Identifying critical layers using SCPT and seismic source moveout

Erick Baziw and Gerald Verbeek
Baziw Consulting Engineers Ltd., Vancouver, Canada

ABSTRACT: In Seismic Cone Penetration Testing (SCPT) the investigator typically attempts to minimize the source-sensor radial offset so that the Straight Ray Assumption (SRA) methodology can be utilized to calculate interval velocities. The basic assumption behind the SRA methodology is that the source raypath follows a trajectory with no or minimal refraction. However, a small sensor-source offset makes it very difficult to identify thin soil layers with significant impedance contrast. The probability of identifying and quantifying such layers utilizing SCPT can be dramatically increased by applying large sensor-source offsets and analysis techniques that incorporate Fermat's principle. This paper shows that by implementing larger sensor-source offsets the source wave can refract and travel within relatively high velocity critical layers for an extended time, which dramatically increases the characterization of the layer or depth under analysis. In addition, this set-up allows for greater SCPT vertical resolution because small depth increments are feasible.

1 INTRODUCTION

Seismic Cone Penetration Testing (SCPT) is an important geotechnical testing technique which provides for low strain ($<10^{-5}$) *in-situ* compression (V_P) and shear (V_S) wave velocity estimates. The V_S and V_P interval velocities form the core of mathematical theorems to describe the elasticity/plasticity of soils and they can be used to predict soil response (settlement, liquefaction or failure) to imposed loads (whether from foundations, heavy equipment, earthquakes or explosions) (Finn, 1984; Andrus et al. 1999; Ishihara, 1982). Accuracy in the estimation of shear and compression waves velocities is of paramount importance, because these values are squared during the calculation of various geotechnical parameters such as the Shear Modulus (G), Poisson's Ratio (μ) and Young's modulus (E). For example, from elasticity theory we know that the formula for the maximum shear modulus is $G_0 = \rho V_S^2$, where ρ is the soil density and V_S is the shear wave velocity.

In SCPT the source wave travels through the stratigraphic profile being refracted at layer boundaries as illustrated in Figure 1. In this figure the angle θ_2 is called the angle of refraction and θ_1 the angle of incidence. Equation (1) defines the relation between θ_1, θ_2, v_1 and v_2. This equation is referred to as *Snell's Law* and is derived from *Fermat's principle,* which states that a wave will take that raypath for which the travel time is stationary with respect to minor variations of the raypath.

$$Sin\ \theta_1 / v_1 = Sin\ \theta_2 / v_2 = p \tag{1}$$

In eq. (1) the quantity p is called the raypath parameter. In Figure 1, V_1 to V_{n+1} represent the consecutive vertices of the seismic ray as it travels from source to the receiver. In eq. (1), if v_2 is less than v_1, then

θ_2 is less than θ_1. However, when v_2 is greater than v_1, θ_2 increases to 90° when θ_1 reaches the critical angle. The critical angle, Θ, is defined as the angle where $\theta_2 = 90^\circ$ and the refracted wave (head wave) is travelling along the interface.

$$\Theta = Sin\ \theta_1 = Sin^{-1}\left(\frac{v_1}{v_2}\right) \tag{2}$$

When a P-wave or SV-wave strikes a boundary both SV-waves and P-waves are reflected and refracted. A SH-wave will only generate refracted and reflected SH-waves at boundaries. The general form of Snell's Law for a P-wave impacting an interface is given as (Shearer, 1999; Sheriff and Geldart, 1982)

$$\frac{Sin\theta_1}{v_{P1}} = \frac{Sin\theta_1^{/}}{v_{P1}} = \frac{Sin\theta_2}{v_{P2}} = \frac{Sin\delta_1}{v_{SV1}} = \frac{Sin\delta_2}{v_{SV2}} = p \tag{3}$$

where θ_1 = the P-wave angle of incidence, $\theta_1^{/}$ = the P-wave angle of reflection, θ_2 = the P-wave angle of refraction, δ_1 = the S-wave angle of reflection, δ_2 = the S-wave angle of refraction, v_{P1} and v_{SV1} = the P-wave and S-wave velocities in medium 1, respectively, and v_{P2} and v_{SV2} = the P-wave and S-wave velocities in medium 2, respectively.

In SCPT the v_S and v_P interval velocities are determined by initially obtaining relative arrival times of source waves as they travel through the stratigraphy and are recorded by one or more offset receivers. The relative arrival times are typically obtained by cross-correlating the recorded source waves or identifying reference features within the seismic trace such as a peak, trough, cross-over point, or first break.

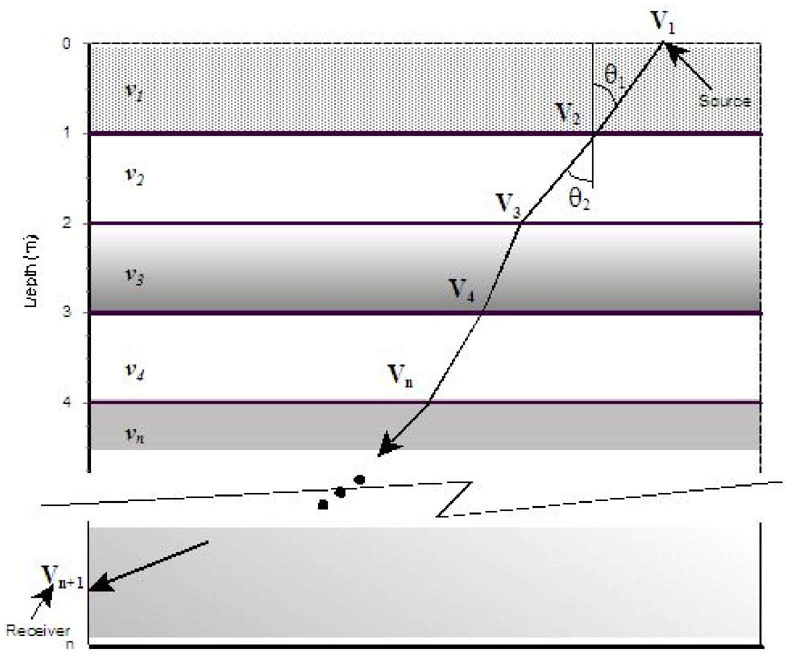

Figure 1. Refraction of a source wave as it travels from source to receiver

Currently the industry standard in obtaining v_S and v_P interval velocities from the relative arrival times is to assume a vertical straight ray travel path from source to receiver. Figure 2 shows a schematic of a typical SCPT configuration. In Figure 2 the interval velocity, v_i, between depth increments z_i and z_{i-1} is given as

$$v_i = (d_i - d_{i-1})/(t_i - t_{i-1}) \tag{4}$$

where t_i and t_{i-1} = the arrival times of the source wave at depths z_i and z_{i-1}, respectively. The calculation of the v_S and v_P interval velocities by eq. (4) is typically referred to as the *Straight Ray Assumption* (*SRA*) methodology. The main assumptions behind this methodology are that the source raypath follows a nearly straight path with no or minimal refraction, and that the down going rays spend an equal amount of time or have the same travel path within each previous interval layer. Investigators typically structure the SCPT configuration so that source radial offset (parameter *l* in Figure 2) is minimized so that the acquired seismic data adheres to the *SRA* assumptions. However, this approach has distinct disadvantages:

- the source wave travels predominantly within the zone that has been disturbed by pushing the receiver(s) into the ground;
- the source wave spends minimal time within each layer resulting in nominal strata layer characterization;
- estimating interval velocities for small interval measurements is very challenging;
- characterizing thin critical layers with (relatively) high wave speed velocities is very difficult;

In addition to these disadvantages there is the issue of Rod Noise (RN), which refers to seismic responses dominated by high impact amplitudes and high bandwidth signals traveling (at approximately the speed of steel (5960m/s)) down the rods used to push the receiver into the ground. This phenomenon typically occurs if the seismic source is in close proximity to the SCPT rods. Figure 3 illustrates the rod noise phenomenon where there is high bandwidth energy at the start of the X, Y and Z axes recordings for a SH wave investigation.

In contrast to the commonly held view that it is desirable to apply minimal sensor-source radial offsets (SSROs), and to overcome the disadvantages listed above it is in fact preferable to maximize this parameter, as long as the proper analytical algorithms for estimating the interval velocities (i.e. algorithms that allow for the incorporation of Snell's Law) are implemented (e.g., Baziw (2002 and 2004) and Baziw & Verbeek (2012))

By implementing large sensor-source radial offsets the source wave can refract and travel within high velocity critical layers for an extended time, which significantly increases the characterization of these types of layers. In addition, this set-up allows for greater SCPT vertical resolution because small depth increments are feasible.

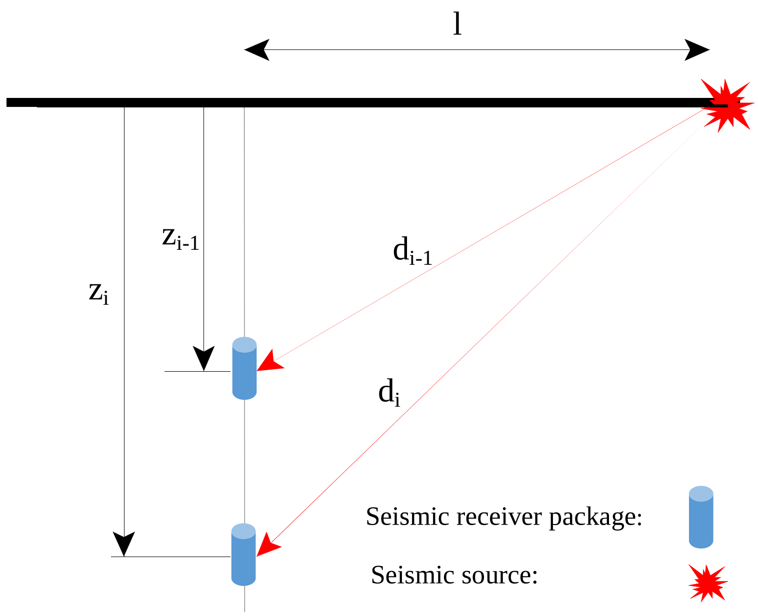

Figure 2. Schematic of a typical SCPT configuration.

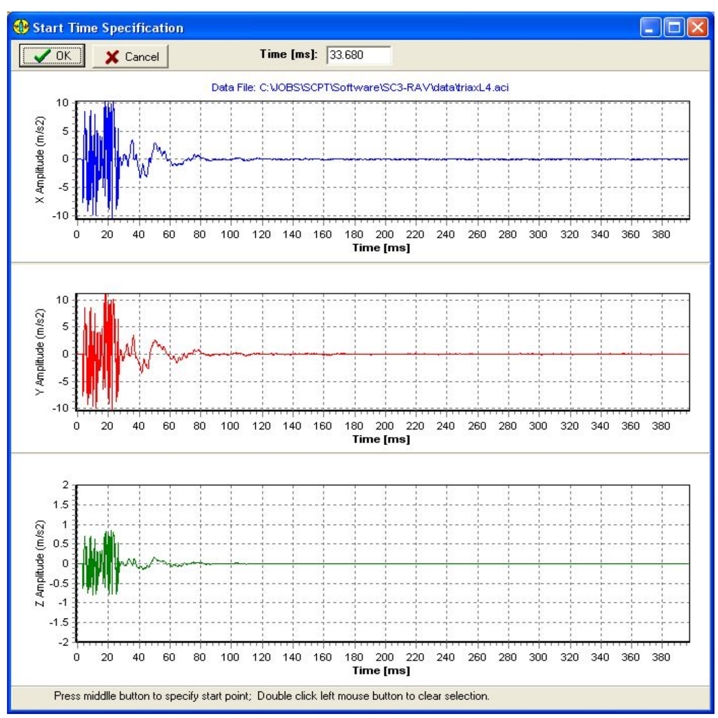

Figure 3. Illustration of high impact amplitudes and high bandwidth signals due to rod noise during a SCPT

2 TEST CASES

In the following two test cases the advantages of implementing relatively large SSROs in conjunction with raypath refraction is demonstrated. In the first test case a simulated P-wave investigation is outlined where the investigator desires to have an indication of the depth of the ground water table. Test Case 2 outlines a simulated S-wave SCPT carried out in diluvial sands where a relatively high S-wave interval velocity layer is embedded within lower S-wave interval velocity layers.

2.1 *Test Case 1*

Test Case 1 outlines a simulated P-wave SCPT where the investigator is interested in obtaining an accurate depth of the ground water table. This P-wave SCPT has variable increment depths where very small increments were incorporated into the test, and a SSRO of 4 m. The soil profile is described as follows:

- depth interval 0 m to 3.8 m: unsaturated sand
- the water table occurs just beyond 3.8 m
- depth interval 3.8 m to 5.0 m: saturated sand
- depth interval 5.0 m to 6.0 m: stiff impermeable clay layer
- depth interval 6.0 m to 7.0 m: low velocity unsaturated sand layer.

Table 1. P-wave test SCPT interval depths and associated arrival times and interval velocities.

Interval Depth [m]	**Arrival Time [ms]**	**Interval Velocity [m/s]**
0-1.5	7.12	600
1.5-2.0	7.45	601
2.0-2.5	7.86	599
2.5-3.0	8.33	601
3.0-3.5	8.86	598
3.5-3.8	9.20	597
3.8-4.1	8.85	1517
4.1-4.4	8.85	1469
4.4-4.7	8.87	1532
4.7-5.0	8.91	1578
5.0-6.0	8.93	2216
6.0-7.0	11	443

Table 1 outlines the associated arrival times for each depth increment of this P-wave SCPT, from which the interval velocities were obtained by applying the Forward Modeling Downhill Simplex Method (FMDSM) (Baziw (2002 and 2004) and Baziw & Verbeek (2012)), which incorporates Snell's Law. These interval velocities shown in Table 1 coincide very well with the typical P-wave velocities given in Table 2.

Figure 4 illustrates the associated source wave raypaths for the arrival times and interval velocities outlined in Table 1. It is obvious that there is significant refraction and that the source waves travel within each layer (e.g., the saturated critical layer) for an extended time, which dramatically increases the stratigraphic profile characterization.

From the arrival times outlined in Table 1 it is clear that it would not be possible to implement the SRA methodology on the measured arrival times. In this case the relative arrival times at certain depth increments are negligible or negative making the application of eq. (4) not possible. If a SSRO = 1m had been implemented in this test case there would have been a theoretical relative arrival between 3.8m and 4.1m of 0.191ms. This assumes that there is a vertical straight ray travel path with slant distances of 3.93m and 4.22m (note: $\Delta t_i = (d_i - d_{i-1})/v_i =$ (4.22-3.93) / 1517). Given the short travel time (and consequently travel path) of the source wave within this layer, any minor measurement error in the relative arrival time will result in a very large error in the corresponding interval velocity. For example, a -0.05 ms error in the relative arrival time (0.141 instead of 0.191 ms) would generate a SRA interval velocity of (.29*1000/0.141) or 2057 m/s for a corresponding error of 26 %. If on the other hand we incorporate the same error in the arrival time at 4.1 m listed in Table 2 (8.85 ms) the FMSDM estimated interval velocity between 3.8m and 4.1m would be 1623 m/s for a corresponding error of only 7%, which is significantly lower

Table 2. Typical P-wave Velocities (after Press (1966))

Unconsolidated Materials [m/s]	
Weathered layer	300-900
Soil	250-600
Alluvium	500-2000
Clay	1100-2500
Sand	
Unsaturated	200-1000
Saturated	800-2200
Sand and Gravel	
Unsaturated	400-500
Saturated	500-1500
Glacial till	
Unsaturated	400-1000
Saturated	1700
Compacted	1200-2100

Consolidated Materials [m/s	
Granite	5000-6000
Basalt	5400-6400
Metamorphic rocks	3500-7000
Sandstone and shale	2000-4500
Limestone	2000-6000

Other [m/s]	
Water	1400-1600
Air	331.5
Steel	5960

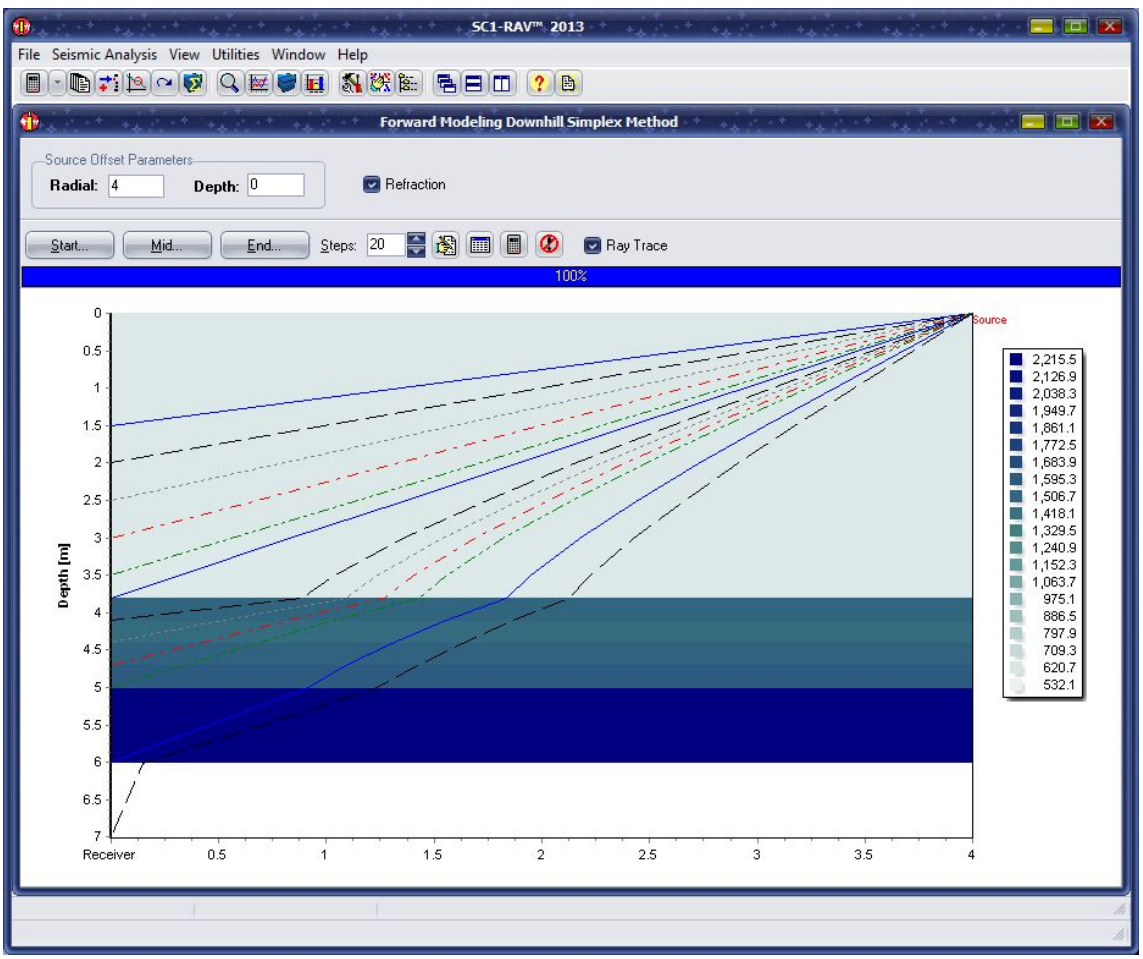

Figure 4. Source wave raypaths taking into account Snell’s Law for the P-wave SCPT data outlined in Table 1.

2.2 *Test Case 2*

Test Case 2 outlines a simulated S-wave SCPT carried out in diluvial sands where a relatively higher S-wave interval velocity layer is embedded within lower SH interval velocity layers. In this SH-wave test it is assumed that S-wave velocities vary between 230 ms and 310 m/s. A relatively high velocity layer resides between depths 3.5m to 4m. The SCPT data acquisition depth interval is set at 0.5m, and the SSRO for this test case was again set to 4.0 m.

Table 3 outlines the associated arrival times for each depth increment of this S-wave SCPT. Applying the FMSDM gives the interval velocities that are also shown in Table 3. From the arrival times it is again clear that it would not be possible to implement the SRA methodology on the measured arrival times for a SSRO = 4m. For example, there is a negative relative arrival time between the depths of 3.5m and 4m.

Table 3. S-wave test SCPT interval depths and associated arrival times and interval velocities

Interval Depth [m]	Arrival Time [ms]	Interval Velocity [m/s]
0-1.0	13.9	297
1.0-1.5	14.5	290
1.5-2.0	15.9	236
2.0-2.5	16.7	293
2.5-3.0	17.7	285
3.0-3.5	18.6	309
3.5-4.0	18.0	589
4.0-4.5	19.4	285

Figure 5 illustrates the associated source wave raypaths for the arrival times and interval velocities outlined in Table 3, showing significant refraction for the interval velocity between 3.5m and 4.0m. This significantly increases the stratigraphic profile characterization.

If a SSRO = 1m had been implemented in this test case there would have been a theoretical relative arrival between 3.5m and 4.0m of 0.820ms. This assumes that there is a vertical straight ray travel path with slant distances of 3.64m and 4.12m (note: $\Delta t_i = (d_i - d_{i-1})/v_i =$ (4.12-3.64) / 589). This small relative arrival time would again result in the same significant error in the interval velocity in case of a minor measurement error. For example, a -0.2 ms error in the relative arrival time (0.62 instead of 0.82 ms) would generate a SRA interval velocity of (.483*1000/0.62) or 779 m/s for a corresponding error of 32 %. The error of 0.2ms was incorporated into the S-wave test due to the fact that S-wave have much lower rise times and bandwidths than P-waves resulting in a lower signal definition. If on the other hand we incorporate the same error in the arrival time at 4.0 m listed in Table 3 (18.0 ms) the FMSDM estimated interval velocity between 3.5 m and 4.0 m would be 638 m/s for a corresponding error of approx. 8 %, which is again significantly lower

3 CONCLUSIONS

To address the *SRA* requirements, many contractors typically attempt to minimize the sensor-source radial offset (SSRO) in a SCPT. Small SSROs have inherent disadvantages: rod noise is a concern, the source wave travels predominantly within the disturbed zone near the push rods; the source wave spends minimal time within each layer resulting in nominal strata layer characterization; estimating interval velocities for small interval measurements is very challenging; and characterizing thin high velocity sensitive layers is very difficult. In addition, soft surface layers require high SH-wave hammer impacts to ensure that sufficient source energy is generated for deeper depths, but these higher hammer impacts dramatically compound rod noise for small SSROs, which may very well result in unusable seismic data.

It has been shown that by applying relatively larger SSROs the source wave can refract and travel within high velocity critical layers for an extended time, which significantly increases the characterization of these types of layers. In addition, the application of relatively larger SSROs mitigates the previously outlined small SSRO disadvantages.

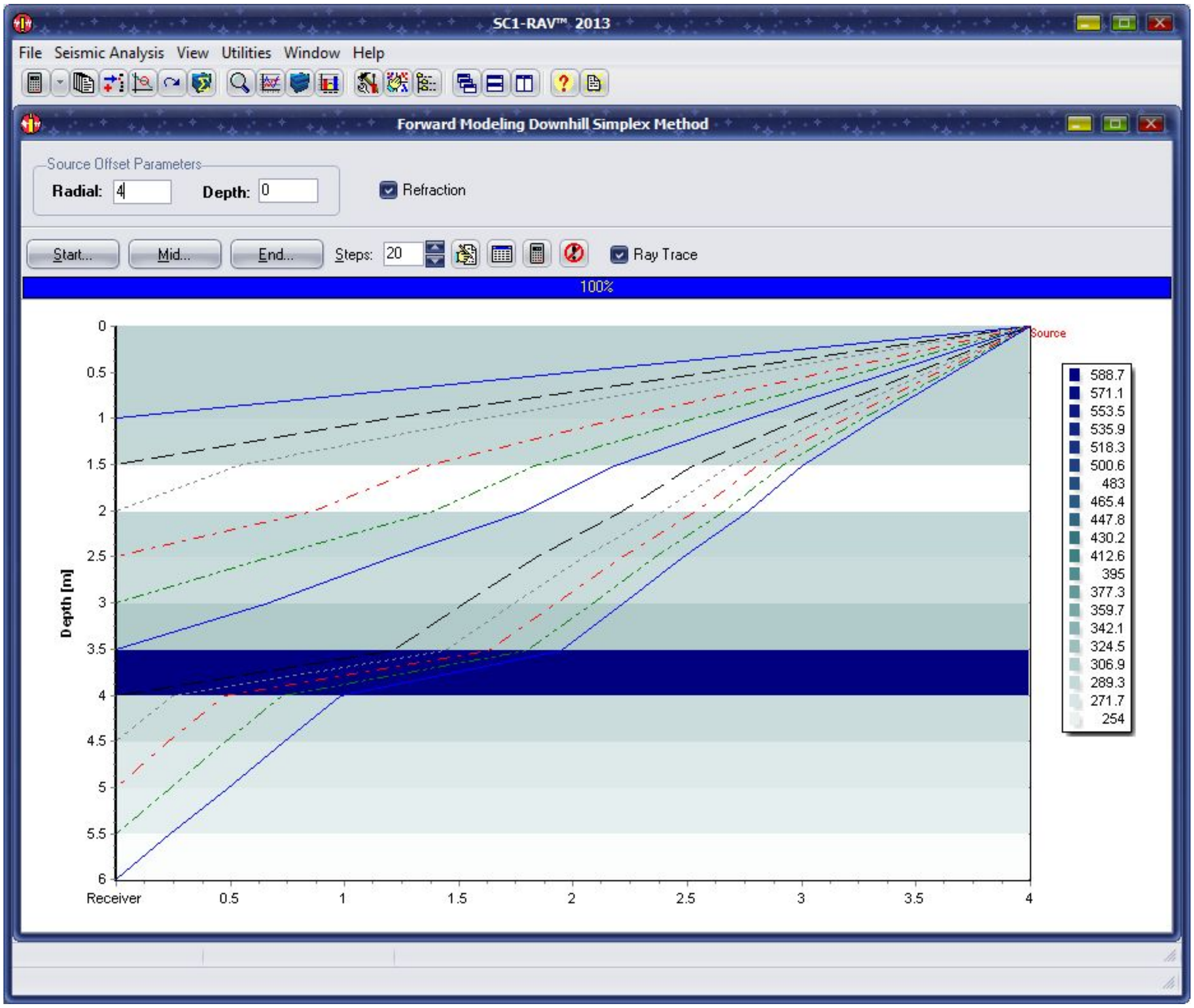

Figure 5. Source wave raypaths taking into account Snell's Law for the S-wave SCPT data outlined in Table 3.

The selection of the SSRO is dependent on several factors such as surface material, source-soil coupling for a SH hammer beam type source, and variability of the soil profile under investigation. The last factor is difficult to ascertain as the variability of the soil profile is only known after the SCPT test is complete. However, based upon our experience a minimal SSRO of 2 m should be applied.

Obviously when applying a larger SSRO the implementation of Snell's Law of refraction must be taken into account when deriving interval velocities from SCPT data, especially for depths less than 5 times the SSRO.

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