Active Multichannel Analysis of Surface Waves with Non-Straight Line Geophone Array

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Abstract. Active multichannel analysis of surface waves (MASW) requires sen- sor placement along a straight line with equal spacing to predict the properties of subsurface earth. However, due to the presence of different obstacles in the field, placing sensors along a straight line is not always possible. To this end, the pri- mary objective of this study is to propose a non-straight line receiver array based active MASW method. The proposed method follows a diverted path near the obstacle while keeping the rest of the geophones in a conventional straight line before and after the shift. Sensors are shifted on an arc of a circle, with the source acting as the center of this circle. Therefore, the distance between the source and shifted sensors remains the same as their original position. This simple maneuver enables us to use existing wavefield transformation techniques without any mod- ification. Multiple field experiments are performed using different non-straight line arrays. Dispersion images obtained from the proposed method resembled theoutcomes of a conventional active MASW survey.

Keywords: MASW; Surface wave; Linear array; Non-linear array; DispersionImage

1 Introduction

Non-invasive surface wave methods such as spectral analysis of surface wave (SASW) and multichannel analysis of surface wave (MASW) are widely used to predict the shear wave velocity profile of sub-surface earth[1–3]. Rayleigh waves are predominantly used for nonintrusive near surface characterization because of their dispersive nature and excellent signal to noise ratio[4–6]. With respect to source characteristics, MASW can be categorized as an active survey and a passive survey. For active surveys, an impact source such as a 20lb sledgehammer is struck on a grounded plate to produce surface waves. While in a passive survey, ambient noises are used as the source for the surface waves. Both MASW methods involve three primary steps, (i) field data acquisition, (ii) generation of dispersion image [7], and (iii) inversion of extracted field dispersion curve. Raw ground roll data on the field are recorded with the help of 24 to 48 geophones. The recorded time-space data is then converted into frequency-phase velocity domain using different wavefield transformation techniques such as phase-shift transform [2], time intercept-slowness transform [8], frequency-wavenumber transform [9], (iv) high-resolution linear Radon transform (HRLRT) [10], and Modified S-transform based HRLRT [11] etc. Modal dispersion curves are extracted from the field dispersion image by manually picking each point along the maxima or using commercial software. These extracted field dispersion curves are used in the inversion analysis to predict the shear wave velocity profile of sub-surface earth. The inversion process starts with an assumed 10 to 20 layered soil profile called a priori information, and with every iteration, the assumed sub-surface model is modified to attain a reliable prediction [4, 12].

The conventional active MASW investigation requires deploying 24-96 geophones along a straight line with even spacing on the ground surface [2]. To date, researchers used the same straight line array to record the active MASW survey data and past research was mainly focused on analyzing the effect of the varying source to offset distance and receiver spacing [13]. Naskar and Kumar [1] first introduced uneven receiver spacing for spectral analysis of surface wave (SASW) tests. Six geophones were used with 2m, 1m, 1m, 2m, and 2m spacing, respectively. Later, uneven receiver spacing was adopted by Park et al.[14] for the MASW survey. They used increasing sensor spacing with an increase in the offset. Park et al.[14] demonstrated that increasing sensor spacing can lead to an increased investigation depth without compromising the resolution of the dispersion image. Zhang and Li [15] conducted a study on uneven receiver spacing using a mobile source. These studies follow a usual linear straight-lined array formation with uneven spacing. Therefore, they require significant modification to the existing wavefield transformation technique. Furthermore, even these methods require a large stretch of straight empty ground to perform field test. Due to different obstacles in the field, a straight-lined arrangement of receivers with large receiver spacing is not always feasible, especially in urban areas. In such a scenario, the field investigator has no option but to find a nearby alternate location or completely abandon the test.

The present study introduces a non-straight line array based active MASW survey on conducting field tests where traditional straight lined array MASW tests are not feasible. It side tracks the geophones near obstacles while keeping the rest of the geophones in a straight line. Therefore, the proposed method can avoid most of the obstacles present in the path of MASW tests. To demonstrate the efficacy of proposed technique, multiple field tests are conducted on two different sites with sensor shift of 1m, 2m and 4m. The number of geophones shifted also varied between 17% to 33% of the total geophones deployed. Dispersion images from these tests are compared with dispersion images generated by traditional straight line array MASW tests. The shifted geophone’s dispersion images are found to be similar and well correlated, proving the usefulness of the proposed approach. The present research work will tremendously help MASW researchers and practicing field engineers.

2 Methodology

The fig 1 depicts the conventional arrangement of the active MASW method and proposed non-straight line array formation. Under the proposed method, a few geophones are laterally shifted near the obstacle. The sensors were shifted following the same propagating wavefront as in the linear formation. Consequently, there will be no time delay in the recorded signal between the geophones before and after the shift. Therefore, the proposed method enables field investigators to use all existing wavefield transformation techniques without any modification.

Let's assume there is an obstacle present after the m^{th} geophone in the MASW survey path and its blocking n number of geophone placement (Fig 1). Thus from $(m + 1)^{th}$ to $(m + n)^{th}$ geophones need to be shifted to avoid the obstacle. The proposed method involves the following steps:

i. Measure the distance between source and geophone that require to be shifted. Let's assume this distance is r.
ii. Draw an arc with radius r and wave source as a center.
iii. Place the geophones on this arc line as per the shift length required.

The position of the other sensors will remain unchanged.

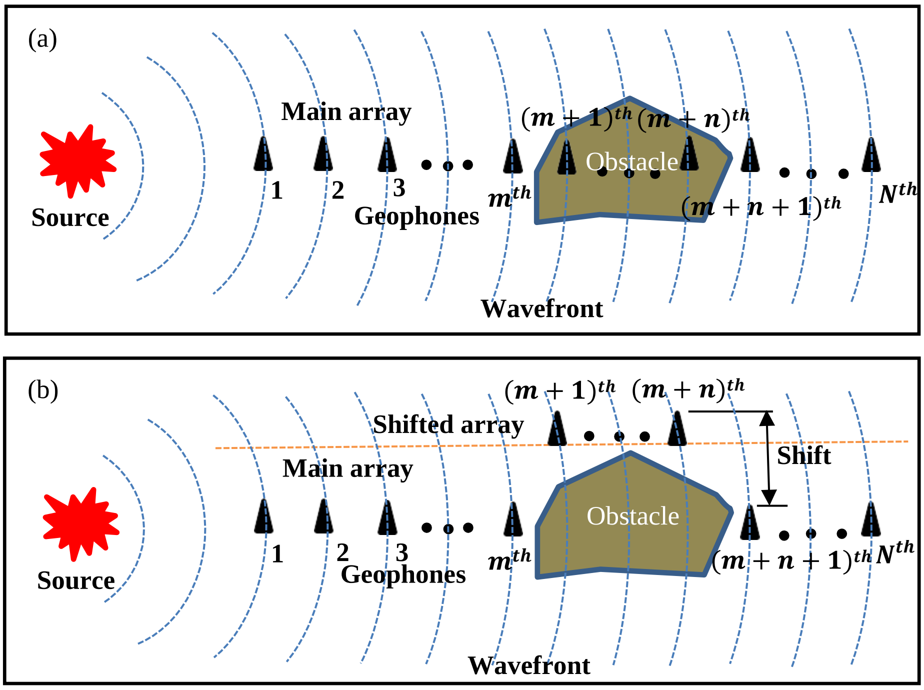

Fig. 1. Schematic of active MASW survey with (a) conventional straight line receiver formation, and (b) proposed non-straight line receiver formation

3 Results

Multiple field MASW tests are conducted on two different sites and nine different set-ups of non-straight line array formation are employed at each site. Dispersion images from these tests are compared with the traditional straight line array based MASW method. The present study employs 24 nos HG-6XT vertical geophones along with a data acquisition system (DAQ link). The natural frequency of the geophone is 4.5 Hz with a tolerance frequency of +/- 0.5 Hz. Sensor spacing and source to first receiver offset is kept at 1 m and 5 m, respectively. Wavefield source energy is generated by striking a 20 lb sledgehammer on a rectangular iron plate (300 mm ×300 mm×20 mm) placed on the ground surface. Field data is recorded with a sampling interval of 0.125 ms for a duration of 2 sec. At each location, among 24 geophones, 4, 6, and 8 geophones are shifted, representing 17%, 25%, and 33% of the total geophones. For each of these shifted geophones, shift lengths of 1 m, 2 m, and 4 m are employed. Thus, capturing the effect of obstacles of different sizes and shapes.

3.1 Field test at site 1

The first field test is conducted near the sports complex located at the IIT Madras campus. Fig. 2-4 provides the dispersion image for four, six, and eight shifted sensors. The first sub-plot [Fig. 2(a), 3(a), and 4(a)] are for the conventional active MASW survey and other sub-plots [Fig. 2-4,(b)-(d)] are obtained for 1 m, 2 m, and 4 m receiver shifts. These figures illustrate the influence of the non-straight line array on the attribute of dispersive characteristics. It can be seen that, for up to 2 m of shift length, shifted dispersion images completely resemble the conventional straight line array based dispersion image. For a shift length of 4m, the shifted dispersion image still resembles the straight line array based dispersion image; however, a small amount of distortion can be observed at relatively higher frequencies. A similar result can be obtained for six and eight shifted geophones. For a shift of 1m and 2m length, the shifted dispersion image completely resembles the traditional straight line array dispersion image [Fig 2-4]. Only for the 4m shift length, a small distortion at the higher frequencies can be observed. Therefore, it can conclude that, for a given shift length, the number of shifted sensors (4-8 numbers) has negligible effects on the outputs. A greater shift length affects the dispersion images more prominently.

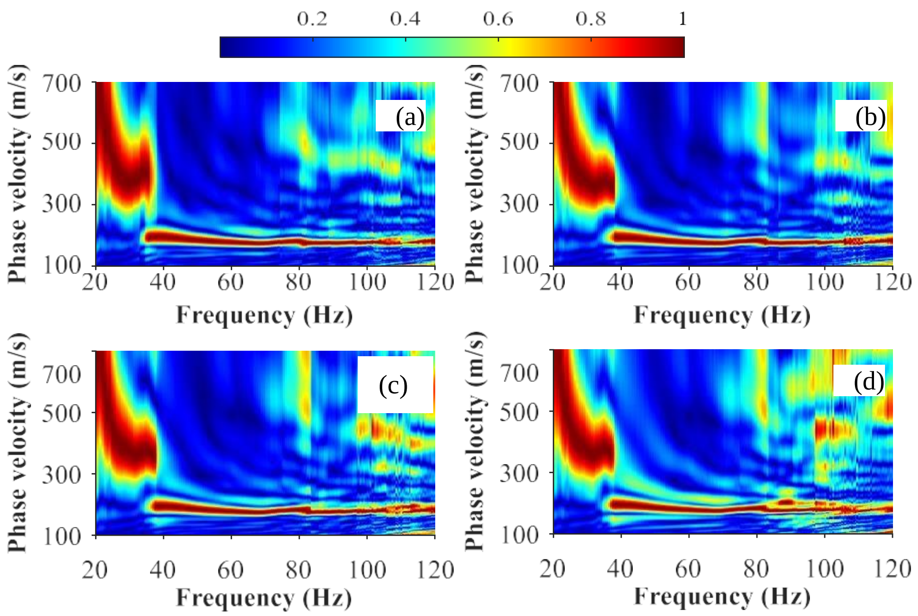

Fig. 2. Dispersion image for (a) without shift (b) 1 m shift, (c) 2 m shift and (d) 4 m shift of four geophones at site 1.

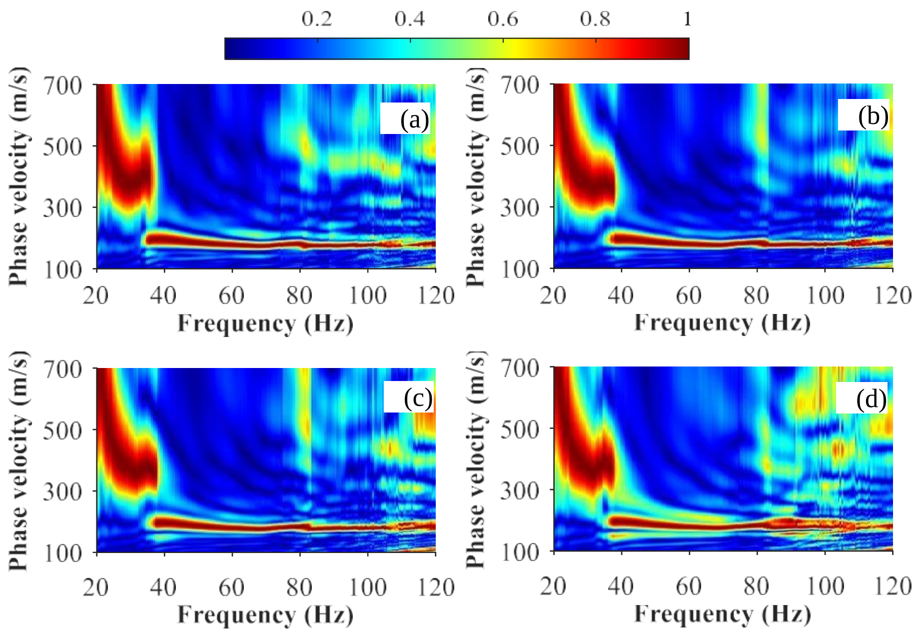

Fig. 3. Dispersion image for (a) without shift (b) 1 m shift, (c) 2 m shift and (d) 4 m shift of six geophones at site 1.

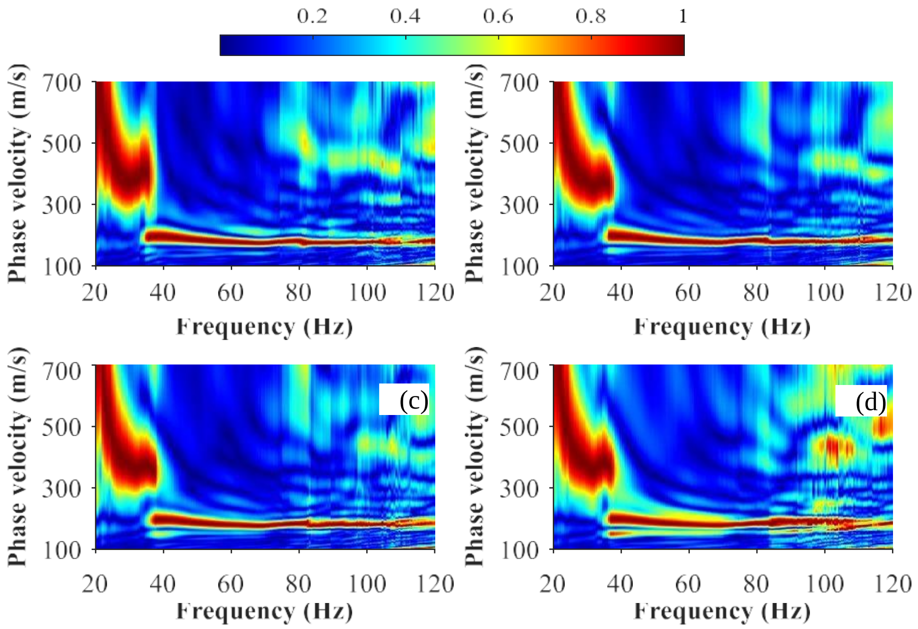

Fig. 4. Dispersion image for (a) without shift (b) 1 m shift, (c) 2 m shift and (d) 4 m shift of eight geophones at site 1.

3.2 Field test at site 2

The second field test is conducted at the KV ground of the IIT Madras campus. Receiver spacing, first offset, sampling frequency, energy source etc. are kept the same as in location 1. At site -2, for four shifted geophones and a shift of up to 4 m lengths, the non-straight line dispersion images closely resemble the traditional straight line array dispersion images [Fig. 5]. The modes are clearly continuous and clearly distinguishable. Similar results have been obtained for the 6 and 8 sensor shifts [Fig 6-7]. However, for six and eight shifted geophones with a 2m of shift, the predominating mode discontinues at a frequency range of 43-47 Hz [Fig. 6(c), 7(c)]. The such discontinuity can be attributed to the presence of a thin layer with sharply contrasting shear wave velocity at this location. It is worth mentioning that, despite the discontinuity, these dispersion images follow almost the same dispersive characteristics as observed in the dispersion image without shifted geophones [Fig. 6(a), 7(a)]. The dispersion image with 4m of shift exhibits negligible distortion. Overall, the dispersion image with shifted geophones resembles quite well with the traditional straight line array dispersion images.

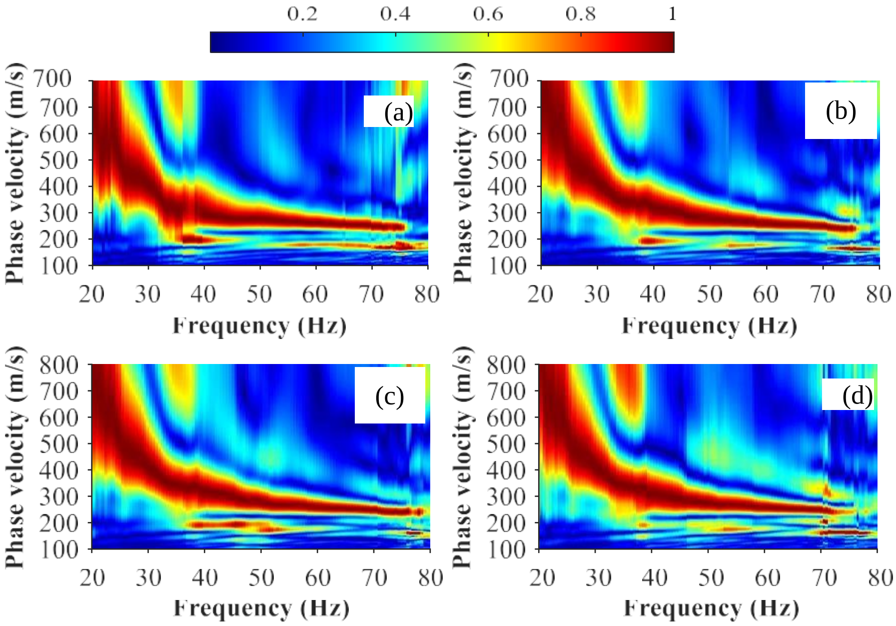

Fig. 5. Dispersion image for (a) without shift (b) 1 m shift, (c) 2 m shift and (d) 4 m shift of four geophones at site 2.

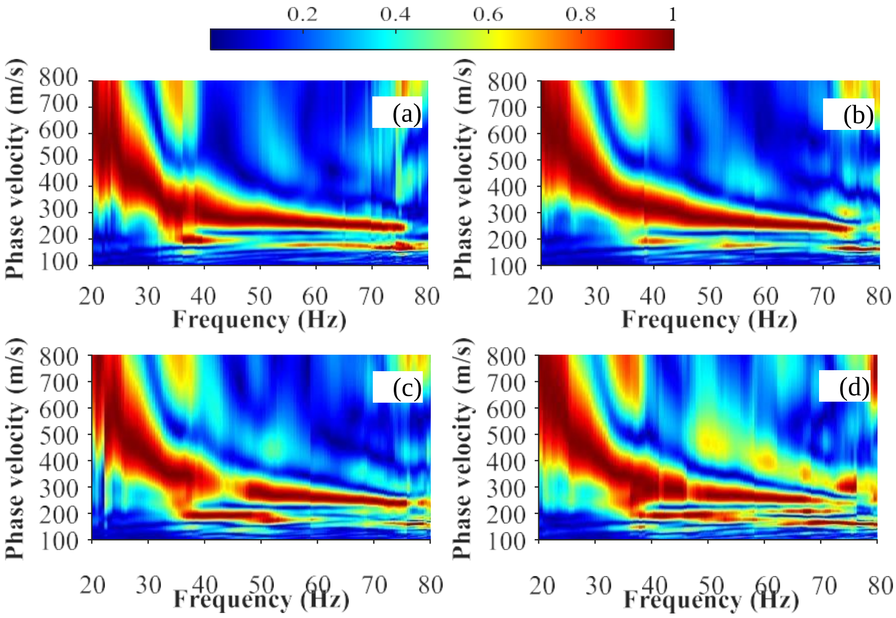

Fig. 6. Dispersion image for (a) without shift (b) 1 m shift, (c) 2 m shift and (d) 4 m shift of six geophones at site 2.

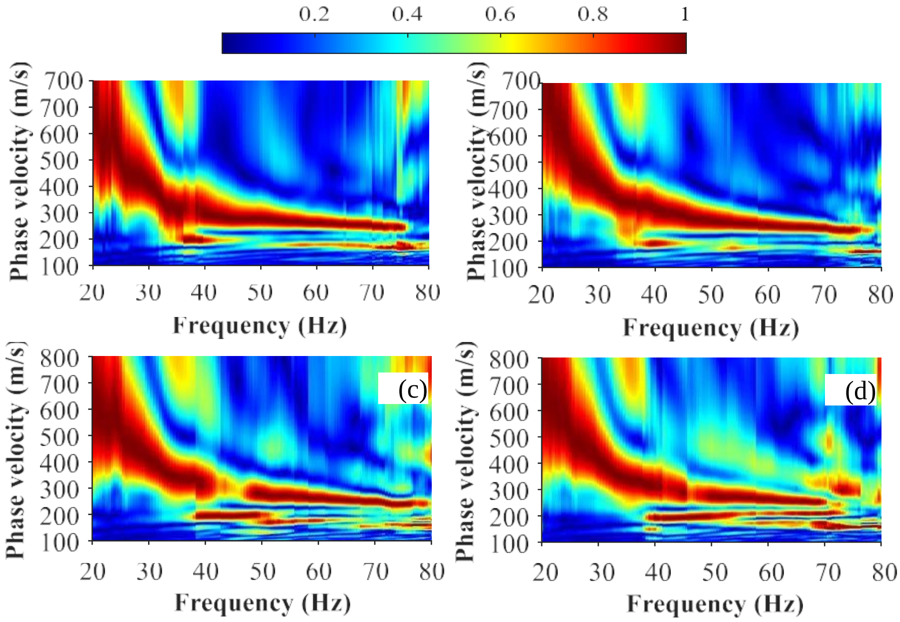

Fig. 6. Dispersion image for (a) without shift (b) 1 m shift, (c) 2 m shift and (d) 4 m shift of eight geophones at site 2.

4 Conclusion

The MASW method requires a long stretch of empty land to conduct the field test successfully. The presence of trees, rocks, houses, etc., on the survey paths, is frequently encountered during the field survey. In such a scenario, the field investigators are forced to change the survey path or, in the worst case, completely abandon the test. A new non-straight line formation of sensor placing is introduced in this paper to perform the MASW test along the obstructed test path. The proposed method shifts the geophones near the obstacle while keeping the source to geophone distance constant. Therefore, the proposed method enables the user to employ all the existing wavefield transformation techniques without any modification. Multiple MASW tests are conducted on two sites with different numbers of shifted geophones and shift lengths. A satisfying resemblance between dispersion images from the traditional straight line array and the proposed non-straight line array demonstrates the efficacy of the proposed technique. Furthermore, the current work assesses the maximum limit of the shift length and the maximum number of geophones that can be shifted without compromising the quality of the dispersion image. Identical dispersion images are obtained for up to 2 m of shift length, and minimal distortion is observed for 4m of shift length. Up to eight geophones are shifted in a combination of four, six, and eight geophones, and identical dispersion images are obtained for all the cases. No detrimental artifacts are observed on dispersion images for the increased number of shifted geophones. The proposed method will be highly beneficial for conducting field MASW tests. It will enable researchers and practicing engineers to conduct MASW tests on difficult sites where laying geophones in a straight line array is not feasible.

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