A Response to Geomil's White Paper on Seismic CPT

Earlier this year Geomil Equipment BV published a white paper on seismic CPT entitled "Seismic CPT: How it works and how it can add value to your Ground Investigation programme through enhanced data capture". While we always encourage efforts to promote Seismic CPT (SCPT), we feel it is important that those efforts accurately reflect what this site investigation method is all about. And unfortunately this white paper falls short in that regard.

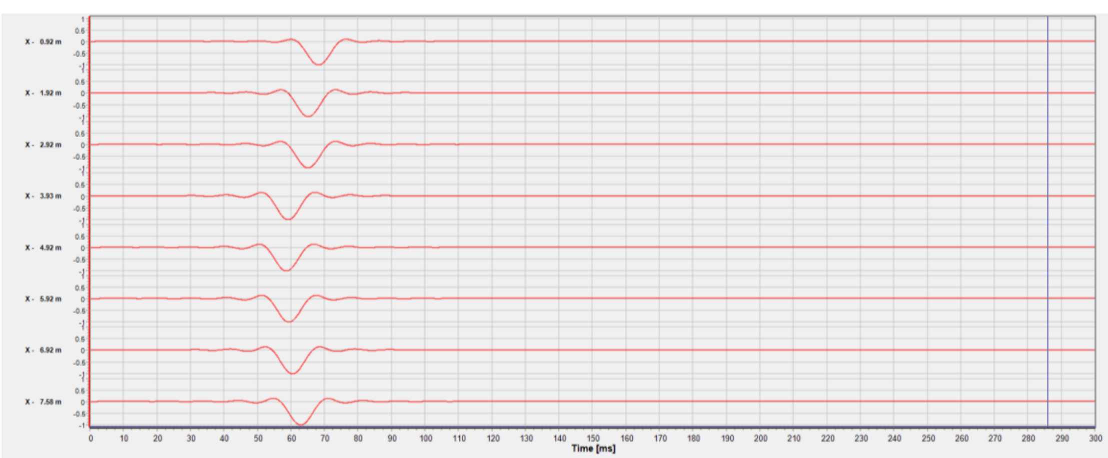
When we approached the author we were told that "the goal of the white paper was to provide an accurate overview on seismic CPT and how it is used in today's market without going into the level of detail you would find in scientific journal". So in this note we want to highlight some of the shortcomings of the white paper (without elaborate equations) to ensure that there are no misunderstandings as test data are analyzed or obtained.

It should be noted that we communicated our concerns with the author of the white paper and were told that our comments would be considered. As this is now more than 3 months ago and no revision to the white paper has been published, we feel that the users of our hardware and software should be aware of our concerns and for that reason we are issuing this Technical Note.

Data Analysis – Ray Path

When discussing downhole seismic testing, which includes SCPT, it is important to realize that seismic waves do not necessarily travel in straight lines between the seismic source and the seismic receiver. Rather than following the path that is the shortest the waves follow the path that takes the least amount of time to reach the receiver. This concept is known as "Fermat's Principle" or the "Principle of Least Time" and any assumption that rays travel in a straight path can easily lead to misunderstanding and even misinterpretation of the obtained results.

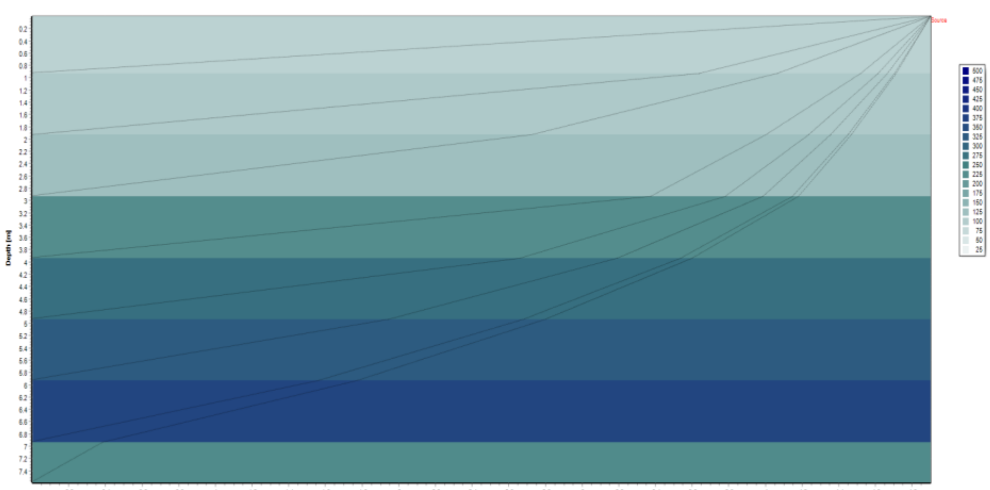
Let's consider the traces that are shown in the figure below.



If the rays would travel in straight lines then the travel distance between source and the receiver has to increase as the receiver moves deeper into the soil profile, which in turn means that a wave will take more time to reach the receiver at a greater depth. However, as is shown in the figure above, this is not necessarily the case. As the receiver moves down from 0.92 m in 1 m increments to a depth of 4.92 m it takes less and less time to reach the receiver at the following depth. And this is not a theoretical example: these are traces that were obtained during an actual site investigation. As shown below, if the interval velocities were derived assuming straight ray paths the results would be meaningless, and the only possible approach would be to drop these traces and claim that no useful data was available near surface. However, by applying an appropriate data analysis method, and taking into account the Principle of Least Time and refraction as waves travel from one layer to another, these earlier arrival times pose no problems and the interval velocities can be determined.

Interval Depth (m)	**Arrival Time (ms)**	**Raypath Refraction Interval Velocity Estimate (m/s)**	**Straight Ray Interval Velocity Estimate (m/s)**
0 - 0.92	56.0729	88.9	88.9
0.92 - 1.92	53	106.6	-90.1811
1.92 - 2.92	52.9167	125.1	-5298.1
2.92 - 3.93	47	224.2	-97.562
3.93 - 4.92	46.4896	283.3	-1297.98
4.92 - 5.92	47.25	322.4	974.5045
5.92 - 6.92	48.3125	365.9	747.6313
6.92 - 7.58	50.7604	228.6	223.3341

When the derived ray paths for this example are plotted as shown in the figure below, it is obvious that seismic waves do not travel in straight lines.



The reality is unfortunately that many analyses methods follow the straight ray approach (often without making the user fully aware of this) and this does not only create problems when you have negative arrival times as shown in the previous example. Take the data set summarized in the following table where there is a relatively slow layer at the top, followed by a denser layer with a much higher interval velocity. As shown in this table, analyzing the data using the straight ray approach would lead to a serious misinterpretation near surface.

Interval Depth (m)	Arrival Time(ms)	True Interval Velocities (m/s)	Straight Ray Interval Velocity Estimate (m/s)
0-1.5	22.9795	112	112
1.5-2.5	24.2555	181	536
2.5-3.5	27.3112	209	267
3.5-4.5	36.6900	101	94
4.5-5.5	40.7033	214	230
5.5-6.5	44.5370	232	246
6.5-7.5	52.1200	128	126

For these reasons it is important that any white paper on SCPT emphasizes how seismic rays travel through soil, which is obviously not the case in the Geomil paper.

Data Analysis – Methodology

The white paper discusses two analysis methods, and states that in both cases "the resulting value is (…) greatly dependent on the input of the engineer and great care must be taken when performing the data analysis". Since no other analysis methods are mentioned, this implies that the analysis results are subjective and this is a mischaracterization. There is an analysis method that has minimal subjectivity and provides even a built-in check to assess the confidence level of the derived results.

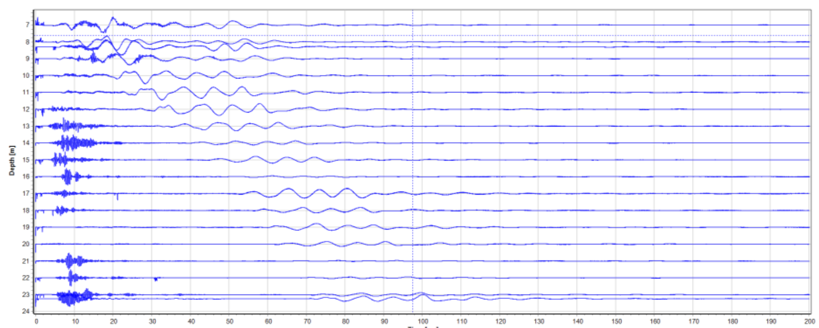
It is common practice to obtain data generated by seismic sources on either side of the CPT string. Rather than combining these data sets (as is the case in the reverse polarity method), we recommend that these data sets are analyzed completely independently. And rather than focusing on the first arrival at each depth, we recommend to use signal markers (a peak or a trough in the seismic trace) and use the extreme value of that marker to determine the relative arrival times for each depth. These relative arrival times are then converted to actual arrival times by identifying the actual first arrival for one particular depth where this first arrival is obvious. The interval velocities can then be determined for each side using the actual arrival times, after which they can be compared with each other. If both analyses generate basically the same results (say within 10 %) there is confidence that the result is reliable as there is an independent confirmation.

It should be noted that the first arrival is not the first peak or the first trough, as stated in the white paper, but rather the moment where the trace clearly deviates, in other words the "first break". Furthermore, the statement "typically, the waveforms have an initial peak of a larger amplitude (…) subsequent diminishing peaks as the energy produced dissipates "is incorrect. Source waves can be zero-phase (e.g., Klauder waves, where the peak occurs at center of source wave), minimum phase (where the peak occurs at beginning of source wave), mixed phase (e.g. Berlage waves, where the peak occurs between the beginning and end of source wave) or maximum phase (where the peak occurs at end of source wave). While we understand that the Geomil's objective for the White Paper was to avoid going into too much depth, and therefore did not want to cover these various wave types, making incorrect general statements is unacceptable as it would confuse the intended audience as they experience source wave peaks that are not at the beginning of the source wave.

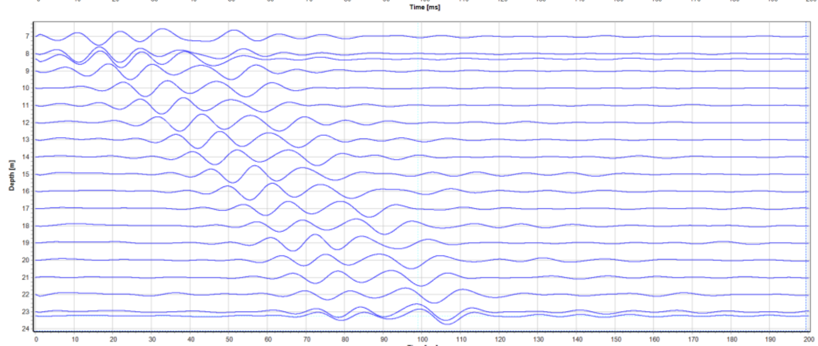
Data Analysis – Signal Feature Isolation

The Geomil white paper issues a warning that when signal decay is used as a smoother that the analysis becomes more subjective. This statement could easily be misinterpreted that signal decay should not be used and the white paper does not mention how signal decay can be used, not as a smoother, but very effectively without making the analysis subjective.

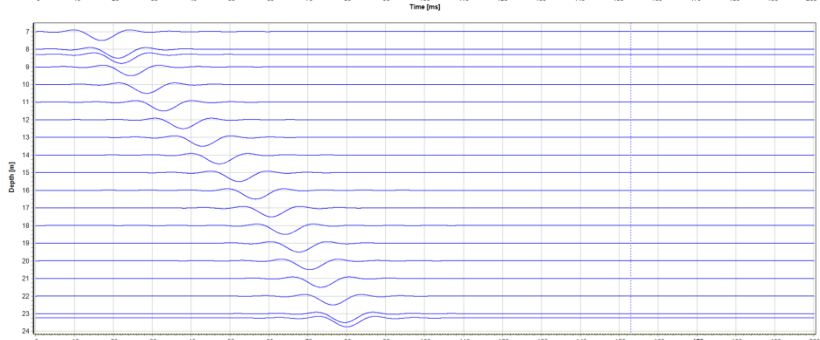
As mentioned earlier, BCE recommends that signal markers are used during the analysis and we also feel that any analysis should be very transparent. This means that the analysis report shows step by step what was done to derive the interval velocity values. And this is where filtering and signal decay come in. In the three figures below the unfiltered traces are shown for a test site, followed by the (minimally filtered) traces. Finally signal decay is applied to clearly isolate the signal markers, not to smooth these markers but to isolate them. In other words, signal feature isolation through signal decay is implemented so that possible source wave distortions (resulting from refractions, reflections, near-field effects, or "dirty" sources) and noise do not negatively affect the ability to estimate arrival times or relative arrival times.



Unfiltered traces



Minimally filtered traces



Traces after signal feature isolation

Data Acquisition – True-interval or Pseudo-interval

The white paper makes the unsubstantiated claim that dual array system, i.e. systems with seismic sensors at two levels, are preferred. This claim is often made when the straight ray analysis method is applied: using the relative arrival for the two sensors the seismic wave velocity can "easily" be determined for the depth interval between the two levels where the seismic sensors are mounted (thus the term "true-interval"). Moreover, so proponents of the true-interval approach would claim, with a dual array it is no longer necessary to worry about the triggering consistency (which is essential for the pseudo-interval approach) since they are only concerned with the difference in arrival time of the wave at the two sensors. But as outlined before, the straight ray approach is flawed and therefore there are no advantages to the dual array system. Furthermore, by allowing inconsistent triggering data stacking is not possible and neither is comparing traces at different depths, which could complicate the data analysis process. Finally the increased length of a dual array cone makes it more cumbersome to work with such a cone and therefore we see no reason to recommend it.

Data Acquisition – Data Stacking

The white paper also discusses the use of stacking during data acquisition to increase the signal-to-noise ratio. It warns that "any background noise and interference should be random allowing the process of data stacking to boost the signal-to-noise ratio". This is exactly why data stacking, which is nothing more than averaging, should not be applied in the field and that can be best explained by an example from an article in the Harvard Business Review in November 2002.

> Now consider the case of the statistician who drowns while fording a river that he calculates is, on average, three feet deep. If he were alive to tell the tale, he would expound on the "flaw of averages," which states, simply, that plans based on assumptions about average conditions usually go wrong. This basic but almost always unseen flaw shows up everywhere in business, distorting accounts, undermining forecasts, and dooming apparently well-considered projects to disappointing results.

Just as the statistician does not know the actual depths, the CPT operator does not know whether the background noise and interference is random. And stacked data sets cannot be "unstacked", while unstacked data sets can be reviewed in the office and stacked if appropriate. For that reason data stacking is an operation that is part of data processing, but not of data acquisition.

Data Acquisition – Generating P waves

A high quality P-wave source applied at the surface requires symmetric (with respect to volume change) displacement within the medium. Nevertheless it is often suggested to apply simply a vertical impact on (a plate placed on) the ground surface. The white paper makes the same suggestion, without clearly stating the disadvantages of this approach:

1. Only one-third of the energy generated by a vertical source on a uniform half-space is transformed into body waves (compression and shear), while the other two-thirds of the energy generated is transformed into surface waves.
2. Source body waves generated at the surface have lower amplitudes than body waves generated in the half-space.
3. P-waves with low Signal to Noise Ratios (SNRs) and low repeatability are generated.

Much more effective P-wave sources are an electrical sparker system and air guns or vertical hammer impacts causing a symmetric displacement of a membrane placed within the medium near surface.

Conclusion

SCPT is a very useful site investigation method if the data acquisition and analysis is performed properly. Unfortunately the method is often applied without adequate understanding of the issues involved, which leads to questionable results.

As providers of SCPT hardware and software we are obviously interested that the method is applied successfully and for that reason our website (www.bcengineers.com) contains a series of Technical Notes that address particular aspects of this test method. This particular Technical Note should be viewed in the same manner: it highlights only some elements that are presented either incompletely or erroneously in the Geomil White Paper that, when implemented in practice, could easily lead to questionable or even faulty results. Therefore this White Paper should be ignored.

Finally, in case of any questions about SCPT we are always happy to provide explanations and guidance. So please feel free to contact us at any time.

Erick Baziw
Gerald Verbeek

BCE's mission is to provide our clients around the world with state-of-the-art geotechnical signal processing systems, which allow for better and faster diagnostics of the sub-surface. Please visit our website (www.bcengineers.com) or contact our offices for additional information:

e-mail: info@bcengineers.com

phone: Canada: (604) 733 4995 – USA: (903) 216 5372