CMP stacking for multi-channel analysis of single-shot surface wave data

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***Abstract*—We demonstrate that common mid-point (CMP) stacking analysis for common virtual-source (CVS) cross-correlation gathers of multi-channel and single-shot surface wave data give accurate phase-velocity curves, and enable us to reconstruct 2D Vs structures with high resolution. Data processing for CMP stacking analysis consists of the following four steps: First, cross-correlations are calculated for every pair of traces in the single-shot gather. Second, correlation traces having a common virtual-source are gathered. Third, dispersion measurements are implemented for each CVS gather with existing dispersion imaging methods, e.g., linear Radon transformation, phase-shift method. Finally, dispersion results of CVS cross-correlation gathers having a common mid-point are stacked to obtain an ultimate dispersion result at the CMP position. With CMP stacking analysis method, it is feasible to reconstruct high-resolution 2D Vs structure by inversing dispersion results at each CMP position. Numerical modelling example indicates the superiority of the new method in improving the accuracy and resolution of subsurface dispersion measurements, compared with conventional MASW method and CMPCC method.**

Keywords—masw, cross-correlation, virtual-source, horizontal resolution, cmp stacking, dispersion measurement, cmpcc

I. INTRODUCTION

As a nondestructive method for obtaining S-wave velocity structures, the multichannel analysis of surface waves (MASW) method has been widely applied[1-3]. The MASW method utilizes a multichannel recording system to estimate near-surface S-wave velocity from high-frequency Rayleigh waves. This technique consists of: (1) acquisition of multi-channel, wide band, high-frequency surface waves along a linear survey line by use of the roll-along mode; (2) creation of efficient and accurate algorithms organized in a straight-forward data processing sequence designed to extract and analyze 1D Rayleigh-wave dispersion curves [4-5]; and (3) development of stable and efficient inversion algorithms to obtain S-wave velocity profiles [6]. Finally, a pseudo-2D shear-velocity section can be constructed by aligning 1D models at the midpoint of each spread [7].

Hayashi and Suzuki[8]develop CMP cross-correlation (CMPCC) analysis of surface waves, in which cross-correlations with the same CMP are gathered [8-9]. Because midpoints of all the cross-correlation pairs coincide with the CMP, local dispersion curves can be estimated with high horizontal resolution from CMP cross-correlation gathers. Note that, to extract high resolution dispersion curves by using CMPCC method, multichannel and multi-shot surface wave data must be provided. If we extract CMP cross-correlations from only one shot gather, the resolution is lower and other many cross-correlations that have different mid-point would be thrown away. For instance, as compared with ten pairs can be extracted from 5 traces, only two traces can be grouped as CMP cross-correlations.

With the increasing shortage of social resources, it is more and more restrictive to implement of multi-shot and roll-along mode survey in the complex and limited urban environment. When only single-shot surface wave data is available, however, it will be hard to extract high horizontal resolution dispersion curves for Vs profile mapping by using conventional MASW method and CMPCC method. The authors have developed following analysis method in order to solve this scientific and engineering problem.

II. CMP STACKING ANALYSIS

Fig.1 demonstrates schematic representation for data processing scheme of the multi-channel analysis of single-shot surface-waves(MASS). With only single-shot surface wave data isavailable, one phase velocity frequency image is converted through MASW method. Clear dispersive later phases can be observed and its apparent velocity changes suddenly at the middle of the spread in the *x-t* domain (Fig. 1a). It indicates that a velocity structure changes laterally in the middle of the spread. Therefore, the phase-velocity curve in the *f-v* image splits into three curves in the frequency range between 30 and 55 Hz (Fig. 1b). It is unsufficient to use one piece of the split dispersion curve to reconstruct 2D Vs structures.

Based on the virtual-source strategy [10], we proposed to turn the single-shot gather to multiple virtual-sources gathers by using cross-correlation [11-12]. A longer receiver array might decrease the horizontal 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 horizontal resolution. However, improved horizontal resolution is traded off against accuracy of phase velocity. We have developed CMP stacking analysis to

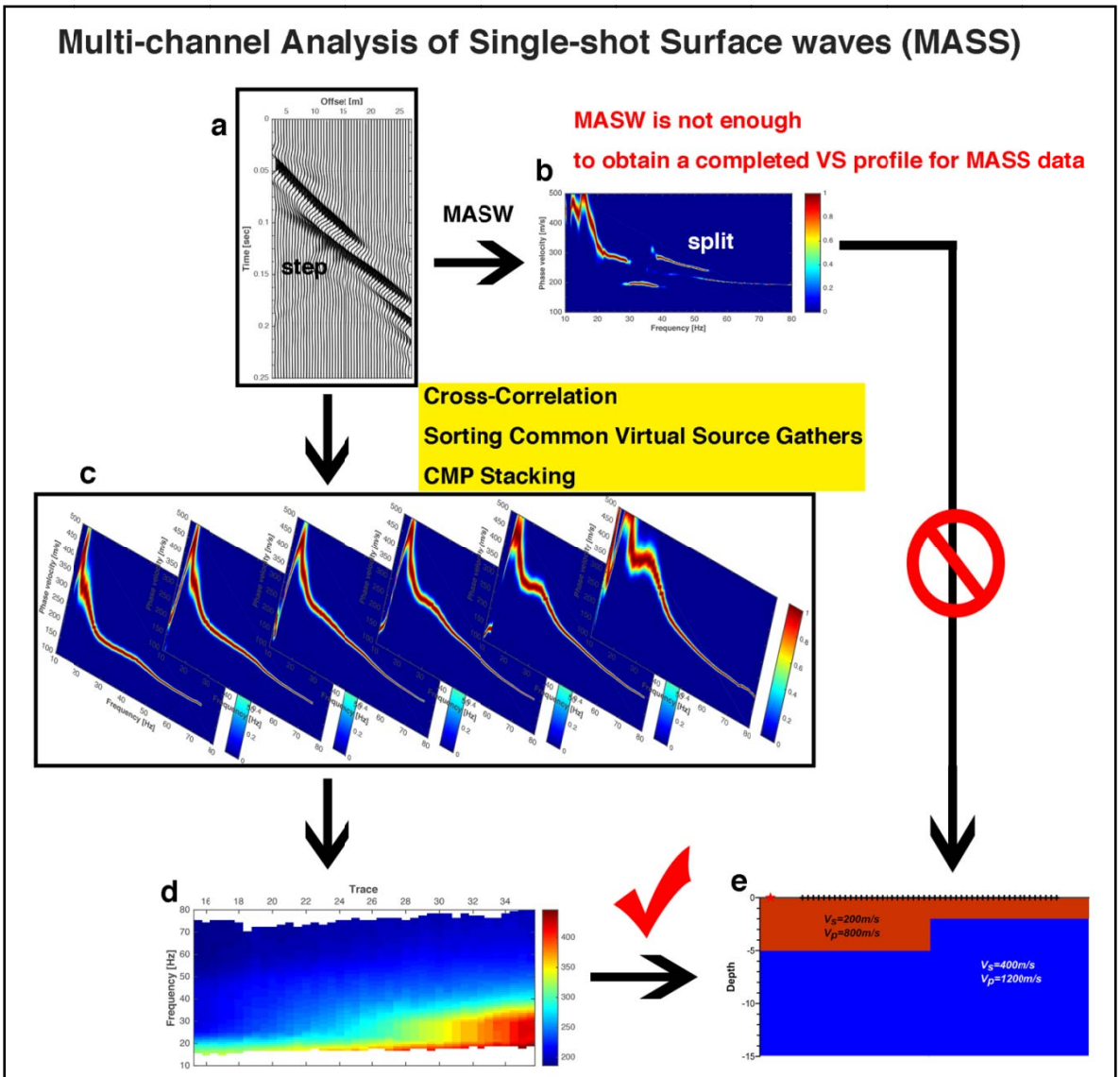

Fig. 1.Schematic representation for data processing scheme of the MASS.

overcome this trade-off and extract a series of high-resolution and continued dispersion curves (Figs. 1c, d) for 2D Vs profile reconstruction (Fig. 1e).

The procedure for CMP stacking analysis is summarized in the following way:

(1). Cross-correlations are calculated for every pair of traces in the single-shot gather. For example, 276 cross-correlations can be calculated from a shot gather that includes 24 traces.
(2). Correlation traces having a common virtual-source are sorted and gathered.
(3). Dispersion energy images are measured for each common virtual-source (CVS) gather with existing dispersion-imaging methods, e.g., phase-shift method [13], linear Radon transformation [5][14].
(4). Dispersion results of common virtual-source cross-correlation gathers having a common mid-point are stacked to obtain an ultimate dispersion curve at the CMP position. For each CMP position, a series of CVS arrays with variable spread-lengths and/or trace-numbers exist. With dispersion measurements from longer CVS arrays and smaller CVS arrays stacked, the horizontal resolution and accuracy are simultaneously promised for the obtained CMP-dispersion result. In some real-world case, CMP weighted stacking with a simple trace-number weighting is suggested for a better trade off between horizontal resolution and accuracy.

III. Numerical Test

A numerical test was performed in order to evaluate the applicability of the proposed method. A two-layer model with a step at the distance of 15m (Fig. 1e) is applied in the test. A stress-velocity, staggered grid, 2D finite-difference method is used for generating theoretical waveform data (Fig. 1a). Forty-eight traces of the vertical-component are modeled with a nearest offset of 3 m and a 1 m trace interval. The total recording length is 500 ms, with a sampling rate of 1 ms, as Fig.1e shows.

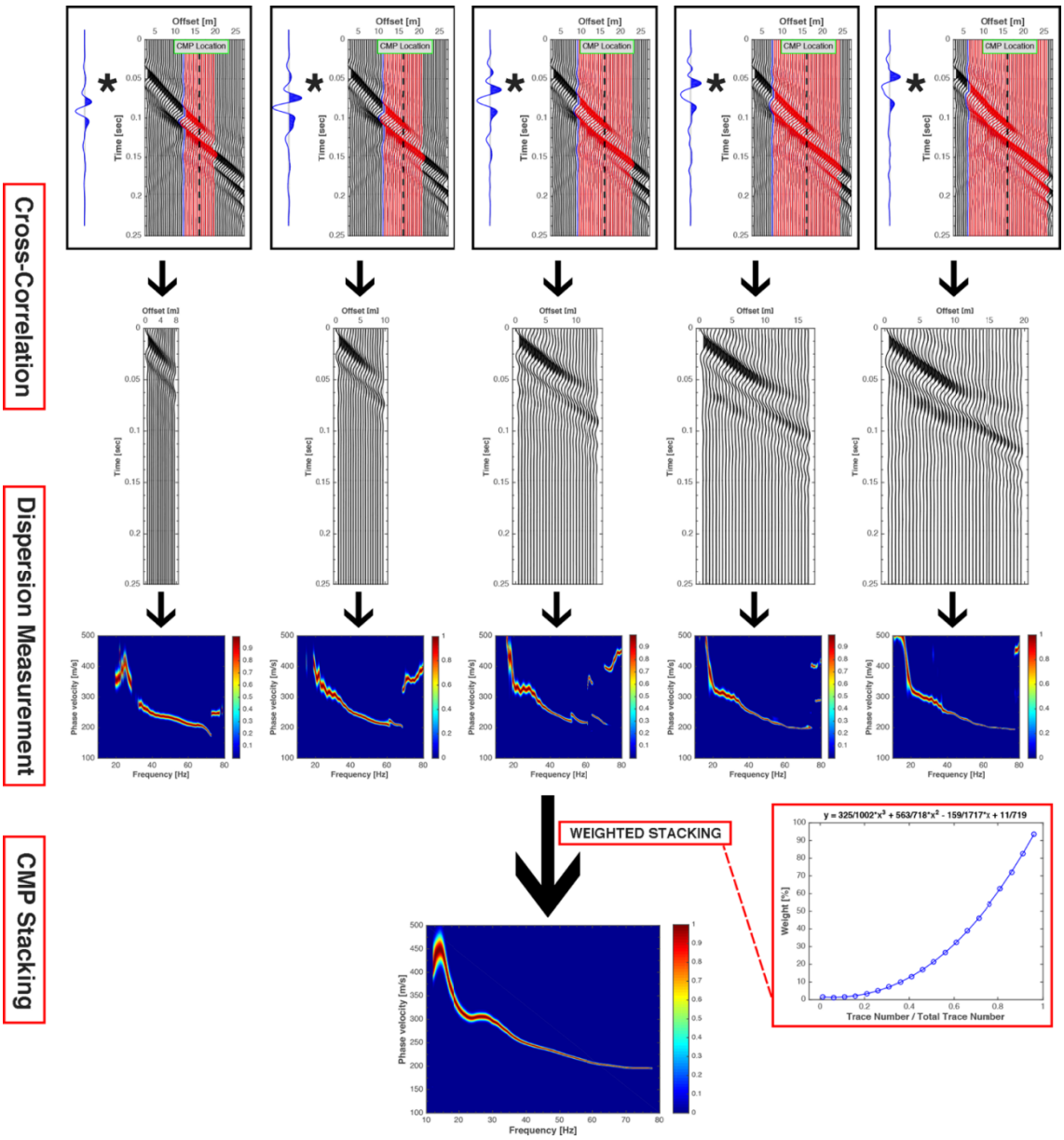

Fig. 2. An example of data processing of CMP stacking analysis for dispersion measurement at site 13.5m based on MASS data.

The CMP analysis was applied to the single-shot theoretical data. Fig.2 displays an example of data processing of CMP stacking analysis for dispersion measurement at site 16.5m based on MASS data. Linear Radon transformation was implemented for dispersion imaging of each CVS gather. The trace-number weighted stacking was used for the trade off between horizontal resolution and accuracy of dispersion results. For the purpose of accuracy, we empirically added more weight to the larger trace-number.

The ultimate CMP-dispersion result will be used for further inversion work to obtain Vs structure. 40 pieces of ultimate and acceptable dispersion curves were obtained for CMP position from 15.5th trace to 35th trace, as Figure 3a displays. A clear step shape occurs from the position 24th trace, which is identical with the numerical model (Fig. 1e).

CMPCC method was implemented for construction, as Fig.3b shows. With limited number of cross-correlation pairs, CMPCC method displays a poor accuracy at low frequency band (<30Hz), especially at the left side of step. Due to common mid-point gathers are used for dispersion measurements in the CMPCC method, rather than common virtual-source gathers in CMP stacking analysis, the biggest trace-number of the former is half of that of the latter, as Figure 3c shows.

IV. Conclusions

In this preliminary paper, we propose a novel strategy for multi-channel analysis of single-shot surface waves. We demonstrate the data processing scheme of common mid-point

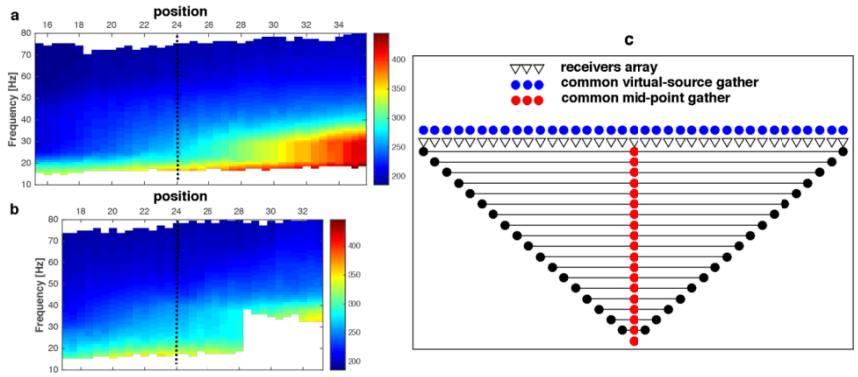

Fig. 3.Extracted dispersion curves distribution for the fault model in numerical modelling test from CMP stacking analysis (a) and CMPCC analysis (b). The dashed line indicates the position of the step at the mid-trace, the 24th trace. (c) demonstrates cross-correlations sortting scheme for CVS gather and CMP gather. The upside-down triangles denotes receiversarray; the blue and red dots denote CVS and CMP gather, separately.

(CMP) stacking analysis for multi-channel and single-shot surface wave data. With dispersion measurements of a series of common virtual-source cross-correlation gathers with variable spread-lengths and/or trace-numbers stacked, CMP stacking analysis gives accurate phase-velocity curves, and enable us to reconstruct 2D Vs structures with high resolution. Theoretical test indicates the superiority of the new method in improve the accuracy and resolution of subsurface dispersion measurements, compared with conventional MASW method and CMPCC method.

The traditional MASW method could obtain only one averaged dispersion measurement from single-shot surface wave. MASW cannot determine high horizontal resolution as well as accuracy of dispersion measurement with a longer receiver array. High horizontal resolution is traded off against accuracy of phase velocity. CMP stacking analysis overcomes this trade-off by using a series of CVS arrays with variable spread-lengths and/or trace-numbers.

CMPCC method would be a good choice for multi-shot surface wave data. As to multi-channel and single-shot surface wave data, however, the accuracy of dispersion curves is poor due to limited CMP cross-correlation pairs. The key difference between CMP stacking analysis and CMPCC method is the cross-correlation gathers used for dispersion measurement. We utilize common virtual-source gathers for CMP stacking analysis, but common mid-point gathers for CMPCC method. Compared with CMPCC method, the advantage of CMP stacking analysis lies in the better usage of the limited cross-correlations in the single-shot surface wave data. As for a same receiver array, the biggest trace-number for CMP stacking analysis is twice that used in CMPCC method.

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