Recommended Data Analysis and Signal Processing Based on the DST Seismic Trace Characterization

Upon receipt of a data set with Downhole Seismic Testing (DST) results the analyst has to decide how to process these data in order to obtain the most reliable results. BCE has developed a characterization method of the acquired data (the so-called Seismic Trace Characterization (STC)) that is based upon various independent parameters or trace metrics of the acquired DST data at a particular depth. Currently, BCE has indentified five trace metrics:

- Parameter 1: the linearity estimates (LIN) from polarization analysis. The LIN trace metric quantifies the correlation between X, Y and Z axis responses.
- 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 deriving relative arrival times.
- 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
- 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.
- 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”.

These parameters are described in more detail in Technical notes 15, and this note provides a guide for the recommend data analysis and seismic signal processing based upon these trace metrics.

Parameter 1: Linearity (LIN)

Linearity estimates are derived from triaxial seismic sensor configurations. For data analyses to obtain horizontal shear wave velocity values the X- and Y-axis responses are of interest. Linearity (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.

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

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.

Shown below is an unfiltered Vertical Seismic Profile (VSP)

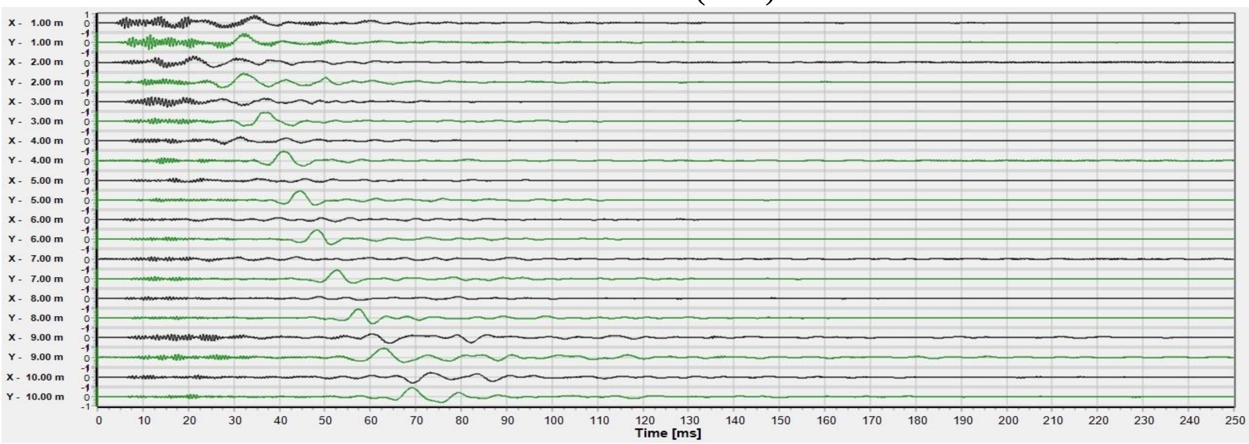


Figure 1: Unfiltered VSP [LIN 1]

After applying a 200Hz low pass filter the VSP becomes as follows:

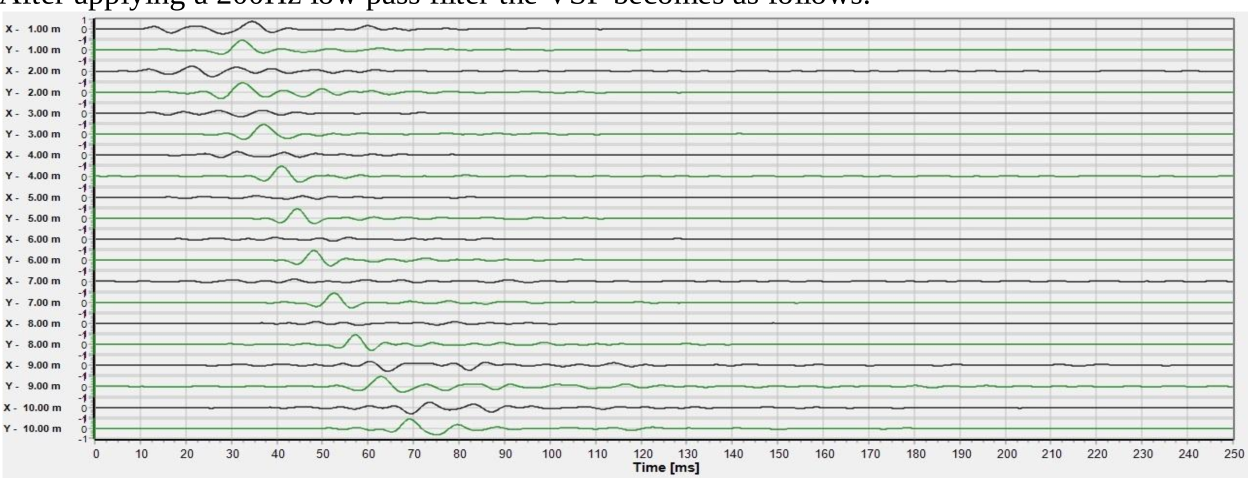


Figure 2: Filtered VSP [LIN 1]

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.

Table 1. Linearity Values for Test Case 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

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 his axis can be used in the analysis. For example, the filtered VSP in Figure 2 clearly showed that the dominant responses reside on the Y axis. The filtered traces recorded at 1m are shown in Figure 3 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.

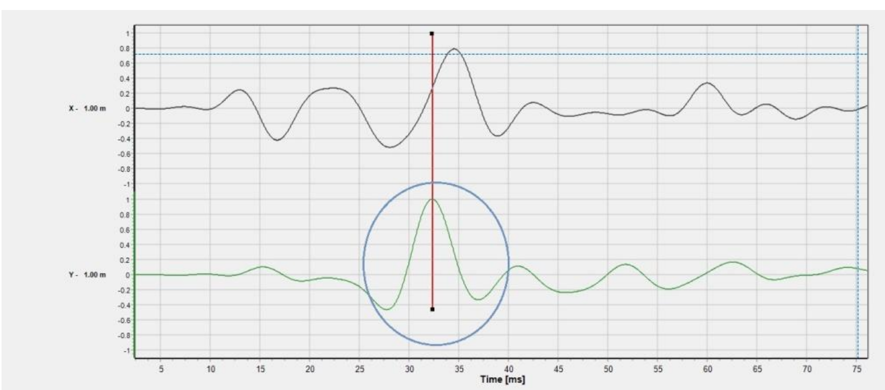


Figure 3: Recorded traces at 1 m [LIN 1]

In SC3-RAV this can be done as follows:

Step 1: Due to the fact that the full waveform is mapped to the X axis it is necessary to rotate the Y axis responses onto the X axis by turning off the X axis and Z axis (Utilities→Specify Full Waveform Component) as shown in Figure 4. Obviously this would not have been necessary if the desired response had been recorded on the X axis.

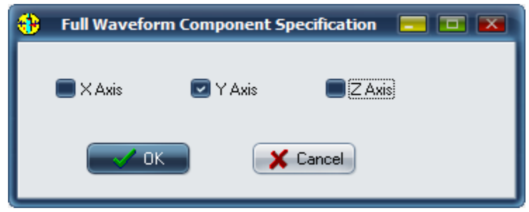


Figure 4: Full Wave Form Component Specification in SC3-RAV

Step 2: Select menu option Seismic Analysis→Polarization Analysis and Seismic Trace Characterization→ Individual Trace and select the trace recorded at 1 m. Then specify the time window which encompasses the Y- axis response (Figure 5A), calculate the incident angle by pressing button Select Incident Angle (Figure 5B), initiate Rotate onto FW Axis (Figure 5C) and finally confirm that the rotated trace has the correct polarity (and if necessary adjust the polarity by selecting 180 Phase Change (Figure 5D). Once this has been done save the trace by selecting option Save P-SV-SH.

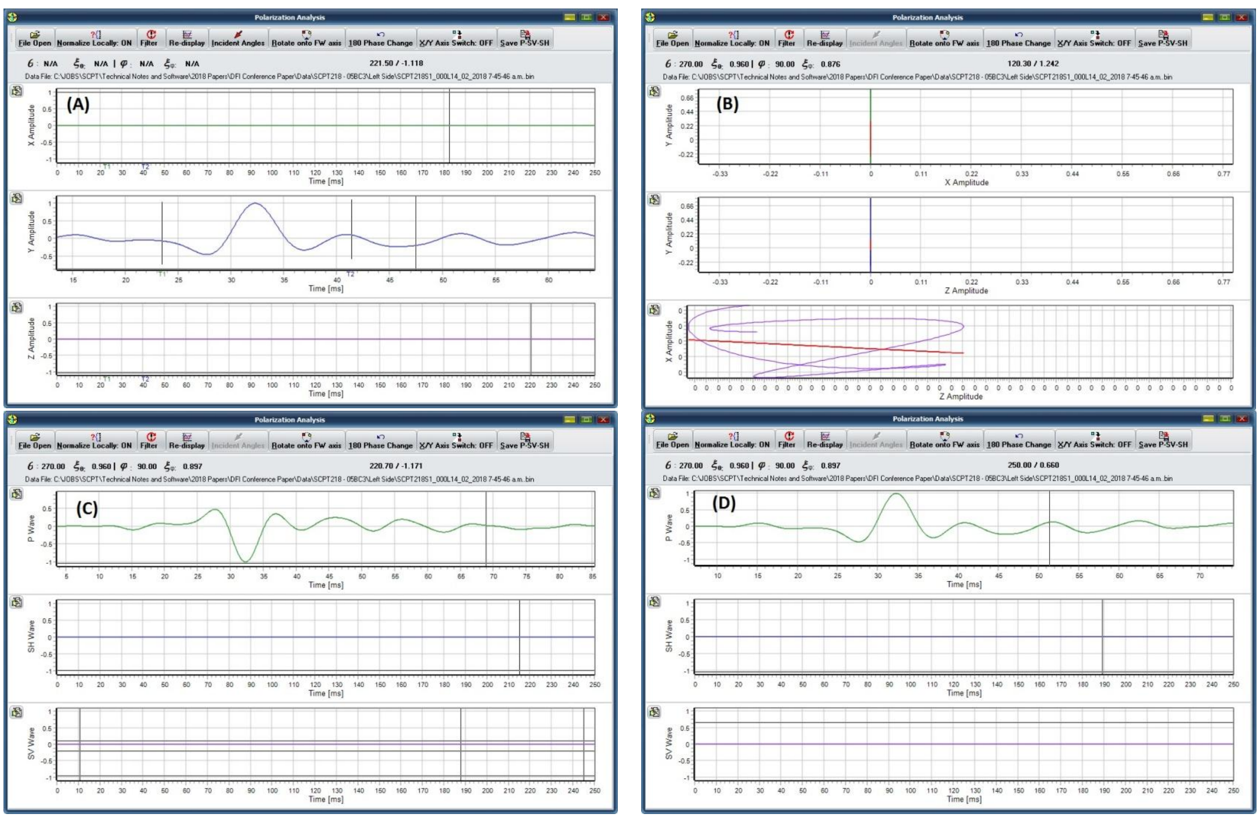


Figure 5: Steps for rotating Y axis responses onto the X axis. (A) Specify time window. (B) Determine incident angle. (C) Rotate Y axis response onto X axis. (D) Change polarity.

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.

Shown below is an unfiltered VSP

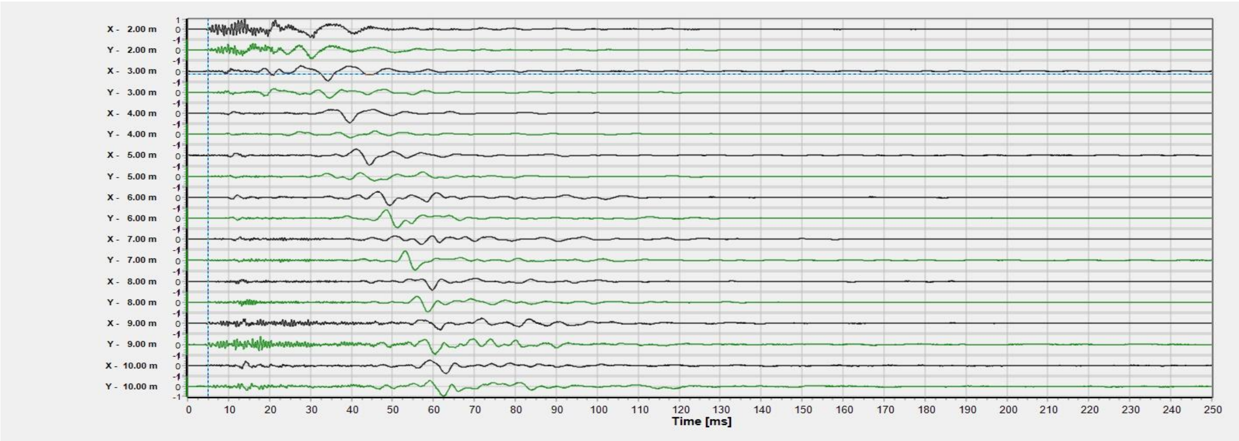


Figure 6: Unfiltered VSP [LIN 2]

After applying a 200Hz low pass filter the VSP becomes as follows:

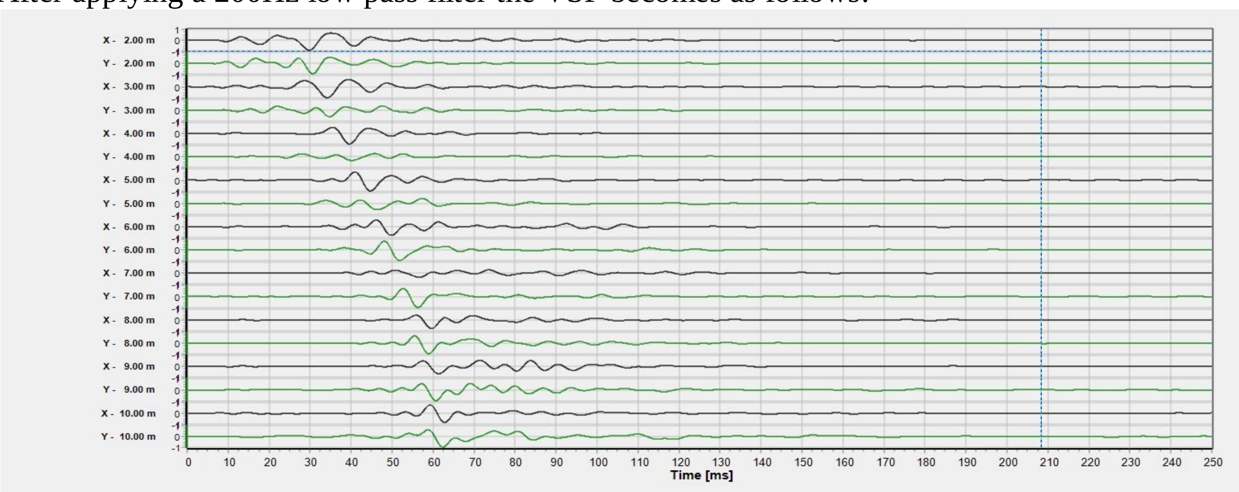


Figure 7: Filtered VSP [LIN 2]

The filtered VSP in Figure 7 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

Table 2. Linearity Values for Test Case 2

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 8 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 gives us confidence 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.

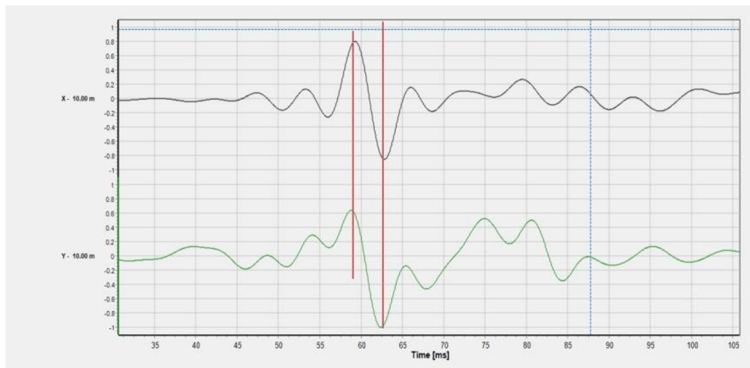


Figure 8: Recorded traces at 10 m [LIN 2]

Figure 9 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. Obviously the Y-axis response must first be rotated onto the full waveform axis and the polarity must be checked (and, if necessary, changed) as was described in the previous case study.

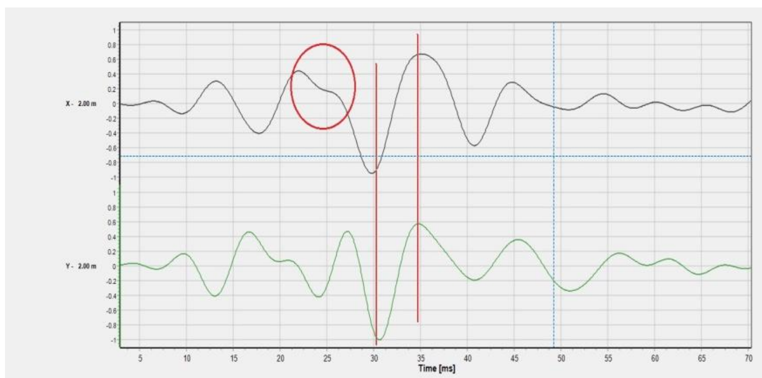


Figure 9: Recorded traces at 2 m [LIN 2]

Alternatively, Individual Polarization Analysis (IPA) can be applied as was previously outlined (i.e., *Seismic Analysis→Polarization Analysis and Seismic Trace Characterization→ Individual Trace*), but in this case the X- and Y-axis responses are enabled and a tighter time window is specified, which focuses on a correlated source wave response (Figure 10A). After that the *Select Incident Angle* is chosen (Figure 10B), *Rotate onto FW Axis* is initiated (Figure 10C) and finally it is confirmed that the rotated trace has the correct polarity (and if necessary adjust the polarity by selecting *180 Phase Chang*e. Once this has been done save the trace by selecting option *Save P-SV-SH*. As is shown in Figure 10D the source wave trough response was rotated onto the full waveform axis (X axis red series)

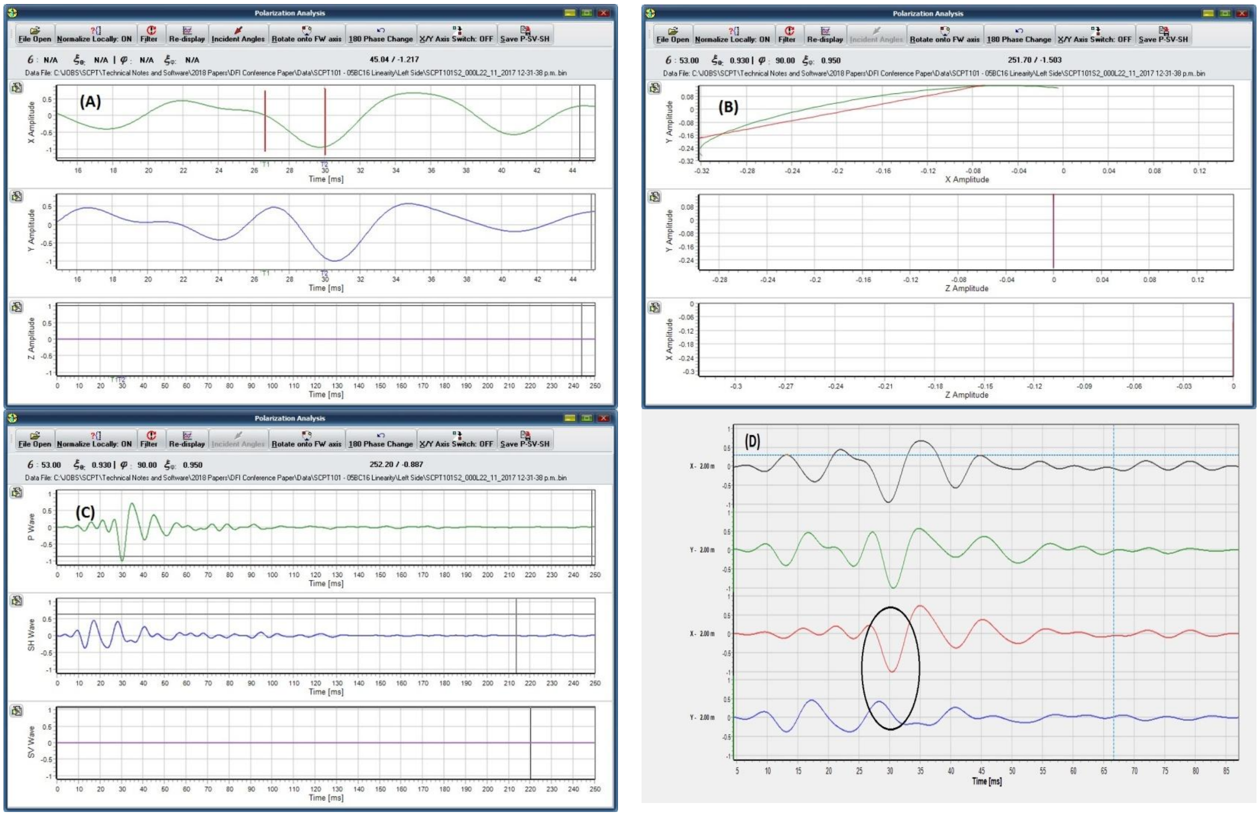


Figure 10: Steps for rotating correlated X and Y axis responses onto the full waveform axis. (A) Specify tight time window. (B) Determine incident angle. (C) Rotate X and Y axis response onto full waveform axis. (D) Troughs on X and Y axis rotated onto full waveform (red time series).

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.

Shown below is an unfiltered VSP

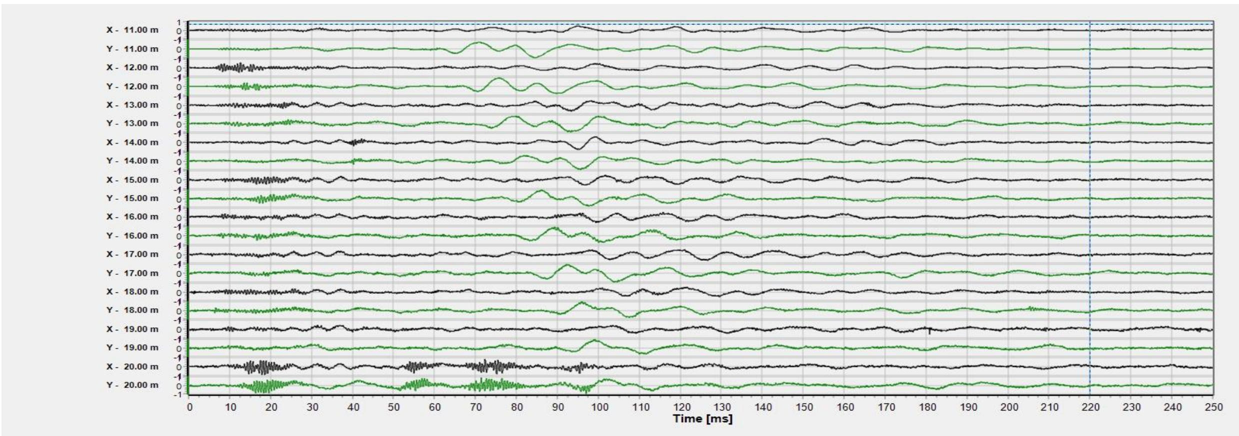


Figure 11: Unfiltered VSP [LIN3]

After applying a 200Hz low pass filter the VSP becomes as follows:

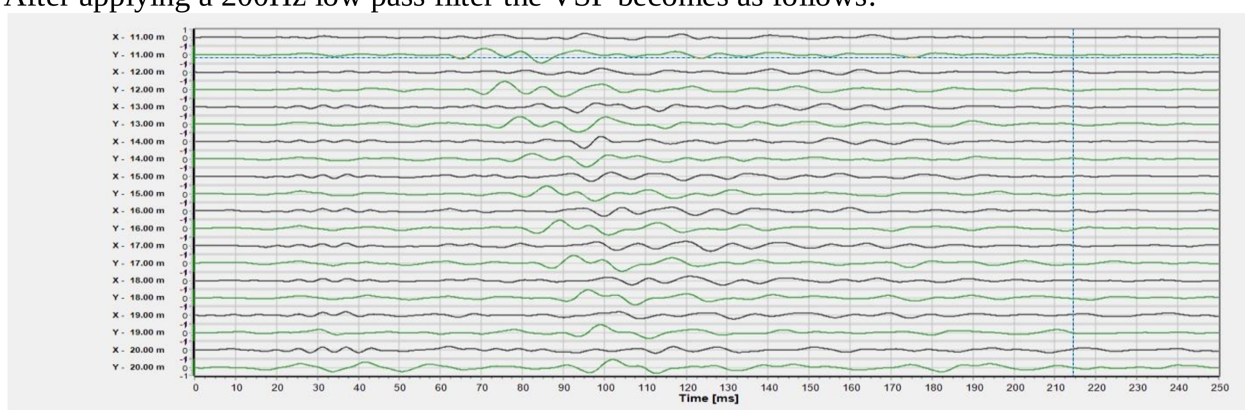


Figure 12: Filtered VSP [LIN 3]

The filtered VSP in Figure 12 illustrates X- and Y-axis responses, with the latter 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, beginning with

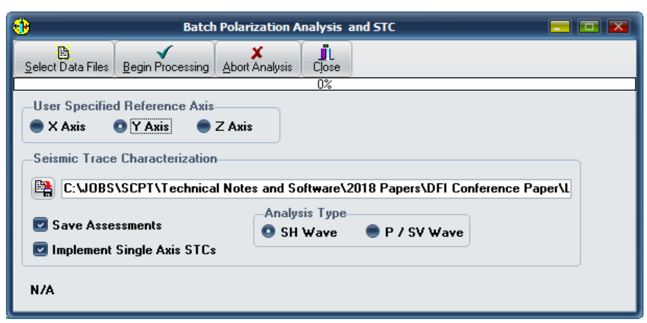


Figure 13: STC dialog box in SC3-RAV

obtaining new trace metrics values for just the higher quality responses, utilizing SC3-RAV™ option *Implement Single Axis STCs* as illustrated in Figure 13.

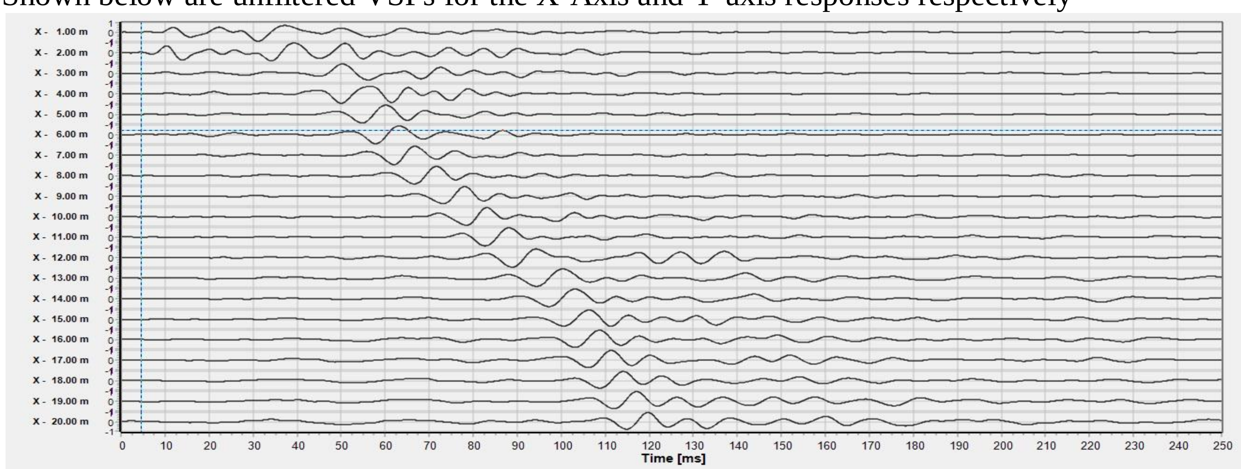
Table 3. Linearity Values for Test Case 3

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

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 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 post analysis, 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

Shown below are unfiltered VSPs for the X-Axis and Y-axis responses respectively



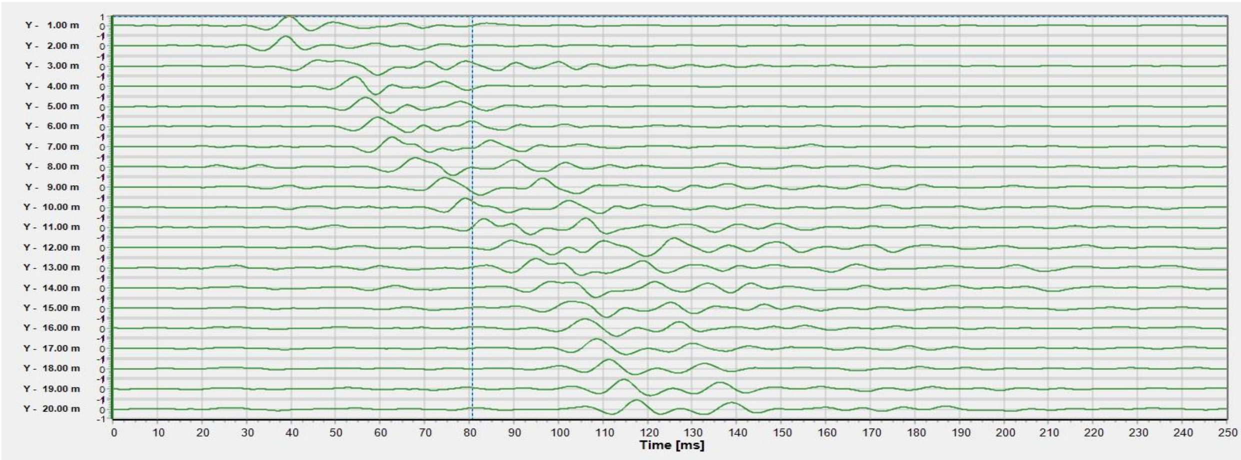


Figure 14: Unfiltered VSPs [LIN 4]

Table 4. Linearity Values for Test Case 4

Depth [m]	Linearity [0-1]
1	0.68
2	0.84
3	0.58
4	0.60
5	0.65
6	0.65
7	0.50
8	0.14
9	0.17
10	0.21
11	0.28
12	0.4
13	0.1
14	0.31
15	0.32
16	0.55
17	0.60
18	0.62
19	0.71
20	0.79

The corresponding LIN values are shown in Table 4, which confirms poorly correlated X- and Y-axis responses. For the depths between 1 m and 4 m it was determined that the Y-axis responses were of higher quality, while for the other depths the X-axis responses are preferred. This is illustrated in Figure 15 where there is significant Y-axis source wave interference between 11 m and 15 m. It should be noted that in the analysis it is important that interval arrival times are obtained for traces between 1 m and 4 m utilizing the Y-axis responses and a reference time for one of the depths between 1m to 4m. Next the X axis responses for traces between 4m to 20m are utilized to obtain interval arrival times with the Y axis arrival time for 4 m as the reference time.

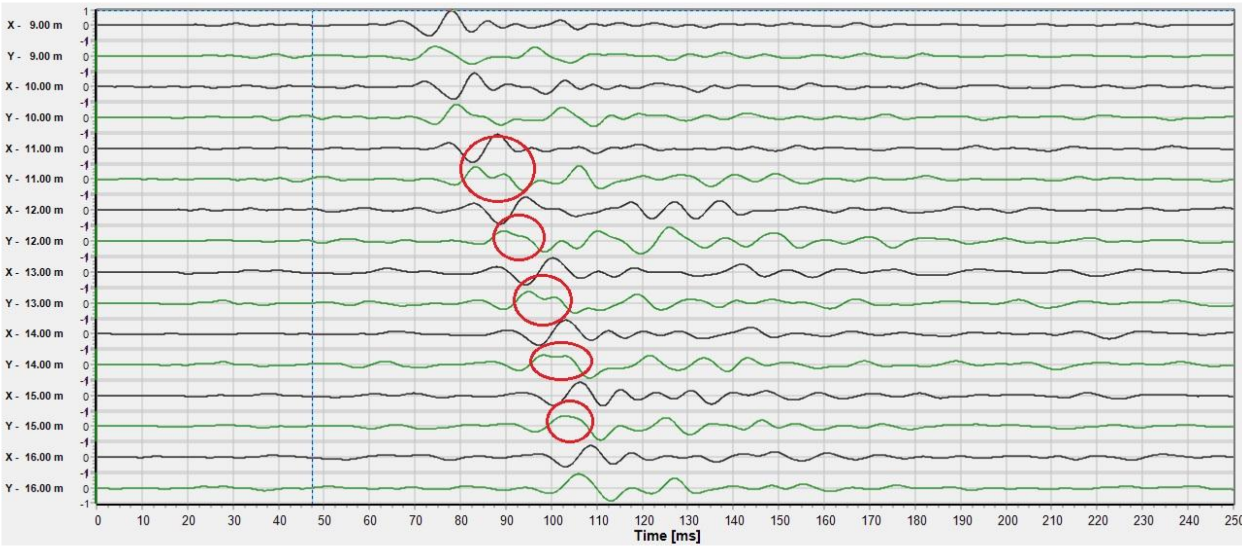


Figure 15: Recorded traces between 9 m and 16 m [LIN 4]

Parameters 2, 3 and 4: Signal Shape Parameter (SSP), PSD (Peak Symmetry Differential), and Cross Correlation Coefficient (CCC):

The SSP parameter quantifies the deviation of the shape of the frequency spectrum from an ideal bell shape, the PSD parameter facilitates the identification of traces whose peak source wave responses have been significantly skewed due to measurement noise or source wave reflection interference, while the CCC parameter gives an indication of the similarity between the two waves being correlated when deriving relative arrival times. All three parameters vary from 0 to 1 where it is desired that they approach the optimal 1.0 value. The three standard signal processing techniques applied to address low SSP, PSD and CCC values are batch signal decay, seismic feature decay and aggressive frequency filtering. Obviously 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. The most appropriate processing technique for various combinations is presented in the various test cases below, which assume threshold values for SSP, PSD and CCC of .0.6, 0.8 and 0.3 respectively.

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 16. Table 5 outlines the corresponding SSP, CCC, and PSD trace metric.

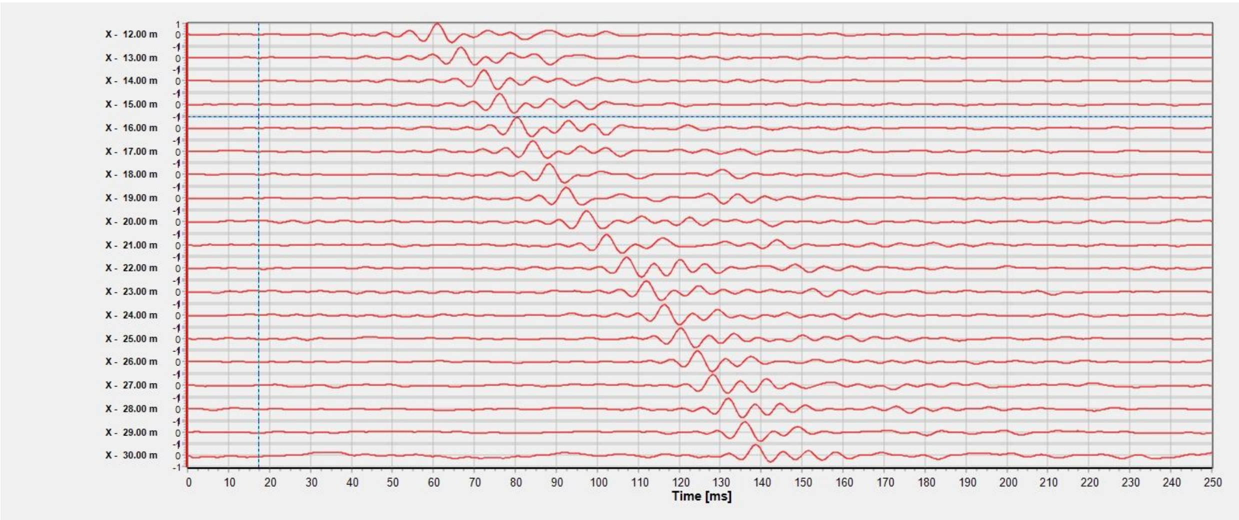


Figure 16: Filtered VSP [SSP PSD CCC 1]

Table 5. SSP, CCC and PSD Values for Test Case SSP PSD CCC 1

Depth [m]	SSP [0-1]	CCC [0-1]	PSD [0-1]
12	0.548	0.9571	0.96
13	0.528	0.9401	0.96
14	0.571	0.9323	0.77
15	0.538	0.9439	0.62
16	0.503	0.9805	0.61
17	0.575	0.9326	0.99
18	0.6	0.9332	0.71
19	0.582	0.967	0.93
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

Clearly only the SSP values are cause of concern and this is readily addressed through batch signal decay, 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 17.

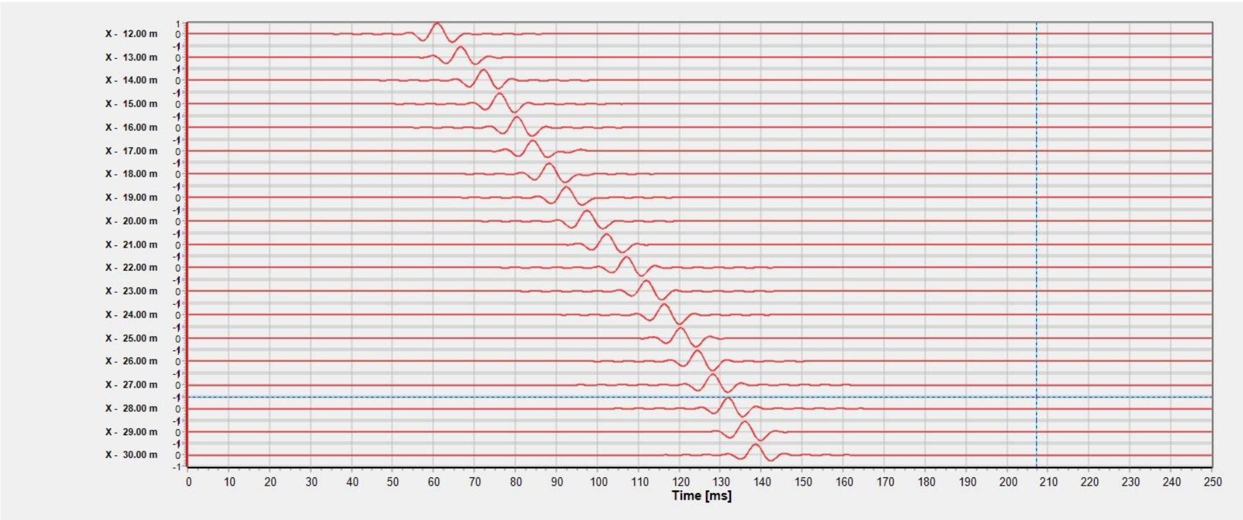


Figure 17: Filtered VSP after bath signal decay [SSP PSD CCC 1]

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 18, while the trace metrics values of SSP, CCC and PSD are given in Table 6 with low PSD values between 4 m and 13 m and also between 17 m and 20 m.

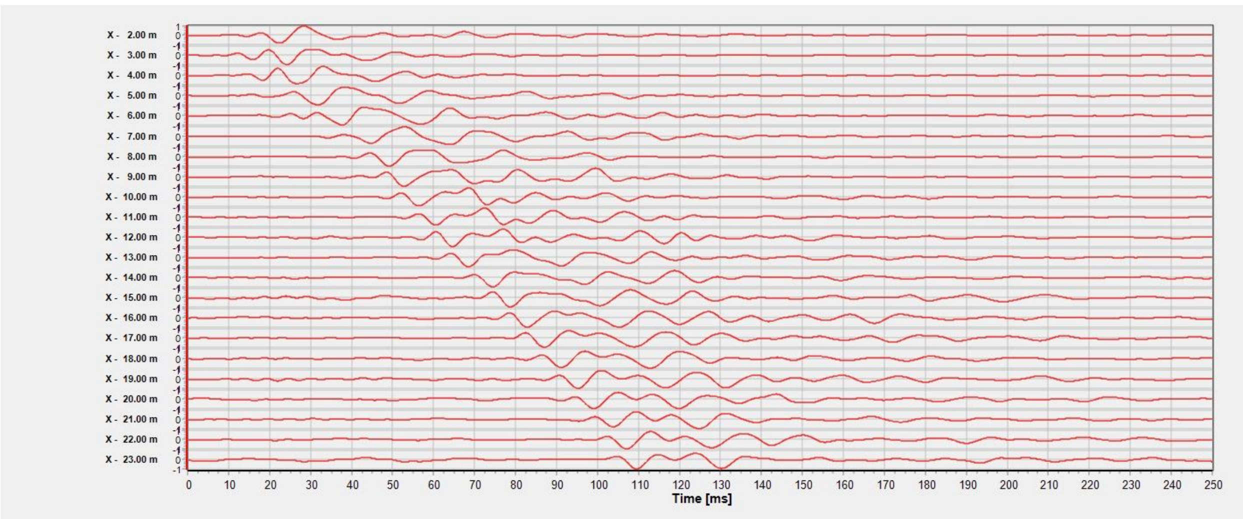


Figure 18: Filtered VSP [SSP PSD CCC 2]

Table 6. SSP, CCC and PSD Values for Test Case SSP PSD CCC 2

Depth [m]	SSP [0-1]	CCC [0-1]	PSD [0-1]
2	0.66	N/A	0.51
3	0.64	0.8119	0.93
4	0.61	0.9536	**0.01**
5	0.58	0.8544	**0.01**
6	0.52	0.9343	**0.01**
8	0.49	0.9124	**0.17**
9	0.53	0.9272	**0.17**
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**
21	0.57	0.9345	0.58
22	0.61	0.9164	0.78
23	0.60	0.9717	0.8

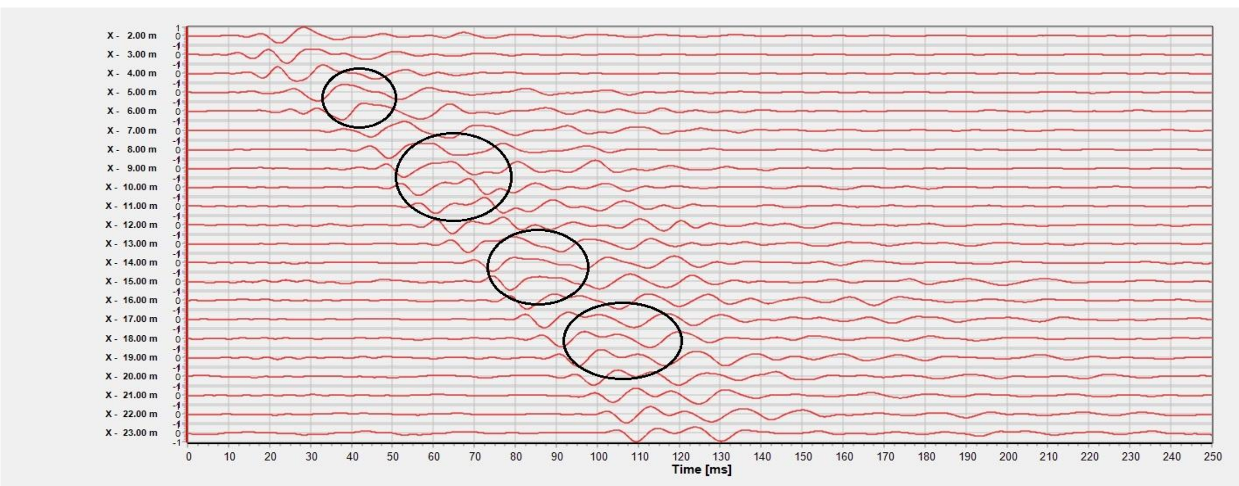


Figure 19: Filtered VSP with peak skewing areas highlighted [SSP PSD CCC 2]

Figure 19 shows the same filtered VSP as in Figure 17, but now black circles 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. This process is referred to as Signal Feature Decay (SFD).

The seismic traces recorded between 12 m and 14 m shown in Figure 20 clearly show that there is minimal first trough distortion. SC3-RAV™ software *option Seismic Analysis→ Signal Decay→Signal Feature Decay* allows for a user specified source wave feature to be isolated throughout the profile, which is demonstrated in Figure 21.

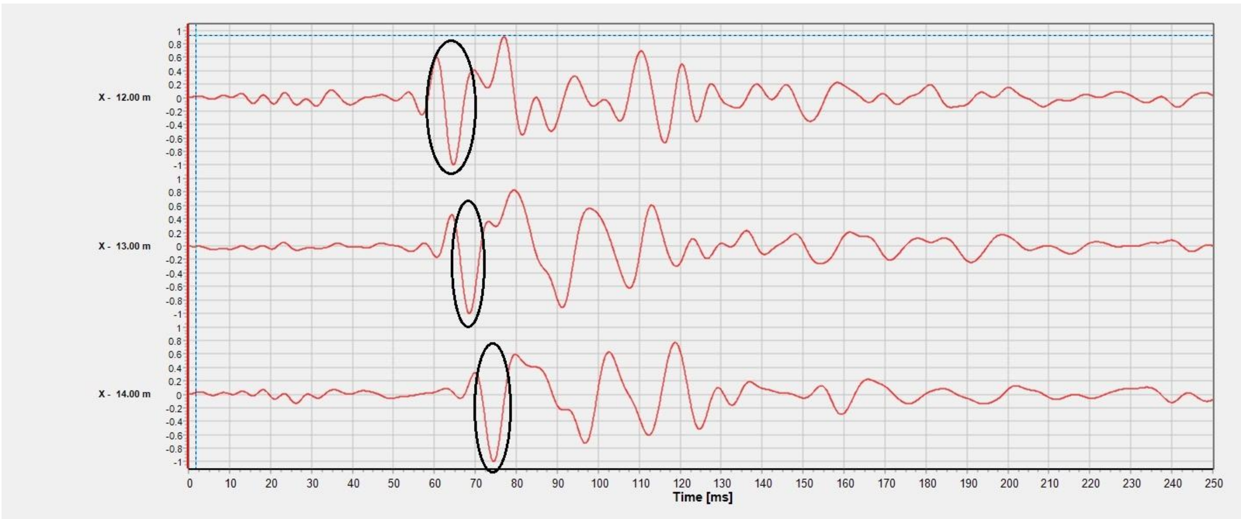


Figure 20: Recorded traces between 12 m and 14 m [SSP PSD CCC 2]

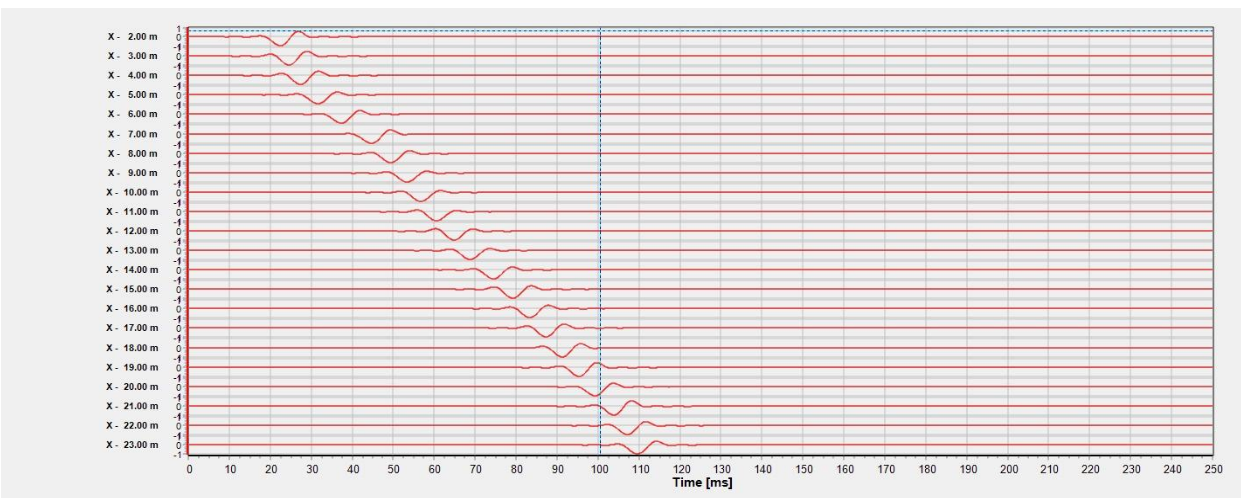


Figure 21: Filtered VSP after signal feature decay [SSP PSD CCC 2]

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

Signal Feature Decay can be applied more broadly in scenarios where you have low SSP and/or CCC and/or PSD. As stated before the main goal is to isolate a source wave signature or feature which has minimal interference. In Figure 22 a filtered (200Hz low pass) VSP is shown with the corresponding SSP, CCC and PSD trace metrics outlined in Table 7, 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 red line in Figure 22 clearly identifies the first trough responses in the entire VSP.

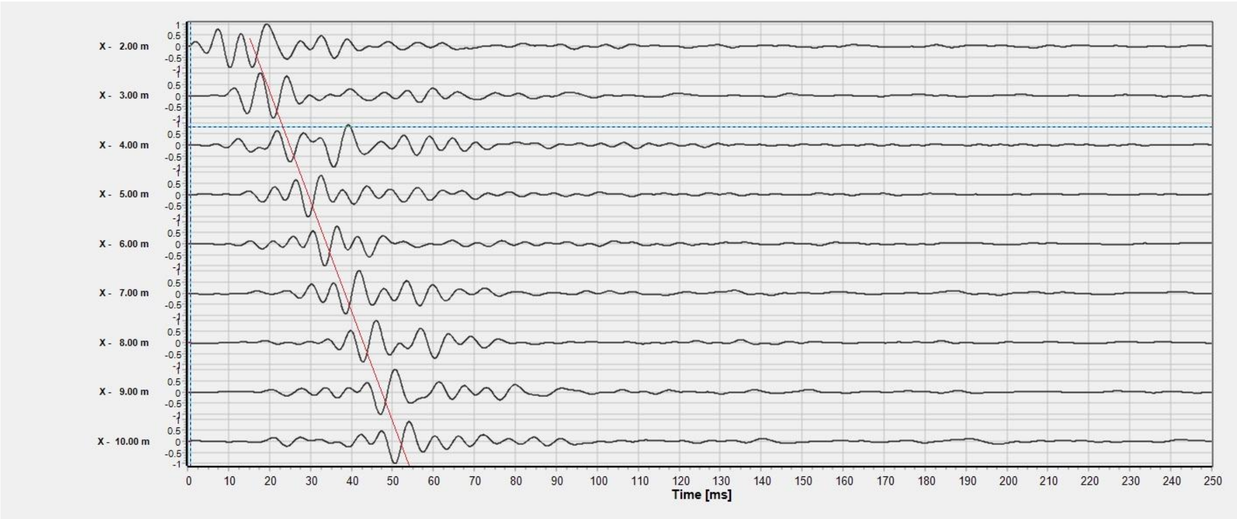


Figure 22: Filtered VSP with the first trough trend line [SSP PSD CCC 3]

Table 7. SSP, CCC and PSD Values for Test Case 7

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

The VSP below shows the isolation of the previously identified first trough response by utilizing SDF.

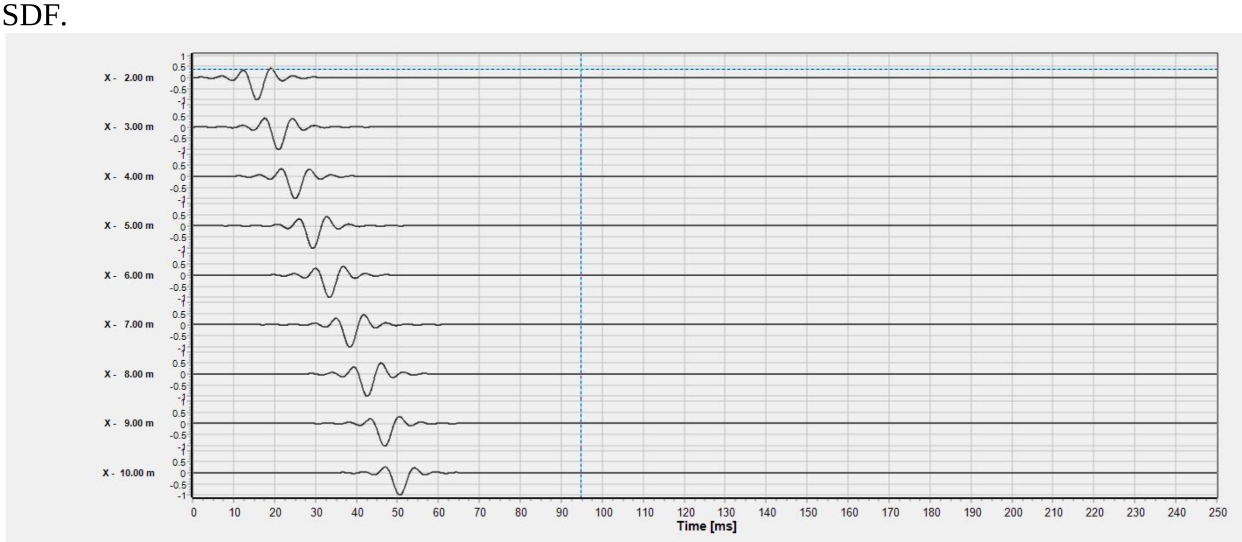


Figure 23: Filtered VSP after signal feature decay [SSP PSD CCC 3]

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

In certain cases the entire VSP shows evidence of interference. 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 Figure 24, where there is evidence of significant source wave distortions throughout the source wave responses. Table 8 outlines the corresponding SSP, CCC and PSD trace metrics.

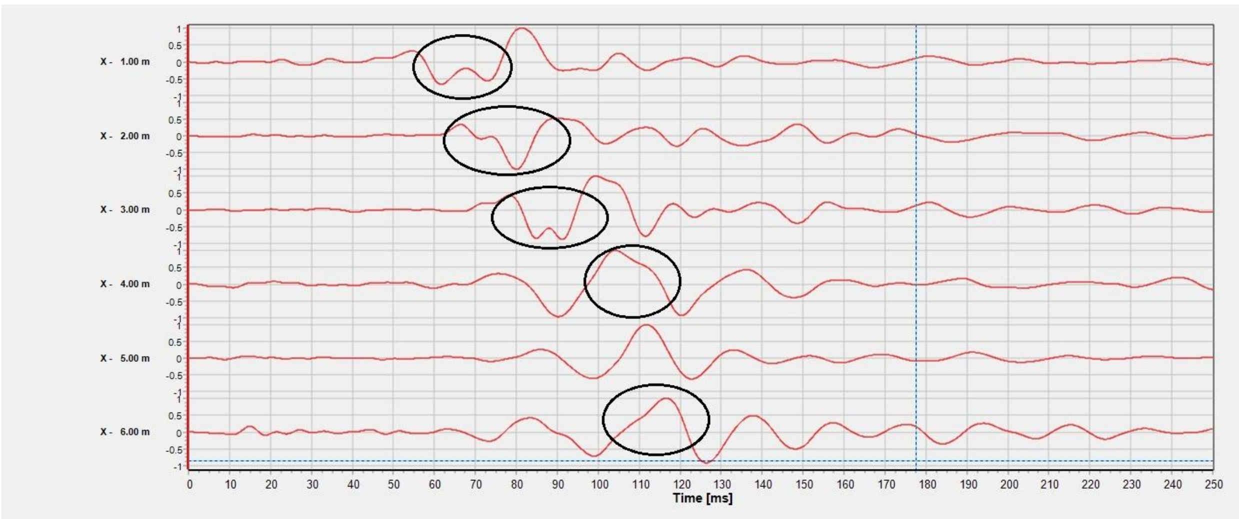


Figure 24: Filtered VSP with the evidence of interference at all depths [SSP PSD CCC 4]

Table 8. SSP, CCC and PSD Values for Test Case 8

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

Figure 25 then shows the data set after applying an aggressive 120Hz low pass filter and SDF on the "smoothed" second peak responses. It should be noted that for even more distorted seismic traces BCE has developed blind seismic deconvolution techniques to increase source wave quality in heavy noise environments.

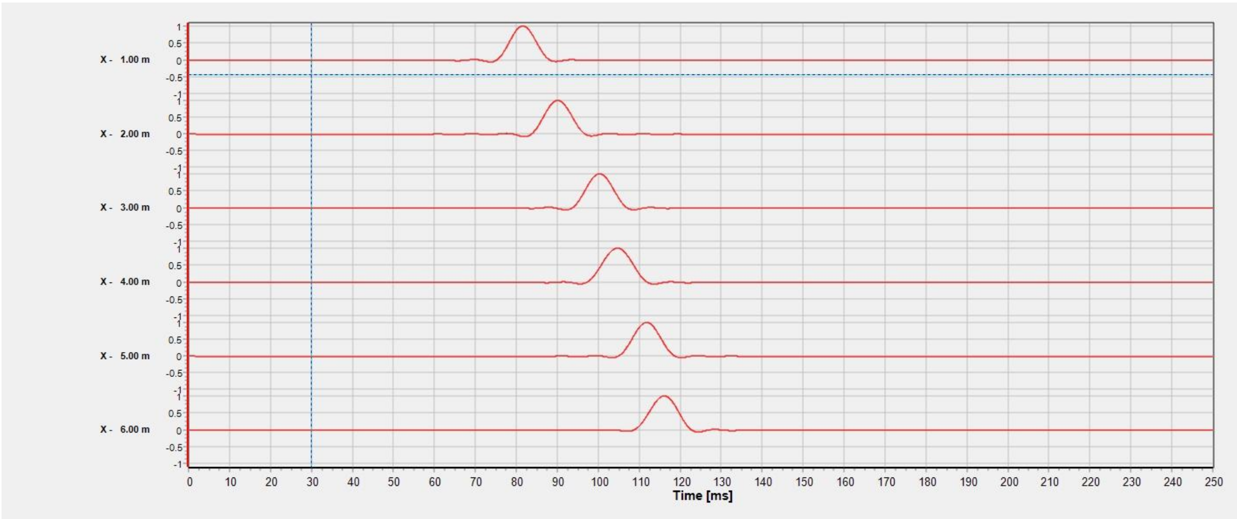


Figure 25: Aggressively filtered VSP after signal feature decay [SSP PSD CCC 4]

Parameter 5: Signal to Noise Ratio (SNR)

The SNR trace metric is currently 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". At this time it is not used to guide the investigator during data analysis as BCE is still in the process of developing the most appropriate response.

The reason that this parameter is included is partly due to the fact that the same parameters used for seismic trace characterization as also used for seismic acquisition characterization, and there the SNR is a very important parameter.

Erick Baziw
Gerald Verbeek

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