# APPENDIX K

## Technical Memorandum – Results of VSP Testing

# TECHNICAL MEMORANDUM

**DATE** March 2013 **PROJECT No.** 12-1125-0045

**VSP TEST RESULTS – CRRRC SITE, OTTAWA, ONTARIO**

This memorandum presents the results of the vertical seismic profile (VSP) testing performed at the Capital Region Resource Recovery Centre (CRRRC) Site (Site) located in the eastern portion of the City of Ottawa. VSP testing was completed in BH-12-2-3 and BH-12-3-3 on February 20 and 21, 2013. Both boreholes were cased with a PVC pipe grouted in place, which extended above ground surface. Borehole BH-12-2-3 consists of about 36.7 metres of overburden overlying limestone bedrock. The overburden consists of approximately 34.6 metres of clay to silty clay overlying about 2.2 metres of sand and silt. Borehole BH-12-3-3 consists of approximately 39.8 metres of overburden overlying shale bedrock. The overburden consists of about 34.1 metres of clay to silty clay overlying about 5.7 metres of sand to sandy silt.

## Methodology

For the VSP method, seismic energy is generated at the ground surface by an active seismic source and recorded by a geophone located in a nearby borehole at a known depth (Figure 1). The methodology can be applied using an active seismic source that produces either compression or shear waves. The time required for the energy to travel from the source to the receiver (geophone) provides a measurement of the average compression or shear wave seismic velocity of the medium between the source and the receiver. Data obtained from different geophone depths are used to calculate a detailed vertical seismic velocity profile of the subsurface in the immediate vicinity of the test borehole.

The high resolution results of a VSP survey are often used for earthquake engineering site classification, as per the National Building Code of Canada, 2010.

## Field Work

The field work was completed on February 20$^{th}$ and 21$^{st}$, 2013, by personnel from the Golder Ottawa offices.

Both compression and shear wave seismic sources were measured using a source located in close vicinity to the borehole. The seismic source for the compression wave test consisted of a 9.9 kilogram sledge hammer vertically impacted on a metal plate, located 2 metres from the borehole. The seismic source for the shear wave test consisted of a 3.0 metres long, 150 millimetres by 150 millimetres wooden beam, weighted down by a vehicle and horizontally struck with a 9.9 kilogram sledge hammer on alternate ends of the beam to induce polarized shear waves. The shear sources were located 2 metres from the borehole. Test measurements started at ground surface and were recorded in the borehole with a 3-component receiver spaced at 1-metre intervals below the ground surface, to a maximum depth of the borehole (40.2 metres in borehole BH-12-2-3 and 44.3 metres in borehole BH-12-3-3).

The seismic records collected for each source location were stacked a minimum of ten times to minimize the effects of ambient background seismic noise on the collected data. The data was sampled at 0.020833 millisecond intervals and a total time window of 0.341 seconds was collected for each seismic shot.

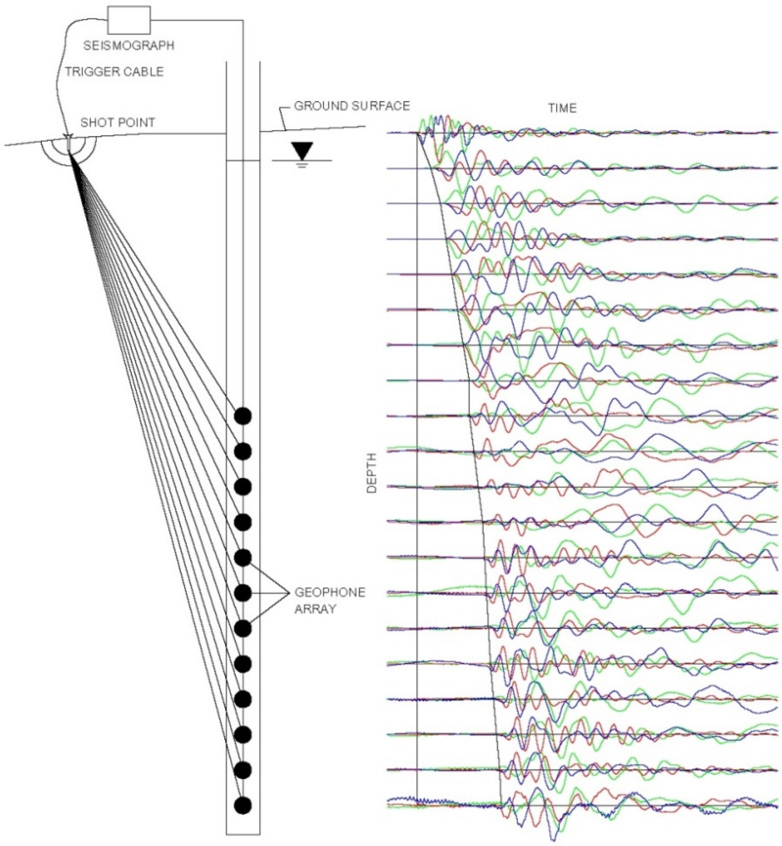



*Figure 1: Example of Layout and resulting time traces from a VSP survey*

## Data Processing

Processing of the VSP test results consisted of the following main steps:

1) Combination of seismic records to present seismic traces for all depth intervals on a single plot for each seismic source and for each component;
2) Low Pass Filtering of data to remove spurious high frequency noise;
3) First break picking of the compression and shear wave arrivals; and,
4) Calculation of the average compression and shear wave velocity to each tested depth interval.

Processing of the VSP data was completed using the SeisImager/SW software package (Geometrics Inc.). The seismic records are presented on the following four plots and show the first break picks of the compression wave and shear wave arrivals for both boreholes overlaid on the seismic waveform traces recorded at the different geophone depths (Figures 2 to 5). The arrivals were picked on the vertical component for the compression source and on the two horizontal components for the shear source.

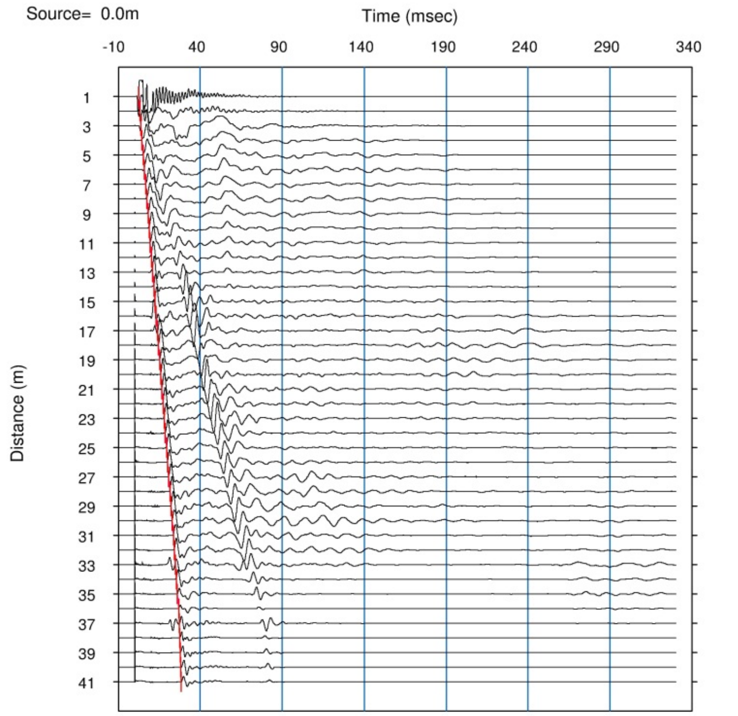



*Figure 2: BH-12-2-3, first break picking of compression wave arrivals (red) along the seismic traces recorded at each receiver depth*

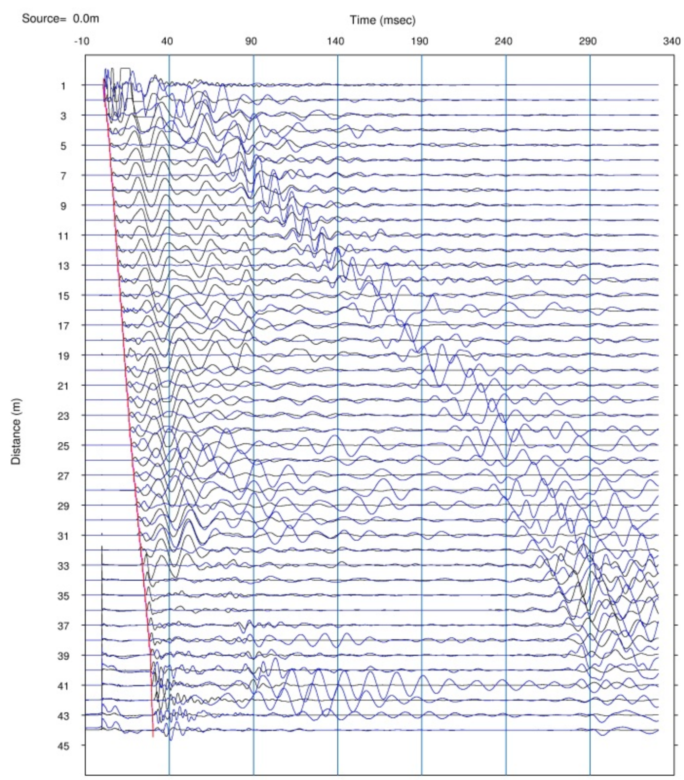



*Figure 3: BH-12-3-3, first break picking of compression wave arrivals (red) along the seismic traces recorded at each receiver depth*

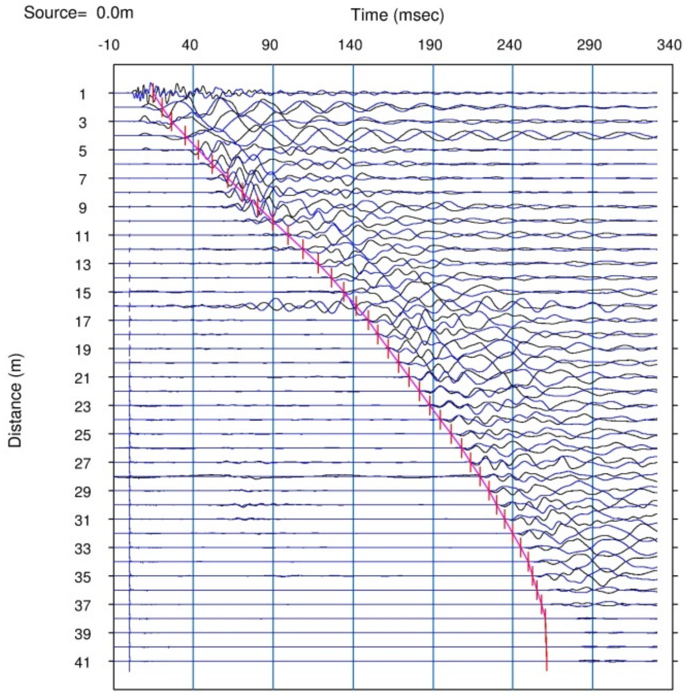



*Figure 4: BH-12-2-3, first break picking of shear wave arrivals (red) along the seismic traces recorded at each receiver depth*

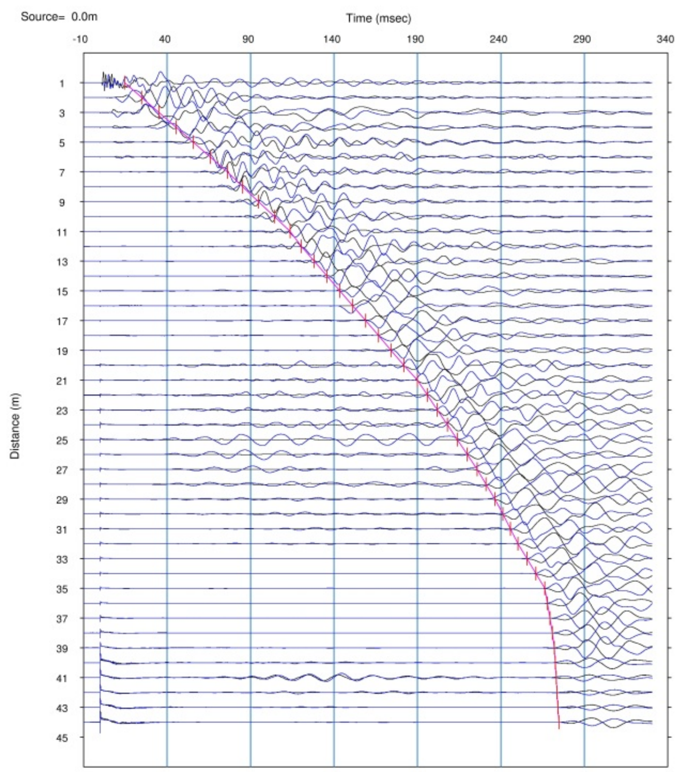



*Figure 5: BH-12-3-3, first break picking of shear wave arrivals (red) along the seismic traces recorded at each receiver depth*

## Results

The VSP results are summarized in Table 1 for BH-12-2-3 and Table 2 for BH-12-3-3. The shear wave and compression wave layer velocities, at the field collected one-metre intervals, were calculated by best fitting a theoretical travel time model to the field data collected at either half or one metre intervals. The depths presented on the tables are relative to ground surface.

The estimated dynamic engineering moduli, based on the calculated wave velocities, are also presented on Table 1 and 2. The engineering moduli were calculated using an estimated bulk density, based on the borehole log, but a more detailed geotechnical investigation would be necessary to determine a more exact density for each layer. For the topsoil down to a depth of approximately 36 metres in BH-12-2-3 and 38 metres in BH-12-3-3, a bulk density of 1,750 kg/m$^3$ was estimated. Further down, to a depth of the bottom of the hole, the bulk density for the bedrock was estimated at 2,300 kg/m$^3$.

The first layer of both boreholes is likely frozen, which is why a relatively high velocity is measured for both the compressional and shear wave velocity.

The average shear wave velocity from ground surface to a depth of 30 metres was measured to be 117 m/s for BH-12-2-3 and 112 m/s for BH-12-3-3.

## Closure

We trust that these results meet your current needs. If you have any questions or require clarification, please contact the undersigned at your convenience.

Yours truly,

**GOLDER ASSOCIATES LTD.**

Stephane Sol, Ph.D.
Geophysics Group

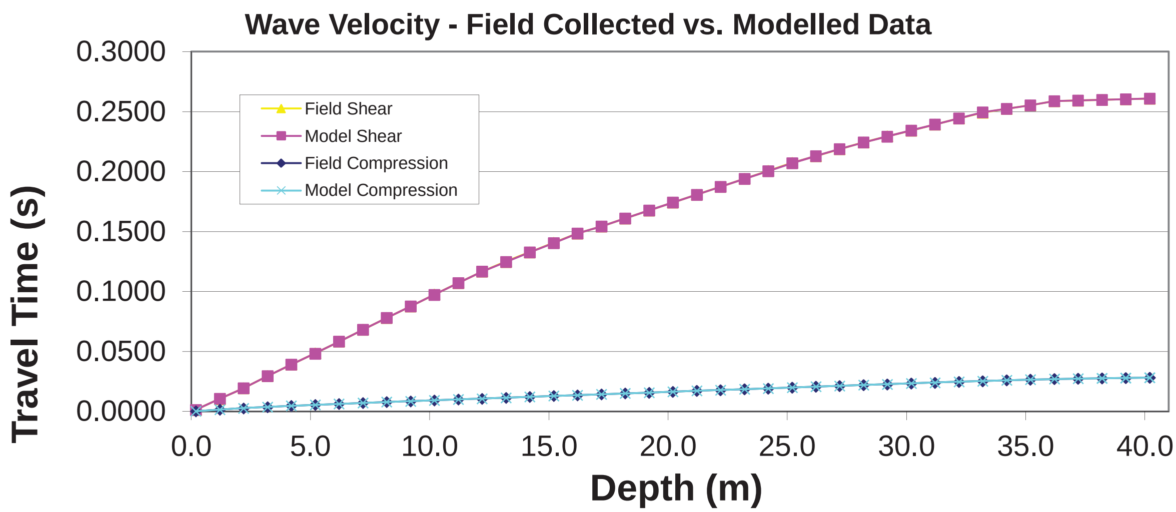
Brian Byerley, M. Sc., P. Eng.
Senior Hydrogeologist, Principal

SS/PF/BTB/sg
n:\active\2012\1125 - environmental and civil engineering\12-1125-0045 crrrc ea eastern on\phase 4500_final_easr\vol 3 - g h&g\appendices\appendix k\12-1125-0045 vsp techmemo final.docx

Attachments: Tables 1 and 2

# TABLE 1
## SHEAR WAVE VELOCITY PROFILE AT BH 12-2-3

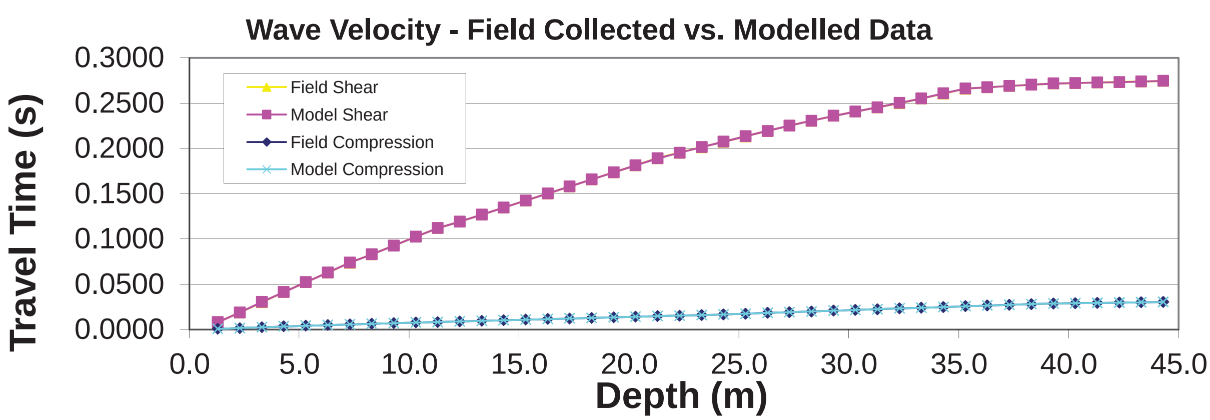
| Layer Depth (m) | | | | Estimated Bulk Density ($kg/m^3$) | Dynamic Engineering Properties | | | |
|---|---|---|---|---|---|---|---|---|
| Top | Bottom | Compressional Wave (m/s) | Shear Wave (m/s) | | Poissons Ratio | Shear Modulus (MPa) | Deformation Modulus (MPa) | Bulk Modulus (MPa) |
| 0.0 | 0.2 | 872 | 138 | 1750 | 0.49 | 33 | 99 | 1286 |
| 0.0 | 1.2 | 747 | 110 | 1750 | 0.49 | 21 | 63 | 948 |
| 1.2 | 2.2 | 820 | 113 | 1750 | 0.49 | 22 | 67 | 1147 |
| 2.2 | 3.2 | 985 | 99 | 1750 | 0.49 | 17 | 51 | 1675 |
| 3.2 | 4.2 | 1115 | 104 | 1750 | 0.50 | 19 | 57 | 2150 |
| 4.2 | 5.2 | 1210 | 108 | 1750 | 0.50 | 20 | 61 | 2535 |
| 5.2 | 6.2 | 1260 | 99 | 1750 | 0.50 | 17 | 51 | 2755 |
| 6.2 | 7.2 | 1230 | 102 | 1750 | 0.50 | 18 | 54 | 2623 |
| 7.2 | 8.2 | 1345 | 102 | 1750 | 0.50 | 18 | 55 | 3142 |
| 8.2 | 9.2 | 1350 | 104 | 1750 | 0.50 | 19 | 57 | 3164 |
| 9.2 | 10.2 | 1370 | 103 | 1750 | 0.50 | 19 | 56 | 3260 |
| 10.2 | 11.2 | 1380 | 103 | 1750 | 0.50 | 19 | 56 | 3308 |
| 11.2 | 12.2 | 1390 | 105 | 1750 | 0.50 | 19 | 58 | 3355 |
| 12.2 | 13.2 | 1390 | 122 | 1750 | 0.50 | 26 | 78 | 3346 |
| 13.2 | 14.2 | 1390 | 125 | 1750 | 0.50 | 27 | 82 | 3345 |
| 14.2 | 15.2 | 1400 | 130 | 1750 | 0.50 | 30 | 88 | 3391 |
| 15.2 | 16.2 | 1400 | 128 | 1750 | 0.50 | 29 | 86 | 3392 |
| 16.2 | 17.2 | 1400 | 165 | 1750 | 0.49 | 48 | 142 | 3366 |
| 17.2 | 18.2 | 1400 | 150 | 1750 | 0.49 | 39 | 118 | 3378 |
| 18.2 | 19.2 | 1420 | 152 | 1750 | 0.49 | 40 | 121 | 3475 |
| 19.2 | 20.2 | 1410 | 152 | 1750 | 0.49 | 40 | 121 | 3425 |
| 20.2 | 21.2 | 1405 | 152 | 1750 | 0.49 | 40 | 121 | 3401 |
| 21.2 | 22.2 | 1400 | 152 | 1750 | 0.49 | 40 | 121 | 3376 |
| 22.2 | 23.2 | 1410 | 152 | 1750 | 0.49 | 40 | 121 | 3425 |
| 23.2 | 24.2 | 1490 | 152 | 1750 | 0.49 | 40 | 121 | 3831 |
| 24.2 | 25.2 | 1450 | 150 | 1750 | 0.49 | 39 | 118 | 3627 |
| 25.2 | 26.2 | 1450 | 170 | 1750 | 0.49 | 51 | 151 | 3612 |
| 26.2 | 27.2 | 1430 | 175 | 1750 | 0.49 | 54 | 160 | 3507 |
| 27.2 | 28.2 | 1350 | 180 | 1750 | 0.49 | 57 | 169 | 3114 |
| 28.2 | 29.2 | 1520 | 200 | 1750 | 0.49 | 70 | 209 | 3950 |
| 29.2 | 30.2 | 1520 | 200 | 1750 | 0.49 | 70 | 209 | 3950 |
| 30.2 | 31.2 | 1520 | 200 | 1750 | 0.49 | 70 | 209 | 3950 |
| 31.2 | 32.2 | 1520 | 200 | 1750 | 0.49 | 70 | 209 | 3950 |
| 32.2 | 33.2 | 1520 | 200 | 1750 | 0.49 | 70 | 209 | 3950 |
| 33.2 | 34.2 | 1520 | 340 | 1750 | 0.47 | 202 | 596 | 3773 |
| 34.2 | 35.2 | 1520 | 320 | 1750 | 0.48 | 179 | 529 | 3804 |
| 35.2 | 36.2 | 1900 | 300 | 1750 | 0.49 | 158 | 468 | 6108 |
| 36.2 | 37.2 | 3700 | 1900 | 2300 | 0.32 | 8303 | 21935 | 20416 |
| 37.2 | 38.2 | 3700 | 1900 | 2300 | 0.32 | 8303 | 21935 | 20416 |
| 38.2 | 39.2 | 3700 | 1900 | 2300 | 0.32 | 8303 | 21935 | 20416 |
| 39.2 | 40.2 | 3700 | 1900 | 2300 | 0.32 | 8303 | 21935 | 20416 |




**Notes**
1. Depth Presented relative to ground surface.
2. This Table to be analyzed in conjunction with the accompanying report.

# TABLE 2
## SHEAR WAVE VELOCITY PROFILE AT BH 12-3-3

| Layer Depth (m) | | | | | Dynamic Engineering Properties | | | |
|---|---|---|---|---|---|---|---|---|
| Top | Bottom | Compressional Wave (m/s) | Shear Wave (m/s) | Estimated Bulk Density (kg/m$^3$) | Poissons Ratio | Shear Modulus (MPa) | Deformation Modulus (MPa) | Bulk Modulus (MPa) |
| 0.0 | 1.3 | 2385 | 165 | 1750 | 0.50 | 48 | 143 | 9891 |
| 0.0 | 2.3 | 1110 | 92 | 1750 | 0.50 | 15 | 44 | 2136 |
| 2.3 | 3.3 | 1020 | 88 | 1750 | 0.50 | 14 | 41 | 1803 |
| 3.3 | 4.3 | 1022 | 90 | 1750 | 0.50 | 14 | 42 | 1809 |
| 4.3 | 5.3 | 1260 | 92 | 1750 | 0.50 | 15 | 44 | 2759 |
| 5.3 | 6.3 | 1480 | 93 | 1750 | 0.50 | 15 | 45 | 3813 |
| 6.3 | 7.3 | 1500 | 93 | 1750 | 0.50 | 15 | 45 | 3917 |
| 7.3 | 8.3 | 1520 | 108 | 1750 | 0.50 | 20 | 61 | 4016 |
| 8.3 | 9.3 | 1530 | 103 | 1750 | 0.50 | 19 | 56 | 4072 |
| 9.3 | 10.3 | 1550 | 103 | 1750 | 0.50 | 19 | 56 | 4180 |
| 10.3 | 11.3 | 1550 | 103 | 1750 | 0.50 | 19 | 56 | 4180 |
| 11.3 | 12.3 | 1560 | 145 | 1750 | 0.50 | 37 | 110 | 4210 |
| 12.3 | 13.3 | 1560 | 125 | 1750 | 0.50 | 27 | 82 | 4222 |
| 13.3 | 14.3 | 1340 | 130 | 1750 | 0.50 | 30 | 88 | 3103 |
| 14.3 | 15.3 | 1550 | 130 | 1750 | 0.50 | 30 | 89 | 4165 |
| 15.3 | 16.3 | 1600 | 128 | 1750 | 0.50 | 29 | 86 | 4442 |
| 16.3 | 17.3 | 1550 | 128 | 1750 | 0.50 | 29 | 86 | 4166 |
| 17.3 | 18.3 | 1600 | 128 | 1750 | 0.50 | 29 | 86 | 4442 |
| 18.3 | 19.3 | 1600 | 130 | 1750 | 0.50 | 30 | 89 | 4441 |
| 19.3 | 20.3 | 1580 | 130 | 1750 | 0.50 | 30 | 89 | 4329 |
| 20.3 | 21.3 | 1580 | 125 | 1750 | 0.50 | 27 | 82 | 4332 |
| 21.3 | 22.3 | 1580 | 165 | 1750 | 0.49 | 48 | 142 | 4305 |
| 22.3 | 23.3 | 1580 | 165 | 1750 | 0.49 | 48 | 142 | 4305 |
| 23.3 | 24.3 | 1400 | 165 | 1750 | 0.49 | 48 | 142 | 3366 |
| 24.3 | 25.3 | 1250 | 165 | 1750 | 0.49 | 48 | 142 | 2671 |
| 25.3 | 26.3 | 1280 | 170 | 1750 | 0.49 | 51 | 151 | 2800 |
| 26.3 | 27.3 | 1250 | 170 | 1750 | 0.49 | 51 | 151 | 2667 |
| 27.3 | 28.3 | 1150 | 185 | 1750 | 0.49 | 60 | 178 | 2235 |
| 28.3 | 29.3 | 1250 | 185 | 1750 | 0.49 | 60 | 178 | 2655 |
| 29.3 | 30.3 | 1200 | 210 | 1750 | 0.48 | 77 | 229 | 2417 |
| 30.3 | 31.3 | 1200 | 215 | 1750 | 0.48 | 81 | 240 | 2412 |
| 31.3 | 32.3 | 1250 | 215 | 1750 | 0.48 | 81 | 240 | 2627 |
| 32.3 | 33.3 | 1200 | 190 | 1750 | 0.49 | 63 | 188 | 2436 |
| 33.3 | 34.3 | 1220 | 185 | 1750 | 0.49 | 60 | 178 | 2525 |
| 34.3 | 35.3 | 1220 | 190 | 1750 | 0.49 | 63 | 188 | 2520 |
| 35.3 | 36.3 | 1220 | 650 | 1750 | 0.30 | 739 | 1925 | 1619 |
| 36.3 | 37.3 | 1250 | 680 | 1750 | 0.29 | 809 | 2087 | 1655 |
| 37.3 | 38.3 | 1260 | 680 | 2300 | 0.29 | 1064 | 2754 | 2233 |
| 38.3 | 39.3 | 1500 | 800 | 1750 | 0.30 | 1120 | 2915 | 2444 |
| 39.3 | 40.3 | 3000 | 1800 | 2300 | 0.22 | 7452 | 18164 | 10764 |
| 40.3 | 41.3 | 3100 | 1900 | 2300 | 0.20 | 8303 | 19913 | 11032 |
| 41.3 | 42.3 | 3200 | 1800 | 2300 | 0.27 | 7452 | 18907 | 13616 |
| 42.3 | 43.3 | 3200 | 1800 | 2300 | 0.27 | 7452 | 18907 | 13616 |
| 43.3 | 44.3 | 3200 | 1800 | 2300 | 0.27 | 7452 | 18907 | 13616 |




**Notes**
1. Depth Presented relative to ground surface.
2. This Table to be analyzed in conjunction with the accompanying report.