NMO-SCTT: A Unique SCPT Tomographic Imaging Algorithm

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ABSTRACT: Seismic Cone Penetration Testing (SCPT) is an important geotechnical testing technique for site characterization that provides low strain ($<10^{-5}$) in-situ interval compression (*Vp*) and shear (*Vs*) wave velocity estimates. Baziw Consulting Engineers has invested considerable resources in advancing the art of SCPT, and in this paper a newly developed Normal Moveout Seismic Cone Tomographic Testing (NMO-SCTT) algorithm is introduced. This algorithm allows for two dimensional imaging of the sub-surface stratigraphy by processing acquired seismic trace arrival times derived with increasing source-sensor radial offsets. This dramatically increases the ability to characterize near-surface stratigraphy, which is very important for accurate liquefaction assessment. As opposed to crosshole tomography, the NMO-SCTT does not require any significant site disturbance aside from a single SCPT sounding, thereby greatly reducing the cost and the environmental impact. This paper outlines the mathematical and algorithmic details of the NMO-SCTT algorithm, which builds upon BCE's established FMDSM algorithm. As such it incorporates Fermat's principle when estimating SCPT interval velocities. In addition a real SCPT data tomographic data set is presented using SCPT seismic data that was acquired at offsets of 1.85m, 5m and 10m, and down to a depth of 20.5m.

1 INTRODUCTION

A fundamental goal of geotechnical *in-situ* testing is the accurate estimation of the shear and compression wave velocities (V_P and V_S, respectively) in the ground. These parameters form the core of mathematical theorems to describe the elasticity/plasticity of soils and they are used to predict the soil response (settlement, liquefaction or failure) to imposed loads (whether from foundations, heavy equipment, earthquakes or explosions). The Seismic Cone Penetration Testing (SCPT) is a common geotechnical technique for measuring *in-situ* V_S and V_P velocities. The main goal in SCPT is to obtain accurate arrival times as the source wave travels through the soil profile of interest, and from these arrival times the V_S and V_P velocities are then calculated.

Baziw Consulting Engineers has invested considerable resources in advancing the art of SCPT. A logical extension of SCPT is Seismic Travel-Time Tomography (STTT), which allows for two dimensional imaging of the sub-surface stratigraphy (Shearer, 1999; Gibowicz, and Kijko, 1994; Nolet, 1987) by processing acquired *Vs* and *Vp* arrival times. In general terms, in STTT the velocity profile is derived by seismic data inversion or iterative forward modeling, while adhering to Fermat's principle of least time. This is a particularly challenging problem in that the seismic raypaths depend upon the unknown velocity structure. A common application for STTT is Crosshole Seismic Tomography Testing (CSTT) as illustrated in Figure 1 (Gibowicz, and Kijko, 1994). In this illustration there is a linearized ray path between the source and receiver, and

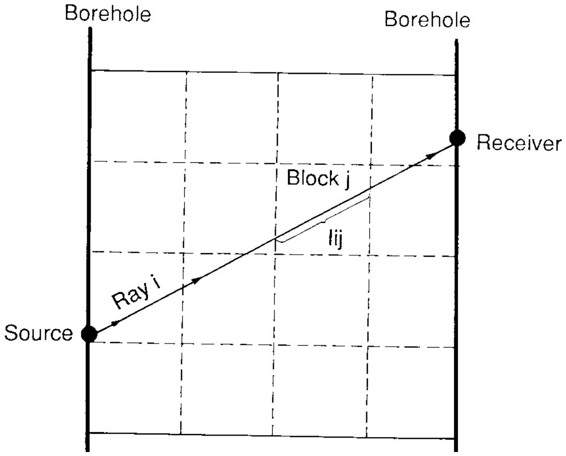

Figure 1. Schematic of a crosshole seismic tomography testing and analysis configuration (after, Gibowicz and Kijko (1994)).

tion of CSTT requires a significant effort to create the necessary source and receiver boreholes and in addition the CSTT analysis is unwieldy due to the fact that there are many velocity blocks with a limited number of source wave intersections, which more than likely will result in instability in the analysis equations.

This paper outlines a new approach, which facilitates the tomographic imaging of the subsurface: the so-called Normal Moveout Seismic Cone Tomographic Testing (NMO-SCTT). In general terms, this approach allows for two dimensional imaging of the sub-surface stratigraphy by processing acquired seismic trace arrival times derived with increasing source-sensor radial offsets. This dramatically increases the ability to characterize near-surface stratigraphy, which is very important for accurate liquefaction assessment as was shown by Bray et al. (2014) through his analysis of the catastrophic liquefaction that occurred in Christchurch, New Zealand in 2010 and 2011.

2 NMO-SCTT TESTING AND ANALYSIS PROCEDURE

Figure 2 shows a schematic of the typical SCPT configuration: a seismic source is used to generate a seismic wave train at the ground surface. One or more downhole seismic receivers are used to record the seismic wave train at predefined depth increments. When triggered by the seismic source a data recording system records the response of the downhole receiver(s). Figure 3 illustrates a schematic of the NMO-SCTT testing and analysis configuration. Here the downhole seismic data sets are acquired at various radial source offsets. Figure 4 illustrates a NMO-SCTT test site where there are beam sources with pendulum hammers with radial offsets of 1.85m, 5m and 10m. While analyzing the data sets 2D velocity models are derived for each subsequent offset resulting in a dramatic lowering of the unknowns since the previously established Velocity values are used whenever the ray path travels through an area that was covered before. For example, the ray path for offset X2 and depth Z2 might travel through areas V2D[1,2], V2D[1,1] and V2D[1,2], in which case for the last two areas the velocity values obtained during the analysis of the data set for offset X1 are used and V2D[1,2] is estimated.

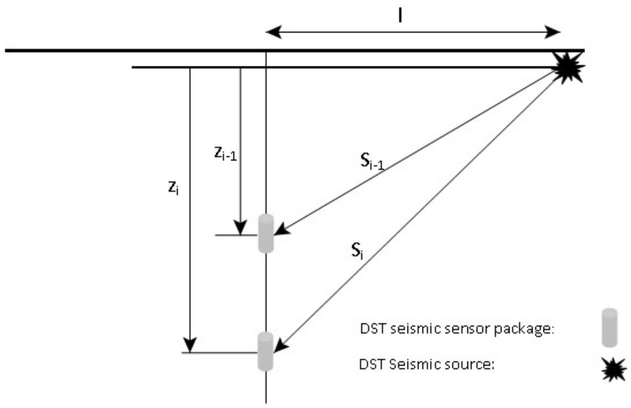

Figure 2. Schematic of the typical SCPT configuration.

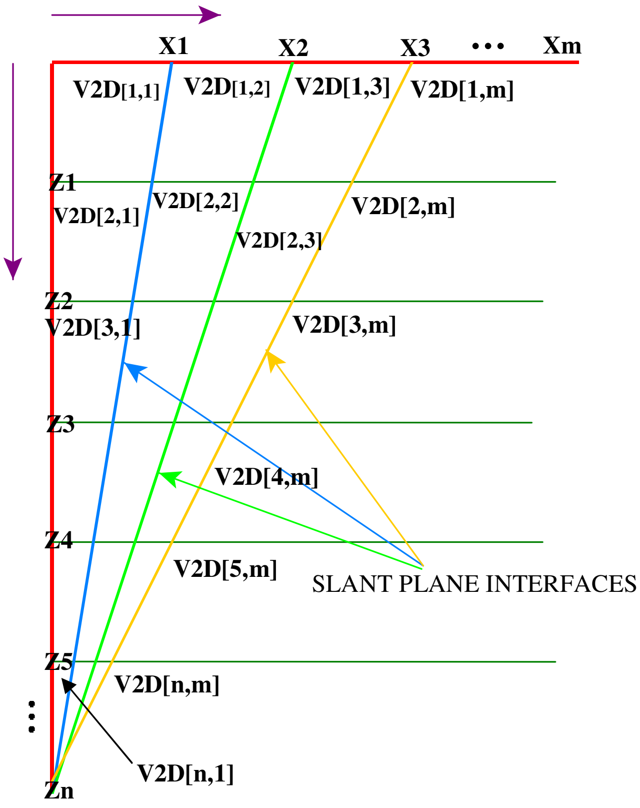

Figure 3. Schematic of a NMO-SCTT testing and analysis configuration.

Figure 4. Wiertsema & Partners of The Netherlands SCTT-NMO-SCPT site setup. SH pendulum hammer beam sources have sensor-sensor offsets of 1.85m, 5m and 10m.

Methodologies employed for solving the seismic tomographic problem rely upon data inversions and the more popular iterative reconstructive techniques such as ART-backprojection, SIRT, conjugate gradient method and LSQR (Shearer, 1999; Gibowicz, and Kijko, 1994; Nolet, 1987). It should be noted that data inversion techniques attempt to determine the solution space by inverting sparse and ill-conditioned matrices, while utilizing singular value decomposition and regularization. Oldenburg (Oldenburg and Li, 2005) has carried extensive research into the application of seismic data inversion, which has proven very challenging. For that reason it was decided to apply reconstructive techniques for the NMO-SCTT algorithm.

The suggested *NMO-SCTT* algorithm implements an iterative technique based on the same mathematical tools (e.g., Newton-Raphson technique and simplex iterative forward modeling) that are used in the single source offset Forward Modeling / Downhill Simplex Method (*FMDSM*) technique (Baziw, 2002; Baziw, E. and Verbeek, G, 2012 and 2014), but with additional slant plane interfaces for each source offset as was illustrated in Fig. 3.

In its current form the *NMO-SCTT* algorithm allows 2D interval velocity estimations for up to seven depth intervals, while for all additional intervals 1D estimations are made, which will also further enhance the accuracy of the 2D. Apart from a practical justification (to control the processing time), there is also a mathematical justification given the cone nature of the *NMO-SCTT* 2D testing environment. As the SCPT depth increases the 2D interval velocities collapse onto the first offset estimates (the apex of the analysis cone is readily approached with an increase in depth) as illustrated in Fig. 3. The performance of the NMO-SCTT algorithm was demonstrated though the processing of challenging test bed simulations (Baziw and Verbeek (2017a)).

The *NMO-SCTT* algorithm implements a Monte Carlo technique where numerous (currently 120 as a default value) searches are carried out when finding the optimal 2D interval velocities. The first search assumes that there is a Transverse Isotropic (TI) medium (i.e., no lateral variation). The subsequent estimates use the Monte Carlo technique for specifying the initial simplex for the search grid. The interval velocity results with the cost function minimum (RMS difference between the actual and derived arrival times) are used and stored within the *NMO-SCTT* tomography database. The Monte Carlo technique was adopted to address the need to search a large solution space for the interval velocities with numerous local minima. To control the processing time a 64-bit parallel processing technique has been incorporated into the algorithm so that full advantage is taken of multi-core processors and hyper-threading technology (resulting in a processing time that is less than half of that with a 32-bit configuration without parallel processing (Baziw and Verbeek (2017b)).

3 REAL DATA ANALYSIS

The NMO-SCTT data set used for this paper was acquired by Wiertsema & Partners during an investigation at a site in Northwest Europe. The SH source waves at this site were generated with pendulum sledge hammers that impacted horizontally point source steel beams located underneath the outriggers withelectrical contact triggers. Figure 4 shows the site setup with radial offsets between the source and the sensor of 1.85 m, 5 m and 10 m. The data acquisition started at a depth of 2m down to a depth of 20.5m. The first seven test depths (2 m, 3.5 m, 5 m, 7 m, 9 m, 11 m and 12.7 m) were used for 2D analysis, while the remaining eight depths (13.5m, 14.5m, 15.5m, 16.5m, 17.5m, 18.5m, 19.5m and 20.5m) were used for 1D analysis.

Figures 5, 6 and 7 illustrate the vertical seismic profile (VSP) for the seismic data acquired at the three sensor-source radial offsets after applying a 200Hz low pass frequency filter.

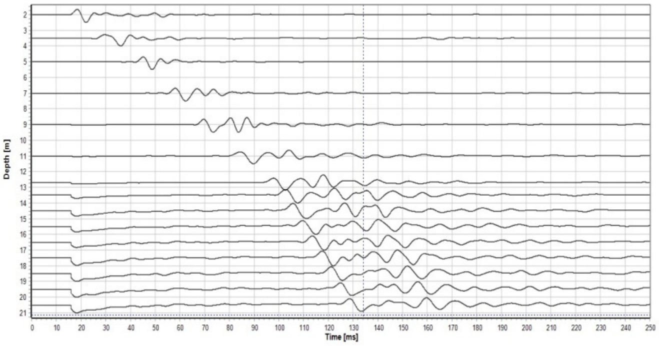

Figure 5. VSP for seismic trace recorded at a sensor-source radial offset of 1.85m.

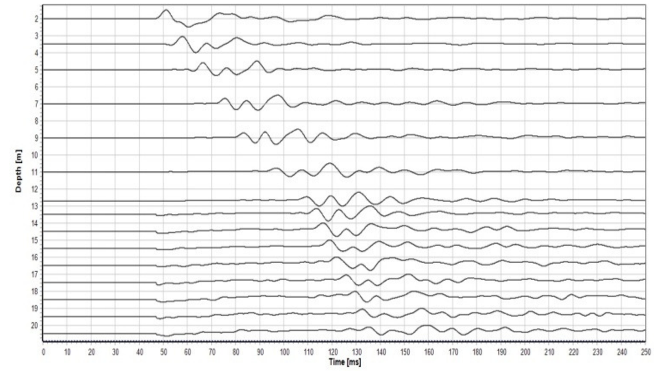

Figure 6. VSP for seismic trace recorded at a sensor-source radial offset of 5m.

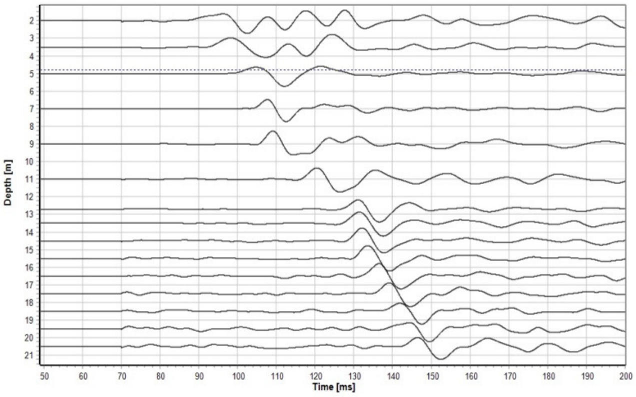

Figure 7. VSP for seismic trace recorded at a sensor-source radial offset of 10m.

Table 1 shows the estimated source wave arrival times for these VSPs, which were then fed into the NMO-SCTT algorithm to derive the interval velocities. The NMO-DSTT residual arrival time errors (difference between the actual and derived arrival times) are also illustrated in Table 1. As can be seen the residual errors increase with radial source offsets. In general terms, this is due to the fact that any errors from the smaller NMO offsets propagate to the larger NMO offsets.

The NMO-SCTT algorithm has the beneficial feature of identifying “actual” arrival times which are erroneous, e.g. due to significant measurement noise and/or interference from reflections or critically refracted rays. To illustrate this Fig. 8 shows the trace recorded at a depth of 2 m from the 10 m radial sensor-source offset. The original arrival time estimate of 90ms resulted in a NMO-SCTT residual error of 4.6ms, implying that an arrival time of 94.4ms is more realistic. As is evident in Fig. 8, the arrival time of the trace recorded 2m is difficult to ascertain and a NMO-SCTT determined arrival time of 94.4 ms is highly feasible due to the natural period of the source wave and significant first break interference.

Table 2 outlines the estimated tomographic interval velocities, showing substantial lateral variations in the interval velocities near surface (0 to 3.5m) and becoming less pronounced for the deeper layers. Figures 9, 10 and 11 illustrate the source wave raypaths for the various sensor-source radial offsets. These figures clearly demonstrate Fermat’s Principle and that source waves do not have straight raypaths, emphasizing the importance to utilize analytical techniques which take into account raypath refraction when estimating the *in-situ* interval velocities.

CONCLUSIONS

The SCPT has proven to be an important geotechnical testing tool for site characterization that provides low strain in-situ interval compression and shear wave velocity estimates. This paper has out-

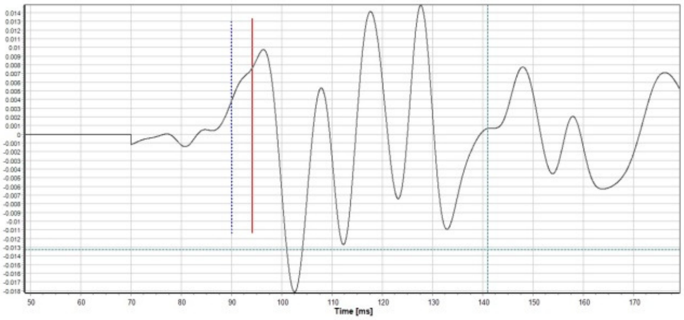

Figure 8. Seismic trace recorded at a depth of 2m from the source with a radial offset of 10m.

Cone Tomographic Testing (NMO-SCTT) algorithm which allows for the two dimensional imaging of the subsurface utilizing standard SCPT instrumentation. As opposed to crosshole tomography, the NMO-SCTT does not require any significant site disturbance aside from a single SCPT sounding, thereby greatly reducing the cost and the environmental impact.

The NMO-SCTT algorithm allows sequentially processes acquired seismic trace arrival times derived with increasing source-sensor radial offsets. In this algorithm an iterative numerical technique is employed which is based upon the same mathematical tools (e.g., Newton-Raphson technique and simplex iterative forward modeling) that are used in the established single source offset Forward Modeling / Downhill Simplex Method (FMDSM) technique. After demonstrating great promise in processing challenging test bed simulation data sets, the NMO-SCTT algorithm was implemented on real data. This paper outlines the results of a real data NMO-SCTT analysis.

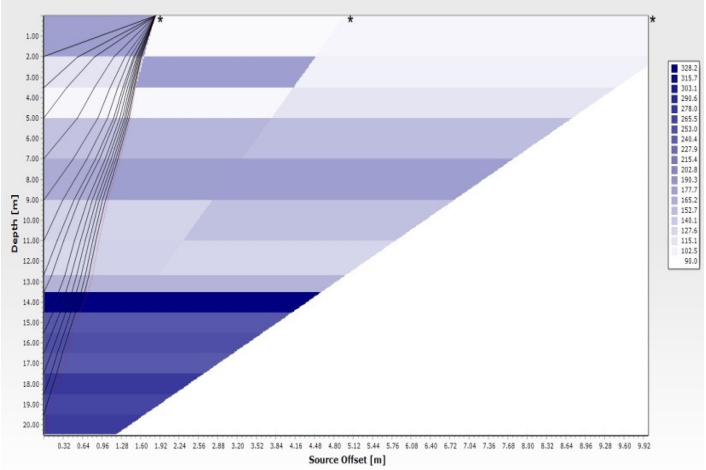

Figure 9. Estimated source raypaths for 1.85m sensor-source radial offset.

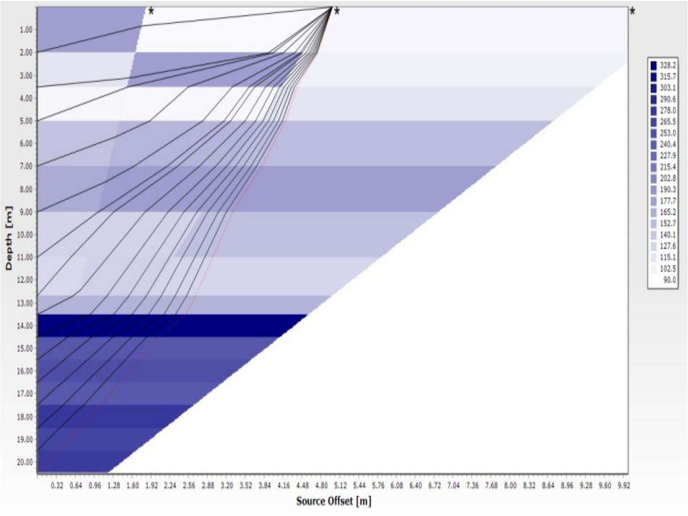

Figure 10. Estimated source raypaths for 5m sensor-source radial offset.

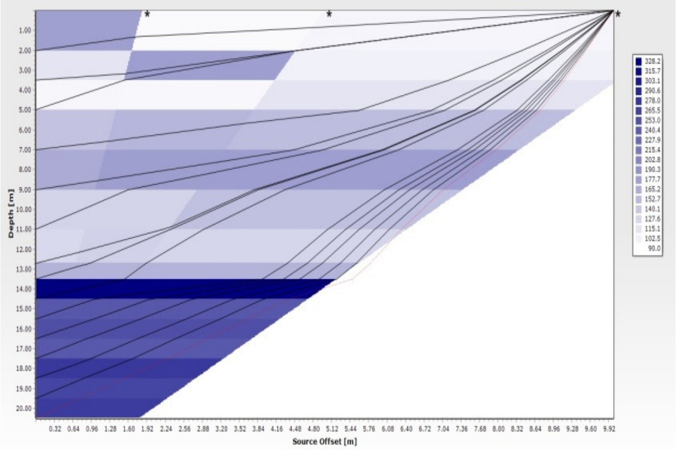

Figure 11. Estimated source raypaths for 10m sensor-source radial offset.

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Table 1. Estimated Arrival Times and NMO-SCTT Residual Time Errors

Depth **[m]**	**Offset** **[m]**	**Arrival Time [ms]**	**Residual Error [ms]**	**Offset** **[m]**	**Arrival Time [ms]**	**Residual Error [ms]**	**Offset** **[m]**	**Arrival Time [ms]**	**Residual Error [ms]**
2	1.85	15.28	0	5	47	*0.06*	10	94.4	-0.334
3.5	1.85	27.22	0	5	52.7	*0.21*	10	90	-0.503
5	1.85	42	0	5	61.32	*-0.27*	10	100	0.491
7	1.85	55.05	0	5	70.24	*-0.004*	10	102.71	0.222
9	1.85	66.46	0	5	78.05	*-0.114*	10	104.694	0.080
11	1.85	81.45	0	5	91.57	*0.136*	10	115.724	-0.032
12.7	1.85	94.89	0	5	104.07	*-0.022*	10	126.195	1.003
13.5	1.85	99.83	0	5	108.22	*-0.037*	10	126.606	-0.727
14.5	1.85	102.78	0	5	111.08	*1.067*	10	127.315	0.058
15.5	1.85	106.75	0	5	113.87	*0.307*	10	128.834	0.337
16.5	1.85	110.62	0	5	116.82	*-0.241*	10	131.648	0.463
17.5	1.85	114.63	0	5	120.67	*-0.087*	10	134.250	0.0871
18.5	1.85	118.23	0	5	124.25	*0.176*	10	137.051	0.361
19.5	1.85	121.99	0	5	127.32	*-0.274*	10	139.21	-0.345
20.5	1.85	125.64	0	5	130.11	*-0.934*	10	141.633	-0.856

Table 2. NMO-SCPTT Estimated interval Velocities

Depth **[m]**	**Offset** **[m]**	**Estimated Interval Velocity [m/s]**	**Offset** **[m]**	**Estimated Interval Velocity [m/s]**	**Offset** **[m]**	**Estimated Interval Velocity [m/s]**
2	1.85	*178.3*	5	*95.1*	10	*99.12*
3.5	1.85	*115.1*	5	*179.58*	10	*103.09*
5	1.85	*97.6*	5	*98.13*	10	*115.3*
7	1.85	*145.9*	5	*157.78*	10	*151.31*
9	1.85	*168.8*	5	*180.03*	10	*180.22*
11	1.85	*131.4*	5	*131.02*	10	*148.78*
12.7	1.85	*125.3*	5	*132.6*	10	*128.32*
13.5	1.85	*160.4*	5	*160.4*	10	*160.4*
14.5	1.85	*328.2*	5	*328.2*	10	*328.2*
15.5	1.85	*246.7*	5	*246.7*	10	*246.7*
16.5	1.85	*254.5*	5	*254.5*	10	*254.5*
17.5	1.85	*246.4*	5	*246.4*	10	*246.4*
18.5	1.85	*274.8*	5	*274.8*	10	*274.8*
19.5	1.85	*263.3*	5	*263.3*	10	*263.3*
20.5	1.85	*271.8*	5	*271.8*	10	*271.8*