Deriving absorption values with Downhole Seismic Testing data

When the absorption is calculated with crosshole seismic test data the Spectral Ratio Technique (SRT) is often applied. The SRT governing equations are outlined below in eq. (1a) to (1c). In these equations $u(z,\omega)$ and $u(z,\omega)$ denote the frequency spectrums ($\omega = 2\pi f$ where f is the frequency) of the traces recorded at depths or distance z and z_0 (where z > z_0), respectively. Q is the desired Quality Factor, T_T is the non-dispersive travel time difference between z and z_0, V is non-dispersive interval velocity for the seismic traveling from z_0 to z, SL is the Spectral Slope, λ is the source wave's wavelength, and α is the absorption coefficient.

$$\ln\left|\frac{u(z,\omega)}{u(z_0,\omega)}\right| = -\frac{\omega(z - z_0)}{2VQ} = -\frac{\omega T_T}{2Q} \tag{1a}$$

$$Q = \left|\frac{T_T}{2 \times SL}\right|, \qquad SL = \ln\left|\frac{u(z,\omega)}{u(z_0,\omega)}\right| \Big/ \omega \tag{1b}$$

$$\alpha = \frac{\pi}{Q\lambda} \tag{1c}$$

What is not necessarily emphasized is that SRT assumes that the source waves travel along the same path. While this is the case for crosshole seismic testing (as shown in Fig. 1), it is not the case for downhole seismic testing. As outlined in Technical Note 1, source wave trajectories adhere to *Fermat's principle*, which means that the raypath travels along the trajectory that minimizes the travel time between points, and that means that every depth the raypath will be different as shown in Fig.2.

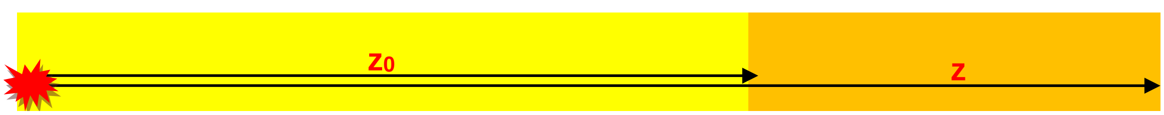

Figure 1. Assumed source wave travel paths when implementing SRT.

Apart from issues associated with the raypath, there is another issue: frequency domain absorption estimation techniques, such as SRT, can be highly susceptible to additive measurement noise. This is best explained with an example. Fig. 3 shows a wave (Wave 1) with a dominant frequency of 55 Hz that is assumed to be recorded at a vertical depth of 5m with a seismic source radial offset (X in Fig. 2) of 1.5m. Assuming that this wave travels through soil with a Q value of 30 Np^{-1}, a relative geometric spreading value of 0.5 and a shear wave velocity of 153 m/s, the wave will reach a depth of 10 m 32 ms later (Wave 2).

Figure 4 illustrates the output after applying the SRT on the traces illustrated in Fig. 3 and as is shown the derived Q value of 31.2 Np^{-1} is very close to the true value of 30 Np^{-1}. However, if a small amount of low frequency measurement noise is applied to Wave 1 and 2 (as illustrated in Fig. 5) the derived results change dramatically as shown in Fig 6: now the derived Q value of 6 Np^{-1} deviates significantly from the true Q value of 30 Np^{-1}.

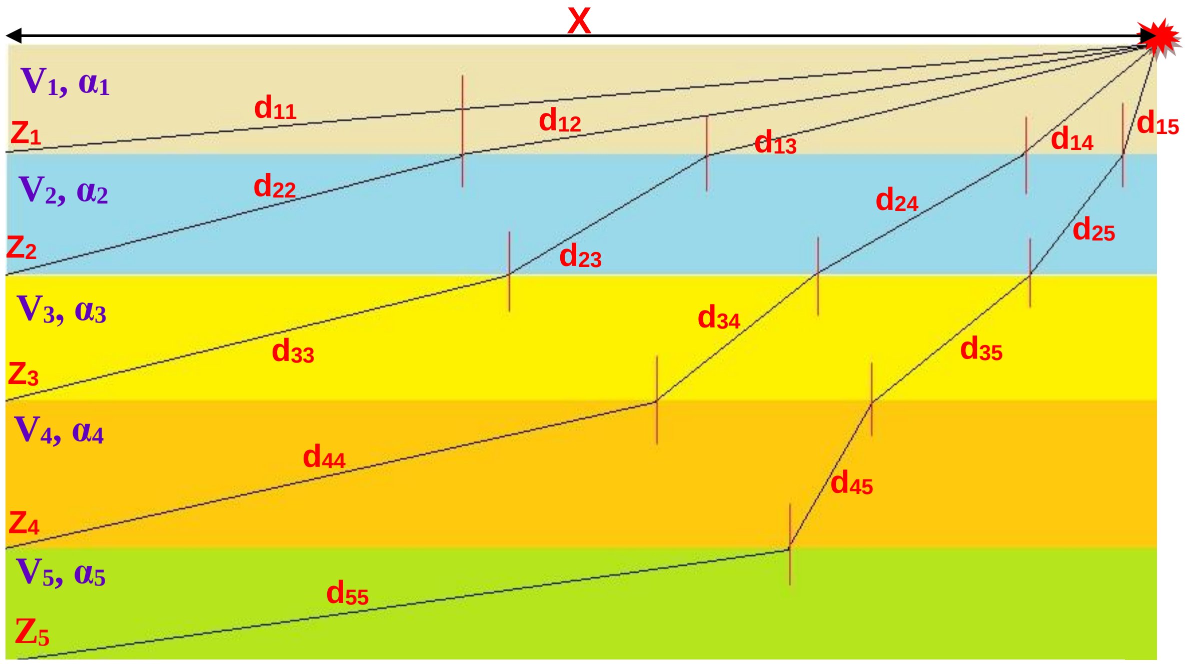

Figure 2. Near surface DST where SRT assumptions are not valid.

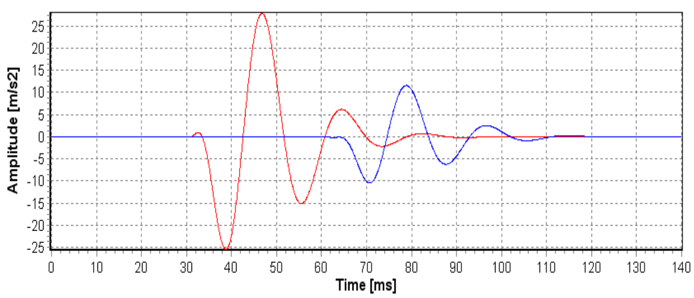

Figure 3. Source Wave 2 (in blue) superimposed on Source Wave 1 (in red) with 32 ms time offset.

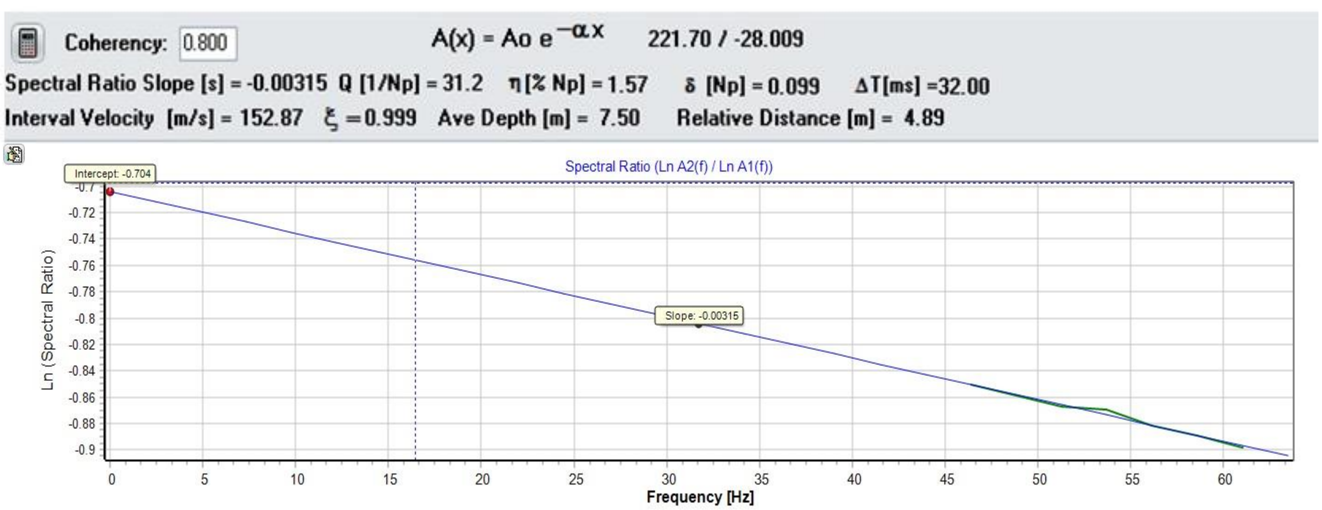

Figure 4. Output from SRT when processing the traces illustrated in Fig. 3. The estimated Q of 31.2 Np^{-1} is very close to the true Q value of 30 Np^{-1}.

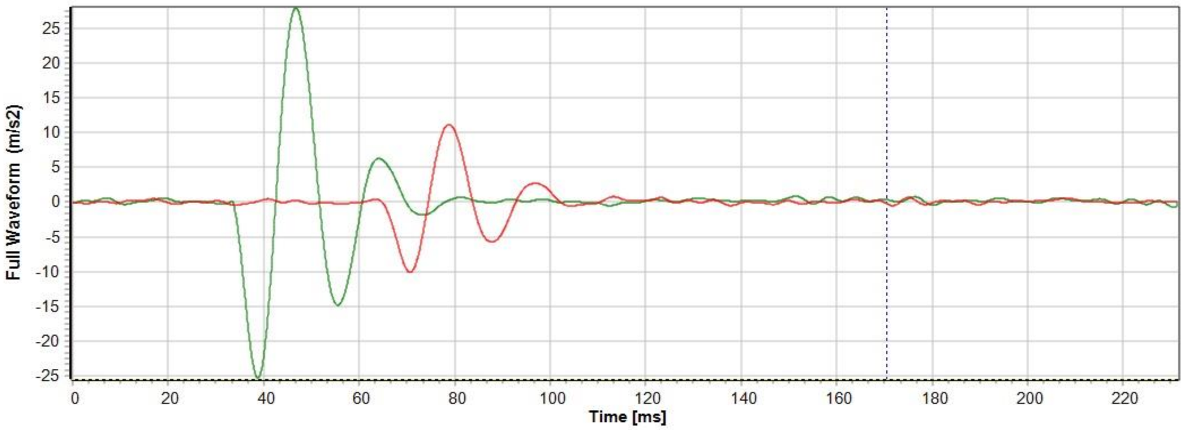

Figure 5. Traces illustrated in Fig. 3 with a small amount of additive measurement noise applied.

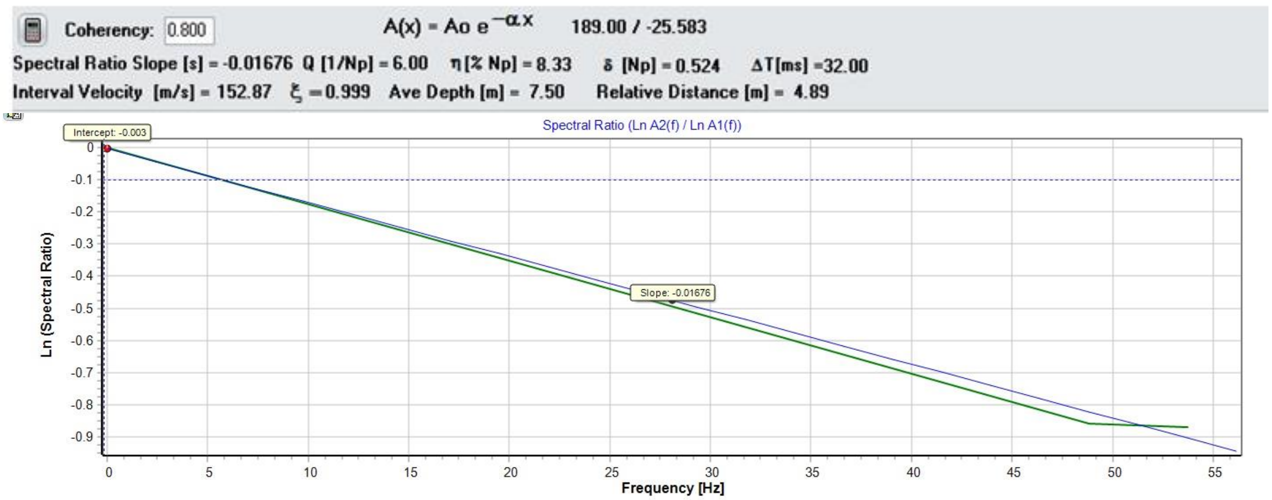

Figure 6. Output from SRT when processing the traces illustrated in Fig. 5. The estimated Q of 6 Np^{-1} deviates significantly from the true Q value of 30 Np.

Figures 7 and 8 illustrate a real data example of the challenges of applying the SRT. In this real data example SCPT seismic traces are acquired at depths of 3m and 15m as illustrated in Fig. 7. As is evident in Fig. 7, the maximum amplitude of the 3m traces is orders of magnitude greater than that of the 15m seismic trace. Figure 8 illustrates the results after applying the SRT on the traces illustrated in Fig. 7. The SRT gives a nonsensical estimated Q of -66 Np^{-1}. This implies that there was an increase in amplitude due to absorption as the source wave travelled to greater depths.

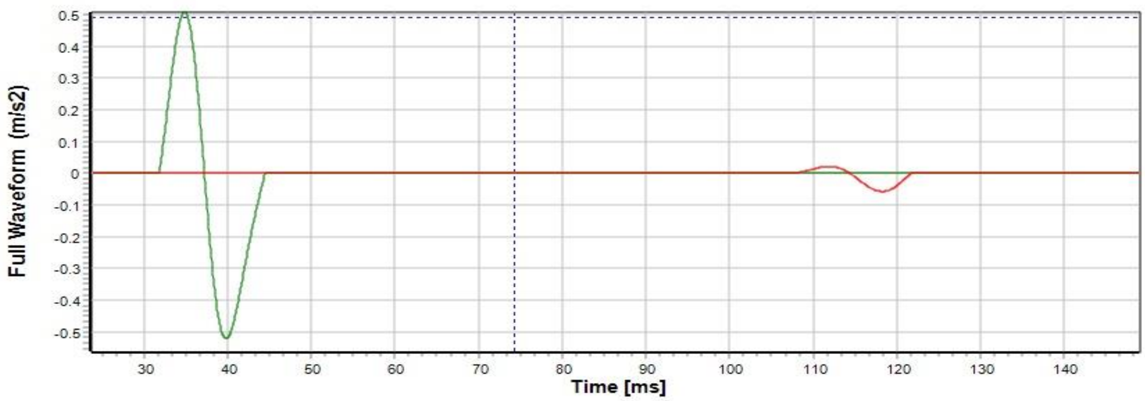

Figure 7. Real SCPT data with seismic traces acquired at 3m (green) and 15m (red).

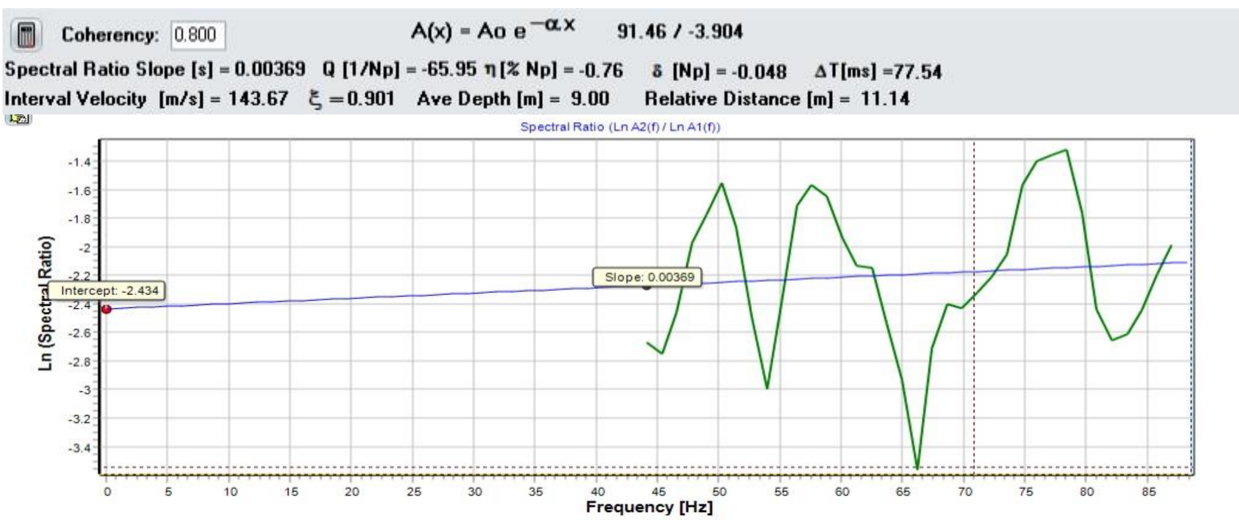

Figure 8. Output from SRT when processing the traces illustrated in Fig. 7. The SRT gives a nonsensical estimated Q of -66 Np^{-1}.

To address these shortcomings BCE has developed a new algorithm: FMDSMAA, which is described in Technical Note 23. This algorithm applies the Forward Modeling/Downhole Simplex Method (FMDSM) to ensure that the assumed raypaths are as accurate as possible and then applies an Absorption Analysis (AA) that uses the absolute value of the full waveform amplitude as outlined in eq. 2.

$$|\rho(t)| = \sqrt{(X(t))^2 + (Y(t))^2 + (Z(t))^2} \qquad (2)$$

where X(t), Y(t) and Z(t) are the orthogonal seismic sensor responses. The maximum $|\rho(t)|$ value is determined over the time window of the source wave responses. For SH wave analysis the Z(t) component can theoretically be ignored. It should be noted that it is significantly simpler to obtain the full source waveform maximum amplitude as opposed to rotating the X(t), Y(t) and Z(t) responses onto the full waveform, which is required for the SRT. Source wave distortion can occur during rotation onto the full waveform for low linearity traces. This can result in frequency distortion and poor SRT results as previously illustrated.

The FMDSMAA technique takes significant soil structure into account where up to eight absorption values (eight layers) are estimated simultaneously along with the geometric spreading exponent. This requires that the FMDMSAA technique utilize several estimated in-situ parameters such interval velocities, source wave travel paths, angles of incidence and reflection, density, and source wave amplitudes when estimating absorption values. The FMDSMAA technique provides for an error estimate and allows for specification of minimum and maximum Q values in the optimal search algorithm. The error estimate is the residual between the synthetic and measured amplitude ratios for each depth increment. The SRT estimates each layer's absorption value independently and only requires the source wave responses at two depth increments.

We recommend that for absorption estimates the results of FMDSMAA and SRT are compared to gain confidence in the derived results.

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