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Incorporation of SH source wave parameter "SH Polarization" within DST seismic trace characterization

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ABSTRACT: Downhole Seismic Testing (DST) is an important geotechnical testing technique for site characterization that provides low strain in-situ interval shear wave velocity estimates, which are fundamental design parameters for static and dynamic soil analysis. A challenging problem in DST is to obtain an accurate assessment or characterization of the quality of the acquired seismic data, which is then used to guide the analysis process to obtain the most accurate interval velocity values. The characterization process is referred to as Seismic Trace Characterization (STC). STC derives various independent parameters of the acquired seismic data at a particular depth, which are then fused together into a single classification. To date Baziw Consulting Engineers has identified five STC independent parameters. These five parameters are the linearity estimates from the polarization analysis, the cross correlation coefficient of the full waveforms at the particular depth and the preceding depth, a uniquely developed parameter referred to as the signal shape parameter, the signal-noise-ratio and the peak symmetry differential, which provides insight into the skewing or time shifting of the peak source wave response. This paper outlines a newly identified seismic trace feature that is independent of the parameters listed above. This new parameter is SH Polarization (SHP), which quantifies the desired polarization of the generated source on the horizontal plane compared with particle motion generated on the vertical plane.

1 INTRODUCTION

The fundamental goal of Downhole Seismic Testing (DST) is to obtain accurate estimates of low strain ($<10^{-5}$) shear (Vs) and compression (Vp) wave velocities. These velocities are directly related to the various soil elastic constants, such as the Poisson's ratio, shear modulus, bulk modulus and Young's modulus. These parameters form the core of mathematical theorems to describe the elasticity/plasticity of soils and they are used to predict the soil response (settlement, liquefaction or failure) to imposed loads. Accuracy in the estimation of these two in-situ velocities is of paramount importance because their values are squared during the calculation of the soil elastic constants. In DST a seismic source wave is generated at the ground surface, and one or more downhole seismic receivers are used to record this wave at predefined depths. From these recorded seismic traces arrival times are estimated and corresponding interval velocities calculated.

Baziw Consulting Engineers (BCE) has invested considerable resources into the characterization of DST traces (Baziw and Verbeek 2016, 2017, and 2018) to address three fundamental concerns. 1) What is the quality of the acquired seismic data sets? 2) What signal processing techniques can be applied to improve the signal-to-noise ratio (SNR) of the seismic data? And 3) What is the appropriate confidence level in the calculated interval velocities estimates? Over time work in addressing these three concerns has resulted in the standardization of a DST post data processing methodology, which has proven highly accurate and reliable. Currently quality assessment through Seismic Trace Characterization (STC) relies upon five independent parameters (Baziw and Verbeek 2016, 2017 and 2018):

- Parameter 1: the linearity estimates (LIN) the linearity or rectilinearity from polarization analysis. The LIN trace metric quantifies the correlation between X, Y and Z axis responses. The linearity approaches unity when the rectilinearity is high and approaches zero when the rectilinearity is low. 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 lower quality traces.
- Parameter 2: the Cross Correlation Coefficient (CCC) of the full waveforms at the particular depth and the preceding depth. The CCC trace metric gives an indication of the similarity between the two waves being correlated when

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deriving relative arrival times. CCC values approaching 1.0 indicate that the two waveforms are highly correlated. CCC values approaching 0 indicate very poor correlation.

- Parameter 3: the Signal Shape Parameter (SSP). The SSP trace metric quantifies the deviation of the shape of the frequency spectrum from an ideal bell shape. SHP values approaching 1.0 indicate that the frequency has a desirable bells shape. SHP values approaching 0 indicates that the frequency spectrum deviates significantly from the desired bell shape.
- Parameter 4: the Peak Symmetry Differential (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 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. Traces with low PSD value are of a lesser quality and require more attention during analysis.
- Parameter 5: Signal to Noise Ratio (SNR). The SNR trace metric is solely provided to quantify what portion of the spectral content of the recorded seismogram resides within the desired source frequency spectrum irrespective of source wave distortions such as near-field effects, reflections, refractions, and “dirty sources”.

As part of the post analysis of the seismic traces these parameters are then converted into a STC grade ranging from A to F where A is highly desirable and F is unacceptable without corrective action. Next they are used as a guide for the data analysis and seismic signal processing (Baziw and Verbeek, 2018). A central part of this processing is the source wave Signature Feature Isolation (SFI) to clearly identify the source wave in the seismic trace by applying an exponential decay function to the remainder of the trace. This can be performed in three different ways:

- ASD or Automatic Signal Decay, where the program identifies the absolute maximum amplitude on all trace under analysis and then applies the decay function on either side of that feature.
- GSD or Guided Signal Decay, where the user identifies a specific feature for the traces under analysis and then applies the decay function on either side of that feature.
- ISD or Individual Signal Decay, where the user identifies a specific feature for each trace under analysis and then applies the decay function on either side of that feature on that particular trace.

The analysis process can then be visualized as outlined in Figure 1.

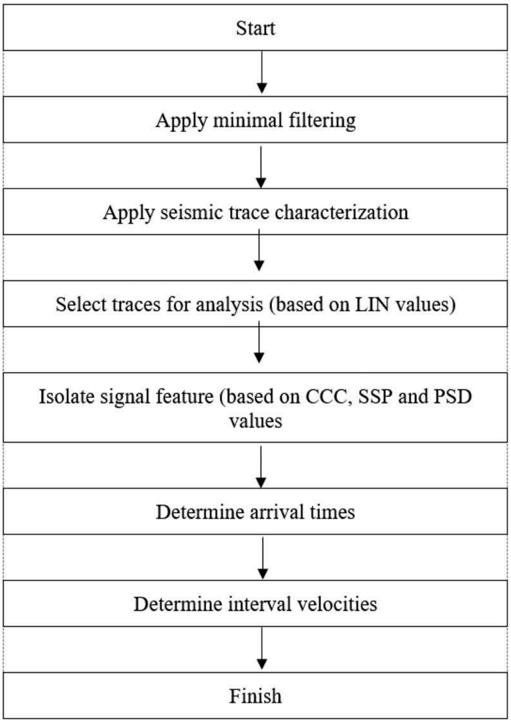

Figure 1. DST data processing flow chart incorporating STC parameters.

In this paper, the preliminary implementation and mathematical details of a new STC parameter is outlined. This new parameter, the so called SH Polarization (SHP), quantifies the desired polarization of the generated source on the horizontal plane compared with particle motion generated on the vertical plane.

2 STC PARAMETER SH POLARIZATION (SHP)

Seismic sources are designed to generate either compression (P),vertically polarized shear (SV) waves or horizontally polarized(SH) shear waves. Figure 2 illustrates the compression and shear source waves impacting upon a triaxial seismic sensor package. As it is shown in Figure 2, the P-wave’s particle motion is in the same direction as the raypath, the SH waves particle motion is perpendicular to the raypath and is parallel to the horizontal ground surface, while the SV wave’s particle motion is also perpendicular to the raypath, but along the vertical normal to the raypath.

P or SV waves generate four outgoing waves when impacting an interface (reflected SV and P waves and transmitted SV and P waves). In contrast, SH waves have the desirable property of only generating one reflected and one transmitted SH at an interface. This results in considerably simplified seismic data sets. A popular SH source is the well-known hammer beam (ASTM, 2017). The hammer-beam consists of applying a hammer blow laterally to the sides of special designed plates fixed at the surface.

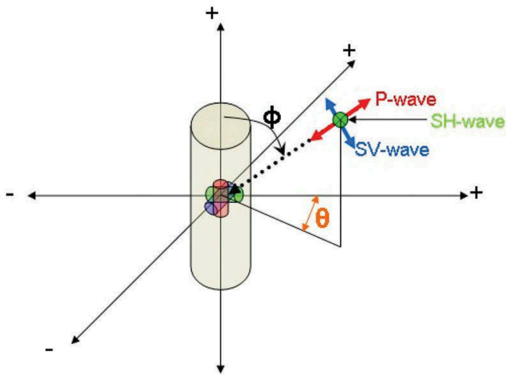

Figure 2. Source P, SV, and SH body waves impacting upon a triaxial sensor package.

The new STC parameter SHP quantifies and applies a grade [A to F] to how closely the measured SH wave seismic traces adhere to the desired polarization of the shear wave on the horizontal plane. The SHP algorithm can be summarized as follows, assuming that a triaxial (x, y and z axes) seismic trace has been recorded.

1. Apply a minimal filter (200 Hz low pass) to the acquired SH source wave.
2. Determine time index, t^*, where the maximum absolute amplitude of the full waveform ($\rho(t) = \sqrt{x^2(t) + y^2(t) + z^2(t)}$) occurs.
3. Establish a time window T which is defined as t^*-Δt to $t^*+\Delta t$ where $\Delta t = 30$ms.
4. Over the established time T calculate the energy of the full waveform, E_ρ, and the energy of the particle motion on the X-Y plane E_{xy} ($xy(t) = \sqrt{x^2(t) + y^2(t)}$).
5. Calculate energy ratio $ER = E_{xy}/E_\rho$.
6. Assign a SHP rank based upon calculated ER value as outlined in Table 1.

Table 1. SHP rank and description.

ER Numeric Value [0-1]	SHP Rank [A-F]	STC Description
0.8 to 1.0	A	very good to good
0.65 to 0.8	B	good to acceptable
0.5 to 0.65	C	acceptable to questionable
0.3 to 0.5	D	questionable to unacceptable
< 0.3	F	unacceptable

The SHP rankings outlined in Table 1 are preliminary values. These values will be adjusted and refined as a greater number DST seismic traces are processed.

3 IMPLEMENTATION OF SHP STC PARAMETER ON REAL DATA SETS

The first and second real data sets outlined in this section were acquired by Perry Geotech Limited located in Tauranga, New Zealand. Figure 3 illustrates a SH source wave DST vertical seismic profile (x, y and z axis responses) of SH DST seismic data acquired on the Left Side (LS) of the seismic probe, while Figure 4 shows the VSP of data acquired on the Right Side (RS) of the seismic probe. The STC parameters for the LS and RS are outlined in Tables 2 and 3, respectively.

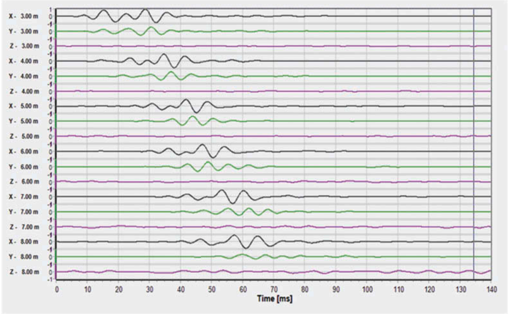

Figure 3. Data Set 1 – real data set. VSP of data acquired on LS of seismic probe (200Hz low pass filter applied).

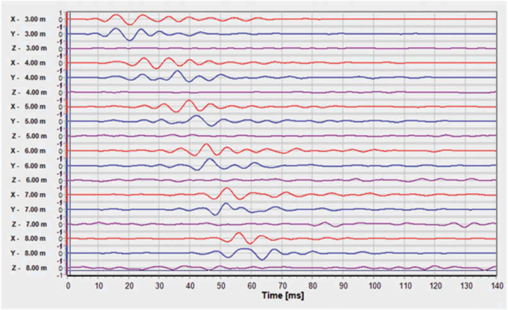

Figure 4. Data Set 1 – real data set. VSP of data acquired on right side of seismic probe (200Hz low pass filter applied).

As is evident from Tables 2 and 3 the data sets from the LS and RS have low STC values of ‘D’s and ‘F’s (predominantly due to low LIN values), but with high SHP rankings. This suggests that the acquired seismic traces have the desirable polarization on the horizontal plane, but will require preferable axis

Table 2. STC parameters for LS for Data Set 1.

Depth [m]	LIN [0-1]	SSP [0-1]	CCC [0-1]	PSD [0-1]	SNR [0-1]	STC [A-F]	SHP [A-F]
3	0.68	0.54	0	0.86	0.71	N/A	A
4	0.71	0.77	0.69	0.81	0.86	D	A
5	0.59	0.71	0.96	0.73	0.88	D	A
6	0.44	0.70	0.99	0.74	0.91	D	A
7	0.60	0.75	0.96	0.57	0.97	D	A
8	0.88	0.80	0.96	0.59	0.92	D	B

Table 3. STC parameters for RS for Data Set 1.

Depth [m]	LIN [0-1]	SSP [0-1]	CCC [0-1]	PSD [0-1]	SNR [0-1]	STC [A-F]	SHP [A-F]
3	0.77	0.76	0	0.89	0.54	N/A	A
4	0.30	0.77	0.77	0.94	0.88	D	A
5	0.21	0.63	0.80	0.82	0.84	F	A
6	0.46	0.65	0.87	0.77	0.88	D	A
7	0.53	0.69	0.93	0.93	0.98	D	A
8	0.34	0.73	0.85	0.97	0.96	D	B

selection (in this case the X axis) given the LIN values. The SHP rankings give added confidence in the ability to isolate SH responses and derive accurate interval velocities after SFI implementation.

Table 4 outlines the estimated LS and RS interval velocities and corresponding spread. As is shown in Table 4 there is overall high correlation between the LS and RS results (desired values should be ≤ 10% spread), with only the estimated values for the depth interval 3.0m to 4.0m showing a spread slightly above 10%.

The second data set is another example where the LS and RS have again low STC values of ‘D’s and ‘F’s (but now due to low PSD values) and high SHP rankings.

Table 4. Estimated LS and RS interval velocities.

	Depth Interval Velocity			
Depth [m]	LS [m/s]	RS [m/s]	Avg. [m/s]	Spread[1] [%]
0.0-3.0	182.4	204.1	193.3	5.6
3.0-4.0	150.4	122.2	136.3	10.3
4.0-5.0	129.4	141.5	135.5	4.5
5.0-6.0	171.3	164.6	168	2.0
6.0-7.0	151.4	141.4	146.4	3.4
7.0-8.0	214.5	239.5	227	5.5

1 The spread is defined as ½ x (LS Interval Velocity – RS Interval Velocity)/Avg. Interval Velocity

For this data set Figure 5 illustrates a vertical seismic profile (x, y and z axis responses) of SH DST seismic data acquired on the Left Side (LS) of the seismic probe, while Figure 6 shows the VSP of data acquired on the Right Side (RS) of the seismic probe. The STC parameters for the LS and RS are outlined in Tables 5 and 6, respectively.

The SHP rankings suggest that the acquired seismic traces have desirable polarization on the horizontal plane, but will require signal feature isolations based upon the LIN and SSP (LS) and PSD (RS) values.

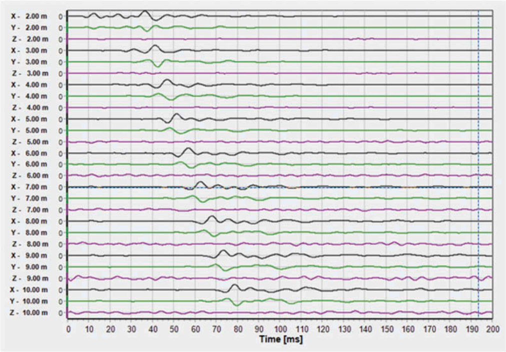

Figure 5. Data Set 2 – real data set. VSP of data acquired on LS of seismic probe (200Hz low pass filter applied).

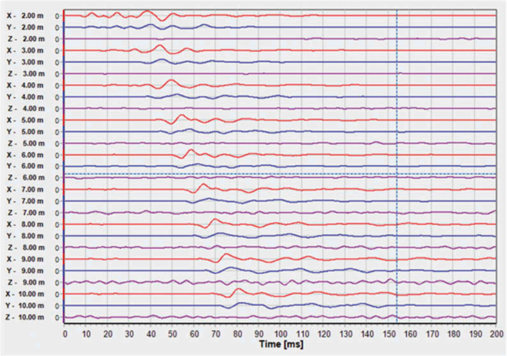

Figure 6. Data Set 2 – real data set. VSP of data acquired on RS of seismic probe (200Hz low pass filter applied).

Table 5. STC parameters for LS for Data Set 2.

Depth [m]	LIN [0-1]	SSP [0-1]	CCC [0-1]	PSD [0-1]	SNR [0-1]	STC [A-F]	SHP [A-F]
2	0.83	0.65	0.62	0.6	0.95	N/A	A
3	0.8	0.79	0.71	0.89	0.97	D	A
4	0.81	0.67	0.88	0.7	0.98	B	A
5	0.77	0.7	0.95	0.58	0.93	B	A
6	0.76	0.63	0.96	0.8	0.97	D	A
7	0.71	0.58	0.97	0.98	0.98	D	B
8	0.75	0.55	0.99	0.96	0.98	D	B
9	0.76	0.5	0.98	0.89	0.98	D	B
10	0.79	0.53	0.98	0.86	0.98	D	A
11	0.78	0.54	0.98	0.86	0.98	D	B
12	0.84	0.55	0.98	0.84	0.98	D	B

Table 6. STC parameters for RS for Data Set 2.

Depth [m]	LIN [0-1]	SSP [0-1]	CCC [0-1]	PSD [0-1]	SNR [0-1]	STC [A-F]	SHP [A-F]
2	0.79	0.58	0.58	0.77	0.98	N/A	A
3	0.88	0.66	0.81	0.77	0.98	B	A
4	0.83	0.69	0.88	0.92	0.98	B	A
5	0.81	0.63	0.92	0.01	0.98	F	A
6	0.8	0.63	0.97	0.01	0.98	F	B
7	0.81	0.55	0.96	0.01	0.98	F	B
8	0.82	0.54	0.98	0.01	0.98	F	B
9	0.84	0.48	0.98	0.01	0.98	F	C
10	0.83	0.58	0.98	0.2	0.98	F	B
11	0.84	0.51	0.99	0.51	0.98	D	B
12	0.84	0.54	0.98	0.65	0.98	D	B

Table 7. Estimated LS and RS interval velocities for Data Set 2.

Depth [m]	Depth Interval Velocity LS [m/s]	RS [m/s]	Avg. [m/s]	Spread[1] [%]
0.0-2.0	103.1	106.5	119.1	0.8
2.0-3.0	120.8	117.4	135.85	0.7
3.0-4.0	134,0	137.7	171.45	0.7
4.0-5.0	179.1	163.8	173.85	2.2
5.0-6.0	160.7	187	158.55	3.8
6.0-7.0	157.7	159.4	171.2	0.3
7.0-8.0	173.9	168.5	176.35	0.8
8.0-9.0	174	178.7	175.6	0.7
9.0-10.0	180.4	170.8	172.8	1.4
10.0-11.0	166.2	179.4	148.1	1.9
11.0-12.0	143.8	152.4	119.1	1.5,

[1] The spread is defined as ½ x (LS Interval Velocity – RS Interval Velocity)/Avg. Interval Velocity

Table 7 outlines the estimated LS and RS interval velocities and corresponding spread for Data Set 2. As is shown Table 7 there is overall very high correlation between the LS and RS results.

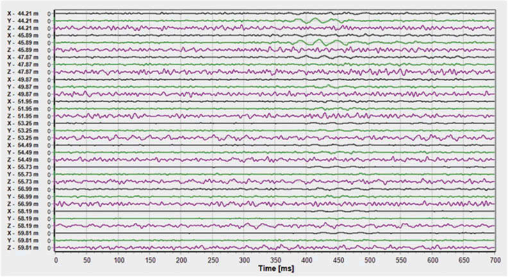

Figure 7. Data Set 3 – real data set. VSP of data acquired on LS of seismic probe (200Hz low pass filter applied).

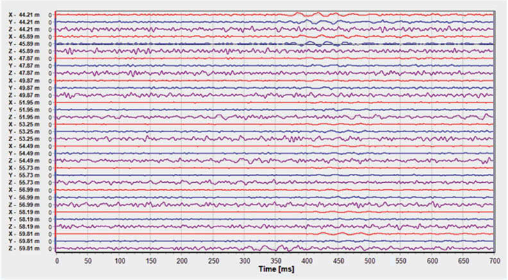

Figure 8. Data Set 3 – real data set. VSP of data acquired on LS of seismic probe (200Hz low pass filter applied).

Table 8. STC parameters for LS for Data Set 3.

Depth [m]	LIN [0-1]	SSP [0-1]	CCC [0-1]	PSD [0-1]	SNR [0-1]	STC [A-F]	SHP [A-F]
44.2	0.87	0.33	0.9	0.89	0.89	N/A	C
45.9	0.85	0.27	0.97	0.34	0.94	D	C
47.9	0.68	0.41	0.95	0.36	0.8	D	D
49.9	0.76	0.46	0.88	0.94	0.81	D	D
51.9	0.51	0.46	0.62	0.01	0.83	F	F
53.2	0.82	0.53	0.47	0.01	0.79	F	F
54.4	0.82	0.55	0.84	0.01	0.81	F	D
55.7	0.63	0.59	0.75	0.64	0.82	F	F
56.9	0.39	0.54	0.97	0.01	0.77	F	F
58.9	0.57	0.51	0.65	0.49	0.79	F	F
59.8	0.87	0.53	0.26	0.85	0.76	F	F

Table 9. STC parameters for RS for Data Set 3.

Depth [m]	LIN [0-1]	SSP [0-1]	CCC [0-1]	PSD [0-1]	SNR [0-1]	STC [A-F]	SHP [A-F]
44.2	0.72	0.37	0.92	0.63	0.88	N/A	C
45.9	0.78	0.31	0.96	0.83	0.91	D	C
47.9	0.62	0.56	0.95	0.25	0.79	D	D
49.9	0.43	0.5	0.87	0.69	0.86	D	F
51.9	0.73	0.48	0.73	0.01	0.89	F	F
53.2	0.71	0.51	0.89	0.45	0.73	F	F
54.4	0.7	0.52	0.72	0.01	0.8	F	F
55.7	0.63	0.5	0.46	0.94	0.7	F	F
56.9	0.75	0.52	0.53	0.28	0.8	F	F
58.9	0.71	0.59	0.89	0.52	0.51	D	F
59.8	0.73	0.14	0.92	0.42	0.86	D	D

The third data set demonstrates that for a data set with poor STC and SHP values it is (generally) not possible to obtain accurate SH interval velocity estimates. Figures7 and 8 illustrate the LS and RS traces for a real data set acquired during an offshore DST investigation. The STC parameters are outlined in Tables 8 and 9, respectively.

The combination of very poor STC and SHP values strongly suggests that it is not possible to isolate source wave response by implementing SFI. And therefore this data set was indeed dropped and not analyzed. This shows the importance of having these parameters available in real-time during data acquisition to ensure that the collected data is useful and can be used to derive interval velocities.

4 CONCLUSIONS

Downhole Seismic Testing (DST) is an important geotechnical testing technique which provides estimates of low strain ($<10^{-5}$) shear and compression wave velocities, but there is a need for a widely accepted seismic trace characterization (STC) methodology of the acquired data.

In the past BCE had identified five independent STC parameters (linearity estimates from the polarization analysis, the cross correlation coefficient of the full waveforms at the particular depth and the preceding depth, the signal shape parameter, the signal-noise-ratio and the peak symmetry differential). In this paper, the mathematical and implementation details of a new STC parameter have been outlined. This new parameter, denoted as SHP, quantifies the desired polarization of a horizontally generated shear wave on the horizontal plane compared with particle motion generated on the vertical plane. SH source waves should have negligible particle motion along the vertical axis.

As illustrated in this paper, the initial assessment of the SHP STC parameter when processing real data sets is very promising, although it is fully expected that the SHP ranking will be refined once the parameter has been applied to additional data sets.

In addition the authors intend to develop an approach to incorporate the SHP ranking into the post-processing methodology for seismic data

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