Multi-channel analysis of surface waves using Common Midpoint Cross Correlation method

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Abstract

Having knowledge about elastic prosperities of different layers of Earth has many useful applications in geophysical and geotechnical engineering projects. One of the important parameters in determination of static constants and the key parameter controlling the amplification of seismic motion during earthquake is shear-wave velocity. Because of the dispersive characteristic of Rayleigh waves when traveling through a layered medium and the important role of S-wave velocity in determination of Rayleigh wave velocity, dispersion of phase velocity of surface waves can be used for near-surface S-wave delineation. In this study Common Mid Point Cross-Correlation analysis of multi-channel surface-wave data (CMPCC MASW method) is used for dispersion curve determination of 2-D seismic reflection survey data. CMPCC MASW analysis is a further extension of Multi-channel Analysis of Surface Waves (MASW) that improves the accuracy and resolution of MASW by overcoming the problem of improved lateral resolution trading off against accuracy of phase velocity at low frequencies. It also enables Spectral Analysis of Surface Waves (SASW) method to perform a pseudo multi-channel analysis in order to distinguish fundamental mode from higher modes visually and therefore solving the spatial aliasing problem of SASW method.

Keywords: Common Mid Point Cross-Correlation, Multi channel Analysis of Surface Wave, Dispersion Curve, Rayleigh wave

Introduction

Determination of S-wave velocity structure in near-surface deposits is very important in engineering, environmental and geotechnical studies. Seismic refraction survey and borehole PS-logging have been around for this purpose for years. However, limited energy of S-wave seismic sources and need for drilled hole in PS-logging, generally make these methods inconvenient for surveying. Looking for a more convenient method of determining near-surface S-wave velocity structures was demanding for seismologists.

It has been shown that dispersion of phase velocity of Rayleigh waves is mainly controlled by thickness and S-wave velocity of the shallow deposits. That is why analysis of surface wave data for near-surface S-wave velocity determination was the subject of many studies in the last two decades. Nazarian *et al.* (1983) employed spectral analysis of surface waves (SASW) for the determination of 1D S-velocity structures in the top 100 m of the sub surface. Most of the surface-wave based techniques have calculated phase differences between two receivers using a simple cross-correlation method. Multi-channel analysis of surface waves (MASW) was introduced by Park *et al.* (1999a, 1999b). In their method phase velocities are directly determined from multi-channel surface-wave data after transforming seismic data to the phase velocity- frequency domain. In the MASW method one can visually distinguish the fundamental mode of Rayleigh wave dispersion from higher modes and body waves. This is the advantage of the MASW method compare to the SASW method.

Miller *et al.* (1999) and Xia *et al.* (1999) applied the MASW method to conventional 2D near-surface seismic shot records, and determined 2D S-wave velocity structures of the shallow layers. According to Park *et al.* (1999a), performing seismic survey with a long receiver array is preferable in order to determine phase velocities at low frequencies precisely. However, a longer receiver array might decrease the lateral resolution of the survey, because the conventional MASW method provides a velocity model averaged over the total length of the array. A smaller array is better for increasing lateral resolution. Improved lateral resolution is traded off against accuracy of phase velocity.

Common Mid-Point cross-correlation analysis of multi-channel surface-wave data was demonstrated by Hayashi and Suzuki (2004) in order to overcome this trade-off.

To enhance the lateral resolution, we aimed to use cross correlations of those pair of traces that have the same common-mid-point locations. This has required using a multi-shot method and moving the receiver spread and shot points, as in the 2D reflection seismic profiling method. In this study we developed a sort of automatic procedure to perform cross correlations of every pair of traces and attribute them to the appropriate midpoint, so Common Mid-Point Cross-correlation gathers (CMPCC groups) are easily obtained.

Data Acquisition

Study area was located east of Toronto, Canada near the community of Whitevale in Durham Region (Fig. 1). A small scale multi-fold 2D seismic survey was successfully conducted in a nearly flat farm field. In this survey a shotgun source firing a 12 gauge blank shotgun shell in a one meter deep, water filled, shot hole was used. Usable frequency content up to 200 Hz was readily obtained. Seismic data set used in this study consists of 46 shot records each of them with 24 geophones, 2m geophone separation, and 8m shot to nearest geophone distance. Fig. 2 shows an example shot record of this data set and its amplitude spectrum. Shot station spacing was 2m and seismic traces were 256 msec long with 0.25 msec sampling interval. Data collected using Oyo-Geospace DAS-1 digital engineering seismograph.

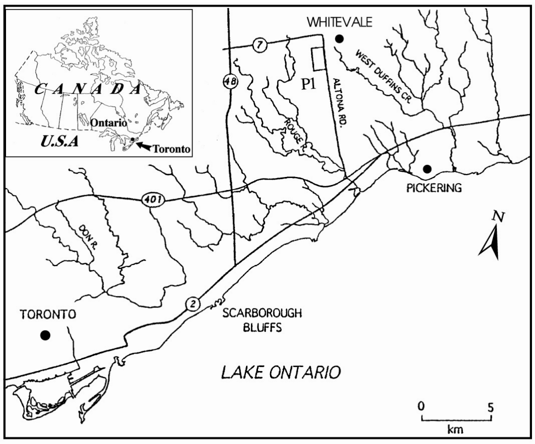

Figure 1. Map indicating study area (rectangle called P1) (Siahkoohi & West 1998).

The geology of the study area consists of about 90 m of Quaternary (Pleistocene) sediments deposited during the last full cycle of continental glaciation and deglaciation (Wisconsin <125 ka). The Pleistocene deposits can be divided into two main depositional sets. The upper deposits (~50 m thick) are pair of Late Wisconsin tills: the Halton and Northern Tills. The two tills are separated by a thin layer (2-10 m) of silt, sand, and gravel which records a short-lived interstadial period. A lower set (~40 m thick) consists of Middle Wisconsin Thorncliffe glacio-lacustrine sediments overlying Sunnybrook till and Early Wisconsin Scarborough glacio-lacustrine sediments. In this area the sediments rest unconformably on Upper Ordovician (460-440 Ma) Whitby shale bedrock (Siahkoohi and West, 1998).Geology of the study area is shown in Fig. 3. The P-wave velocity of layers on the figure is obtained from processing of reflection seismic data.

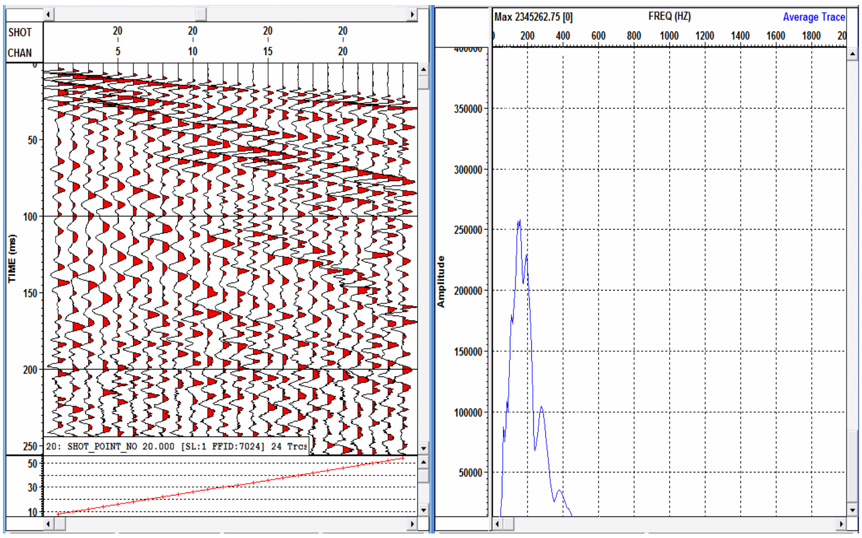

Figure 2. Shot record #20(after AGC) and average amplitude spectrum of traces within the shot record.

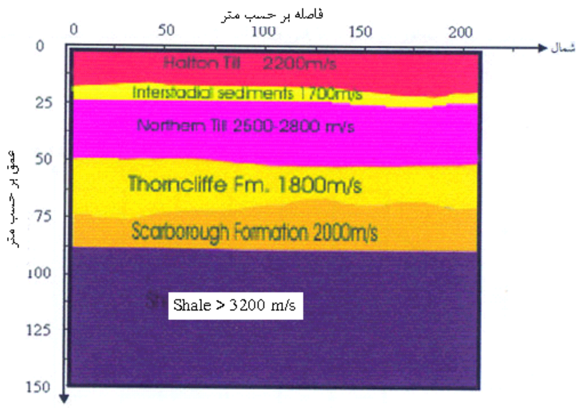

Figure 3. The geology of the study area obtained from previous studies with P-wave velocity of layers (Siahkoohi & West 1998).

CMPCC Surface Wave Data Analysis

Data processing in this study can be described as following steps:

Step (A): First, common mid point cross-correlation gathers are calculated (for the mathematical description of the cross correlation method of time series see Oppenheim *et al.* 1996).

Step (B): Then, phase velocity-frequency wave field transformation is applied to the CMPCC gathers.

Step (C): Finally, 1-D S-wave velocity profile is reconstructed from phase velocity dispersion curve using forward modeling for every CMPCC gather.

Step (D): A 2-D Vs profile can be obtained by interpolating of 1-D velocity profiles.

Summarized Data processing procedure is shown in Fig. 4. Each step of this flowchart will be explained.

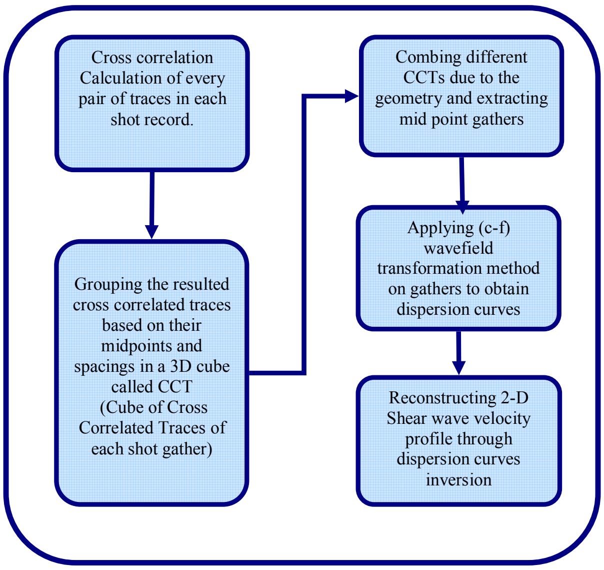

Figure 4. Data analysis flowchart.

After preliminary data preparation, the following steps are applied in order to perform Step (A):

- In each shot gather, every pair of traces is cross-correlated. In total 276×46 cross correlations are carried out over our data set.
- Cross correlated traces having a common mid-point are grouped together.
- At each common mid-point, correlated traces that have an equal spacing are stacked in the time domain.
- Traces are ordered with respect to their spacing, at each common midpoint.

Fig. 5 and Fig. 6 illustrate the concepts used in Step (A).

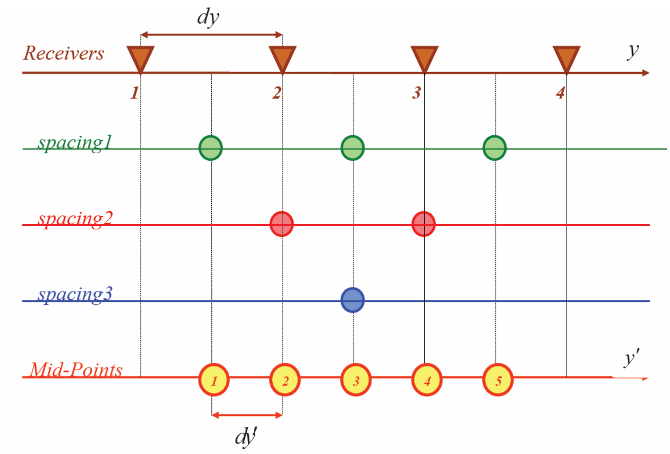

Figure 5. Illustration of receivers and mid-points relation.

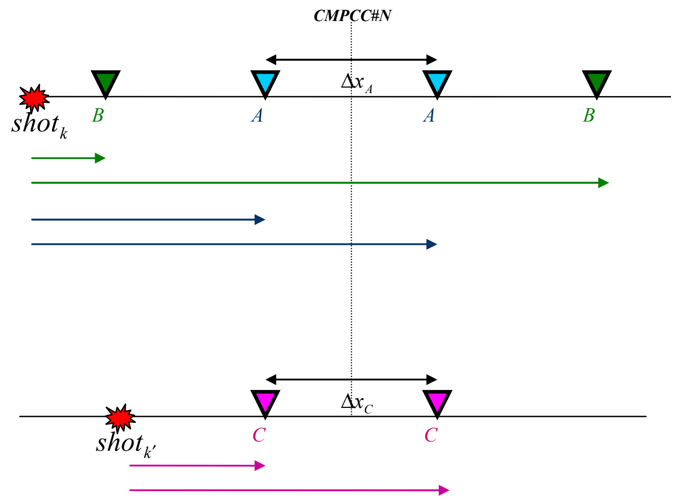

Figure 6. Cross correlated traces at a common mid-point from different shots having the same spacing.

As it was explained, in the CMPCC method grouping cross correlated traces based on their midpoint and pair separations is crucial. In this study we developed a sort of automatic procedure to perform cross correlations of every pair of traces of each shot and attributing them to the appropriate place in a 3-D array called Cube of Cross Correlated Traces of each shot gather (CCT) according to their midpoint and spacing. The resulted cube consists of cross correlated gathers assigned to the midpoint locations where traces within each gather are ordered based on pair spacings. Fig. 7 demonstrates the algorithm of this automatic procedure and Fig. 8 provides easier imagination of CCT cube.

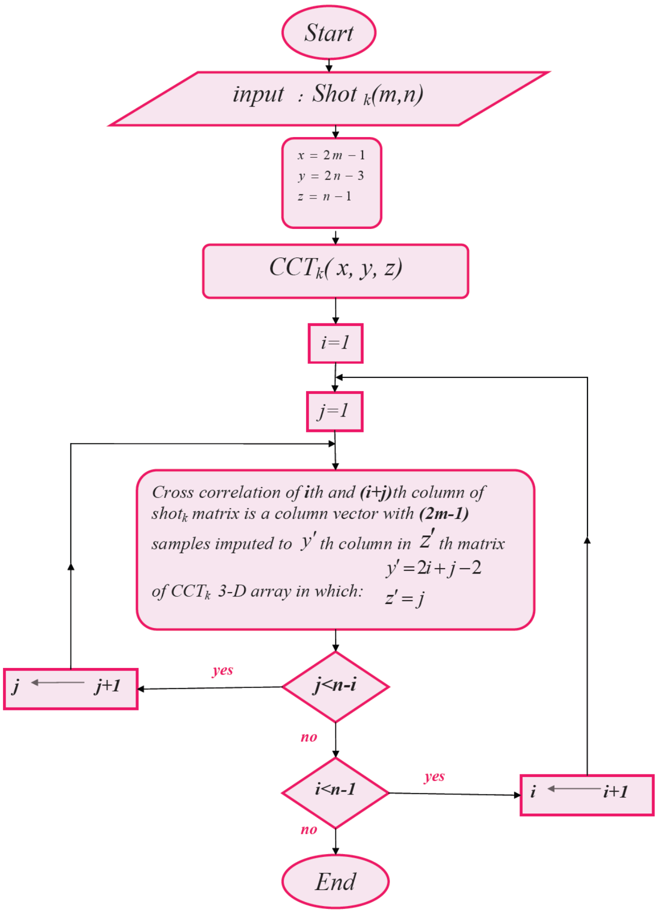

Figure 7. Algorithm generating CCT cubes.

Then different CCTs are combined due to the geometry and common mid point cross correlation gathers are extracted from the resulted 3-D array.

In Step (B) Phase velocities are calculated at each midpoint gather. Dispersion curves of different modes can be imaged directly from the full wavefield (c-f) transformation method applied on CMPCC gathers.

(c-f) transformation method can be summarized as below:

The Fourier transformation is applied to time axis of offset-time domain of a record.

Then an integral transformation is applied. The integral transformation can be thought of as the summing over offset of wave fields of a frequency after applying offset-dependent phase shift determined for an assumed phase velocity to the wave fields; This process is identical to applying a slant stack to the equivalent time-domain expression of the wave field for a single frequency. After changing the variables, phase velocity-frequency image is obtained. The locus along peaks over different values of frequency permits the images of dispersion curves to be constructed in the c-f domain. In this way, the midpoint gathers in distance-time space are transformed into c-f space directly.

After this step, 1-D Vs profile is reconstructed for each CMPCC gather by using forward modeling. Interpolation of 1-D Vs profiles of different positions can provide the 2-D Vs profile.

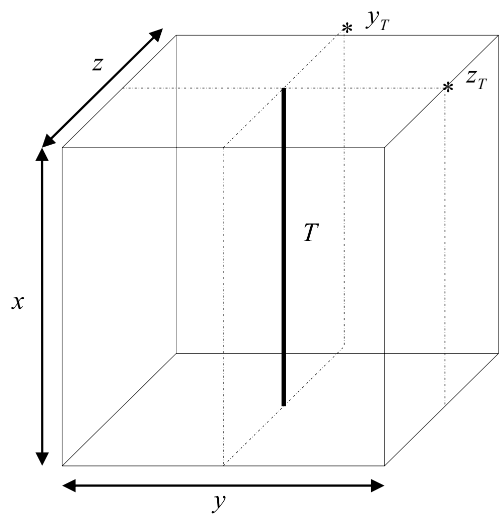

Figure 8. A simple figure for better imagination of CCT 3-D array.

Application to Field data

The method was applied to the collected field surface-wave data. After applying this process on our real data set, 135 CMPCC gathers are generated. Spacing between adjacent CMPs in this study is one meter.

Fig. 9a, 9b and 9c show the c-f image of some CMPCC gathers and their 1-D Vs profiles. The CMPCC gathers shown here are respectively from the beginning, middle and the end of our survey line. Finally a 2-D Vs profile can be reconstructed by interpolation of 1-D Vs profiles at different CMPs.

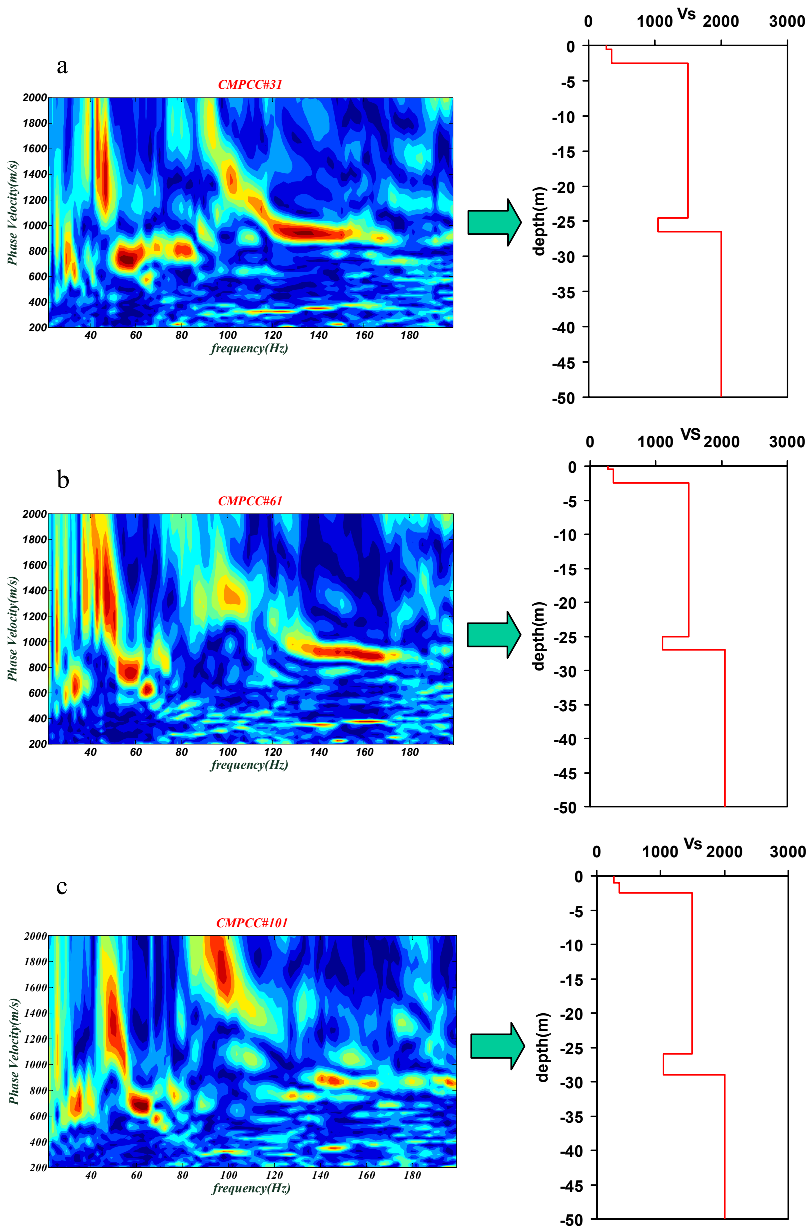

Figure 9. The c-f image of CMPCC gathers number 31, 61 and 101 and their 1-D Vs profiles.

Conclusions

MASW method can determine phase velocities precisely using whole waveform data while the SASW method cannot determine high-frequency phase velocities from large-spacing cross correlations because of spatial aliasing. The method employed in this study is a further extension of MASW that enables us to determine phase velocities from multi-shot data directly, by using cross correlated traces at midpoint gathers. In this method even if each source wavelet and its phases are different, cross correlations can be stacked because for the purpose of this study we use the correlation only to store the phase differences between two traces. The phase differences contained in the source wavelet have been removed.

On the other hand resolution of (c-f) image is superior to that obtained by using a pre-existing transformation method especially when the record contains a relatively small number of traces over relatively narrow range of source-to-receiver offset.

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