect a larger spread (defined as ½ x (LS Velocity – RS)/Avg. Velocity) than desired (the objective is to have the spread within 10 %). Given the SNR values it can be concluded that the results for the right side are most likely more reliable, given the higher quality seismic traces at that side.

Table 8. RS and LS SNR and Interval Velocity Values

Depth [m]	SNR RS [0-1]	SNR LS [0-1]	RS Velocity [m/s]	RS Velocity [m/s]	Percent Difference (%)
2.000	0.95	0.74	N/A	N/A	
2.500	0.89	0.57	290	230	11.5
3.000	0.87	0.64	265	200	14

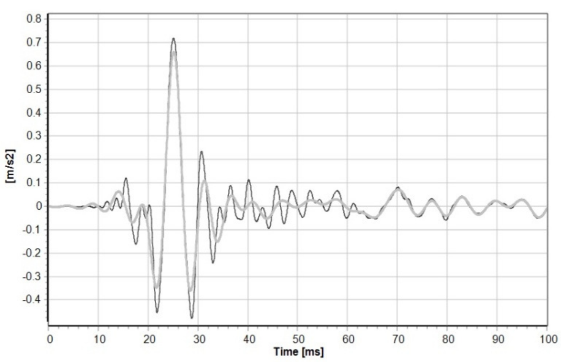

Figure 18. Unfiltered (black trace) superimposed upon filtered trace (light grey) for RS recorded at 2.5m.

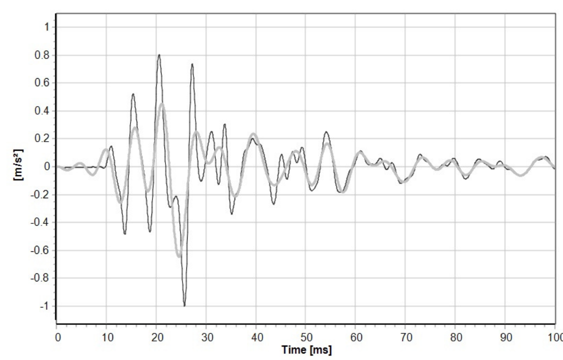

Figure 19. Unfiltered (black trace) superimposed upon filtered trace (light grey) for LS recorded at 2.5m.

CONCLUSIONS

Downhole seismic testing (DST) is a very popular applied seismology site characterizing tool within geotechnical engineering. One of the fundamental goals of DST is to quantify the shear wave interval velocities as this is an important parameter for evaluating the liquefaction potential due to fact that it is influenced by many of the variables that influence liquefaction. This paper has outlined BCE's newly Seismic Trace Characterization (STC), which is based on various independent seismic trace metrics of the acquired DST data at a particular depth. There are currently five independent trace metrics which are linearity (LIN), cross correlation coefficient (CCC), signal shape parameter (SSP), peak symmetry differential (PSD) and signal-to-noise ratio (SNR). LIN values nearing 1.0 identify seismic recordings which have highly correlated responses on the relevant axes and strong directionality. This will be the case for seismic traces recorded in TI medium with minimal measurement noise, clean source waves, and no signal distortions (e.g., reflections). The CCC between the two DST seismic traces gives an indication of the similarity between the two waves being correlated. The SSP parameter quantifies the deviation of the source wave frequency spectrum from a desirable bell-shaped curve. High quality DST seismic traces are found to have characteristically bell-shaped curves similar to the probability density of a normal distribution. The PSD trace metric facilitates the identification of traces whose peak source wave responses have been significantly skewed due to measurement noise or source wave reflection interference. The peak responses of a seismic trace are critical when deriving arrival time estimates as they act as the predominant time markers. Finally, the SNR parameter quantifies the extent that the desired source wave frequency spectrum resides within the unfiltered recorded seismic trace. This paper has demonstrated with real data that the five STC parameters are highly beneficial in post signal processing where varying signal processing tools are applied based upon the derived STC values. In addition, the STC parameters quantify the quality of the recorded DST traces which provides for an assessment of the resulting derived interval velocities. It is the authors' intentions to have the application of STC parameters to post data analysis evolve based upon the data analysis of additional data sets..

REFERENCES

Aki, K. and Richards, P.G. 2002. Quantitative Seismology, 2nd edition, Sausalito, California: University Science Books.

Andrus, R.D., & Stokoe, K.H. (1997). "Liquefaction resistance based on shear wave velocity". National Center for Earthquake Engineering Research (NCEER) Workshop. Salt Lake, Utah, pp. 89-128.

ASTM (American Standards and Testing Methods). (2017). "D7400: Standard Test Methods for Downhole Seismic Testing." ASTM Vol. 4.09 Soil and Rock (II): D5877-latest.

Baziw, E. (2002), "Derivation of Seismic Cone Interval Velocities Utilizing Forward Modeling and the Downhill Simplex Method", Can. Geotech. J., 39(5), pp.1181-1192.

Baziw, E., and Verbeek, G. (2012). "Deriving Interval Velocities from Downhole Seismic Data", Geotechnical and Geophysical Site Characterization 4 – Mayne (eds), CRC Press, 1019–1024.

Baziw, E. and Verbeek, G. (2014). "Identifying Critical Layers using SCPT and Seismic Source Moveout." In the Proceedings of the 3rd International Symposium on Cone Penetration Testing, CPT'14, May 12-14, 2014 - Las Vegas, Nevada, 357-364.

Baziw, E., and Verbeek, G. (2016a), "Frequency spectrum "bell-curve" fitting as a component of SCPT interval velocity accuracy assessment", 5th International Conference on Geotechnical Site Characterization (ISC-5), Queensland – Australia, 5-9 Sept. Australian Geomechanics Society, 1431-1436.

Baziw, E. and Verbeek, G., (2016b)," Interval Velocity Classification Technique in Downhole Seismic Testing", http://www.bcengineers.com/images/BCE_IVC_2016.pdf.

Baziw, E. and Verbeek, G. (2017), "Quality Assessment of Seismic Data Sets and the Impact on Interval Velocity Estimates in DST", In Proceedings of the DFI 42nd Annual Conference on Deep Foundations, New Orleans - USA, October 24-27, 2017. Article #2821; publication #1037 (AM-2017).

Bray, J.D., Zupan, J.D., Cubrinovski, M. and Taylor, M., (2014), "CPT-based liquefaction assessments in Christchurch, New Zealand". Las Vegas, NV, USA: 3rd International Symposium on Cone Penetration Testing (CPT '14), 12-14 May 2014. 1-21. http://www.cpt14.com/cpt14-papers. (Conference Contributions - Papers in published proceedings).

Kanasewich, E.R., 1981, Time sequence analysis in geophysics. 3rd ed., The University of Alberta Press, Edmonton, AB. Chapter 19.

National Research Council, Commission on Engineering and Technical Systems (1985), Committee on Earthquake Engineering Liquefaction of soils during Earthquakes: Washington, D.C., National Academy Press.

Seed, H.B. (1979) "Soil liquefaction and cyclic mobility evaluation for level ground during earthquake", J. Geotech. Engr. Div., ASCE, 105, GT2, 201-225.

Seed, H.B., & Idriss, I.M. (1982) Ground motions and soil liquefaction during earthquakes: Earthquake Engineering Institute Monograph Series.