

Subsurface Characterization using MASW: Preliminary Experimentation and analysis

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Abstract— This paper describes the application of Multichannel analysis of surface waves (MASW) to characterize the subsurface. Active MASW survey has been conducted in the plain terrain near the Civil Engineering Department, IIT Guwahati. The output signals collected in the geophones during the experimentation (time-domain signals) is post-processed through Fast Fourier Transform (FFT) with the aid of a developed Matlab code to obtain the frequency-domain signals. Following the existing phase-shift method, summed-up normalized amplitude with varying phase velocity curve is determined which is very important for the identification of energy accumulation in the dispersion image space. A commercially available software known as EasyMASW is introduced to obtain the shear wave velocity profile of the soil. EasyMASW results shows that the shear wave velocity is affected by the sampling frequency of data acquisition. The ambiguity in the results obtained from EasyMASW is also highlighted.

Keywords—dispersion analysis, phase-shift, multichannel analysis of surface waves, frequency-domain.

I. INTRODUCTION

Multichannel Analysis of Spectral Waves (MASW) is a non-destructive seismic exploration method for evaluating stiffness of the subsurface. In comparison to the conventional seismic survey methods such as cross-hole and down-hole, the MASW proves to be less expensive and less time consuming. It is fully

implemented on the ground surface (non-invasive), covers the subsurface continuously in a manner similar to ground-penetrating radar (GPR), and provides enhanced coverage. Ground penetrating radar (GPR) and Nuclear magnetic resonance (NMR) are the geophysical methods which determine the image of the subsurface by employing electromagnetic radiation. However, these methods are subjected to limitations. In the case of GPR, the saturated clay layers remain fuzzily identified due to unwanted signal attenuation. If magnetic minerals are present in the subsurface, the NMR method proves to be ineffective. MASW overcomes these limitations and proves to be a more efficient technique in recent days.

MASW survey was carried out in the plain terrain near Civil Engineering Department of IIT Guwahati to determine its dynamic soil properties in terms of shear wave velocity. Samples were collected at various sampling frequencies (15000Hz, 3750Hz, 500Hz, and 50Hz). Dispersion procedure was carried out as per the phase-shift method described in [5]. This paper describes about the effect of sampling frequency related to the data acquisition (Number of samples collected per second) on the estimated shear wave velocity of the area investigated.

II. CONCEPT OF MASW

Fig. 1 describes the overall procedure of MASW which collects or acquires multichannel field records in time domain. These records are used to produce the dispersion image of the various waves generated by one of the existing dispersion analysis methods. After obtaining the

dispersion image, the energy accumulation pattern of various curves is studied and the suitable curve is extracted and subsequently used for the inversion analysis. Inversion is the process of back-calculation of the shear wave velocity profile with the subsurface stratification depths.

There are two frequently used methods for MASW survey, namely Active and Passive MASW. The active MASW adopts the conventional seismic refraction mode of survey using an active seismic source such as hammers, weight drops, electromechanical shakers, and bulldozers. The maximum depth of investigation is in the range of 20-30m. This can vary with the site and the active source used. Passive surface wave techniques measure noise which includes surface waves originating from ocean wave activity, traffic, factories involving vibrating equipments, wind, and microtremors. Passive surface waves technique can often image shear wave velocity structure to depths over 100m, provided sufficient noise sources and space for the laying of receiver array is available. The active survey provides a dispersion curve in a relatively high frequency (short wavelength) range (20-50 Hz), for example, corresponding to wavelengths of (1-30 m). Passive survey is carried out in low frequency and higher wavelength due to which a larger receiver spacing is used than which is normally used for active survey due to which a processed dispersion image usually lacks information at shallower depths. Therefore, active survey is used to obtain the information of soil profile at shallower depth. The effectiveness of active and passive MASW survey was shown in [1] and the authors have hinted about the advantages of combined active and Passive MASW. In [2], the active and passive MASW was used for site effect studies in the Jammu city in J&K, India. The V_s profile derived from MASW show the lateral and vertical variations in shear wave velocity. The combined active and passive MASW survey helps the conduct of a proper modal analysis as shown in [3]. In [4], a comparative test of active and passive MASW method in the southern part of Ljubljana was conducted. Comparison of active and passive MASW showed that if the depth of investigation does not exceed 30 m, much

more clear dispersion image of surface waves is obtained with active method.

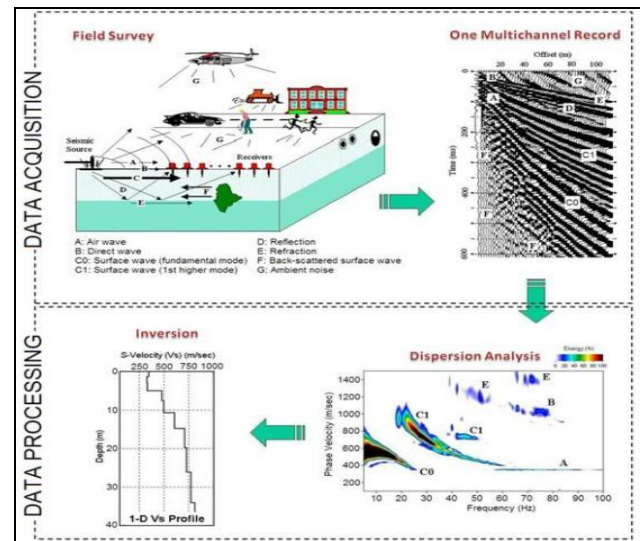


Fig 1: Overall procedure of MASW [1,9]

III. EXPERIMENTATION PROGRAM

To analyse the dispersion curve, field experiment was carried out in the plain terrain near the Civil Engineering Department IIT Guwahati. Sampling frequency was varied during the conduct of the experiment and data acquisition. Samples were obtained at the sampling frequencies of 15000Hz, 3750Hz, 500Hz, and 50Hz. For each sampling frequency, four hammer impacts were provided where each hammer impact is used to acquire and store the received signals. The parameters, offset distance and geophone spacing, were maintained constant to 2m.

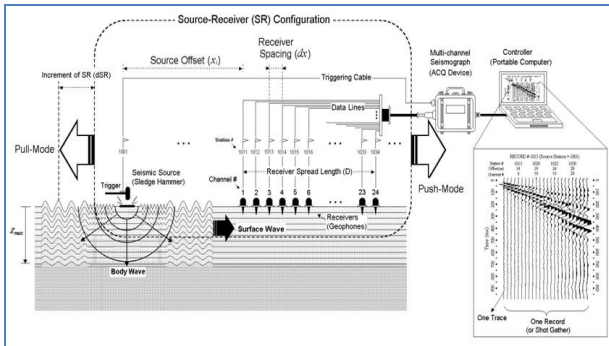


Fig 2(a): Active MASW survey in the field.



Fig 2(d): Data Acquisition System

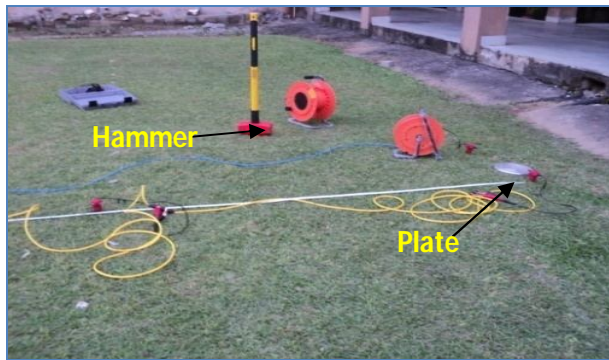


Fig 2(b): Hammer and plate



2(c): Geophones in a linear array

Active MASW survey was carried out as shown in Fig 2a. Waves were generated at the source by striking a plate by a sledgehammer of weight 9.82kg (Fig. 2b) and the geophones being placed in a linear array (Fig. 2c). In the present case reported, 12 numbers of geophones receivers were used. These geophones are the devices which measures displacements or vibrations as generated voltage. These signals are recorded through the data acquisition system connected to geophone arrays and further used for post-processing.

IV. RESULTS AND DISCUSSION

A. Dispersion Analysis

Dispersion of waves is the phenomenon related to the waves travelling through a wide area with different frequency, wavelength and phase velocity and with gradually enhanced wavefront. Dispersion analysis is carried out to obtain the dispersion curves which are plots of phase velocity versus frequency of the propagating waves. It is obtained by Fast Fourier Transform (FFT) of the time-space domain signal to achieve the result in frequency domain. When more than one phase velocities exist for given frequency, it is referred as multimodal dispersion. The slowest one in this case is called fundamental mode and next faster one is called as the first higher mode and so on (Fig. 3). In contrast to the earlier used wave analysis techniques as mentioned in [5], the multichannel approach does not attempt to calculate individual phase velocity, but

constructs an image space where dispersion trends are identified from the pattern of energy accumulation in this space. Then, necessary dispersion curves are extracted by following the image trends of maximum energy accumulation. All types of seismic waves propagating are imaged if they take any significant energy. In this imaging process, a multichannel record in time-space ($t-x$) domain is transformed into either frequency-wavenumber ($f-k$) or frequency-phase velocity ($f-C$) domain. The traditional $f-k$ method is of the former type, whereas the $\pi-\omega$ transformation [6] and the phase-shift method [5] are two instances of the latter type. It is generally known that the $f-k$ method results in the lowest resolution in imaging, whereas the phase-shift method achieves higher resolution than $\pi-\omega$ methods [7].

According to the fundamental hypothesis of the linear physics (Fourier's Theorem), any signal can be represented as the sum of independent signals, referred as harmonics of the signal. These harmonics, for one-dimensional analysis, are trigonometric functions sine and cosine, and act independently, not interacting with each other. Focusing on each harmonic component, the final result in linear analysis will be equivalent to the sum of partial behaviours corresponding to different harmonics. The Fourier analysis (FFT spectral analysis) is a fundamental tool for the spectral characterization of the signal.

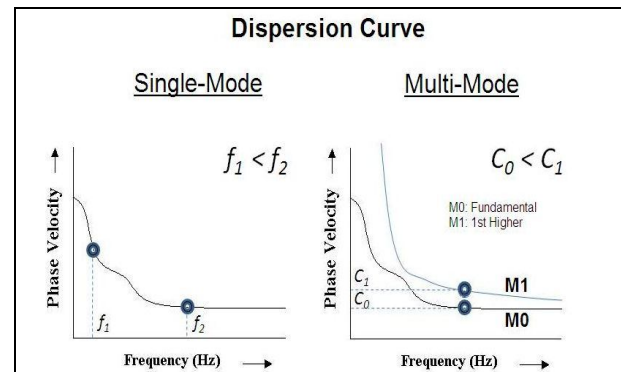
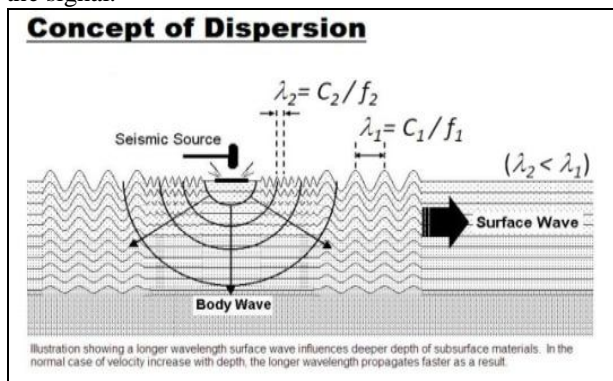


Fig 3: Concept of dispersion [5,9]

The analysis of Rayleigh waves, using MASW technique is performed with the spectral treatment of the signal in the transformed domain, where quite easily, the signal for the Rayleigh waves is identified from other types of signals. In addition, the propagating Rayleigh waves is expressed as a function of frequency content of the signal. The velocity-frequency link is called dispersion spectrum. The dispersion curve identified in the $f-k$ domain is called the experimental dispersion curve, and is represented as the maximum amplitudes of the spectrum.

B. Analytical Investigation for Dispersion

This paper reports the utilization of the phase-shift method proposed by [5] to obtain the dispersion image. As per [7], phase-shift method achieves higher resolution than $\pi-\omega$ and $f-k$ methods. In this phase-shift method (Fig. 4), the summed up amplitude of frequency domain records is determined with varying phase velocity. First, the amplitude of each channel is determined and subsequently the phase-shift for each channel is calculated and then summed up with respect to the varying phase velocity. To obtain the dispersion curves, all 2-D curves at different frequencies are to be assembled to obtain a 3-D image showing the energy distribution as the function of phase velocity and frequency. A MATLAB code has been developed as a preliminary attempt to obtain the summed up amplitude.

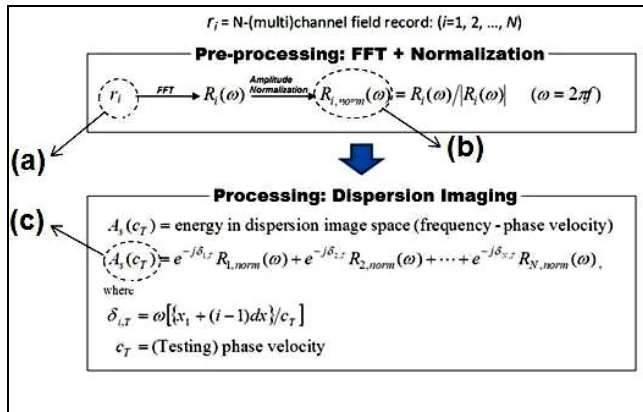


Fig 4: Dispersion imaging scheme [5,9]

Figure 5(a) depicts the time domain signals as collected by the geophone array (Sampling frequency – 3750 Hz), while Figure 5(b) shows the frequency content and its single-sided spectral amplitude. The time-domain figure identifies the travel of the wave through the geophone array, while the frequency domain signals help to identify the modes of vibration of the soil system. Since the code for dispersion imaging scheme is in the preliminary level, the details are not furnished herein. Figure 6 (a-c) depicts a typical normalized summed-up amplitude curve at sampling frequency of 15000Hz for $N=12$ condition (i.e. summing up all the 12 channels) and frequencies of 3.66Hz, 69.5Hz and 728 Hz. These figures help to identify the phase velocity which is pertinent at the specified frequency, the pertinence being highlighted at that phase velocity in which the normalized summed-up amplitude reaches a magnitude of 1. This is to be further used in the identification of the dispersion image space.

Fig 5(a): Time domain signal collected by Geophone array

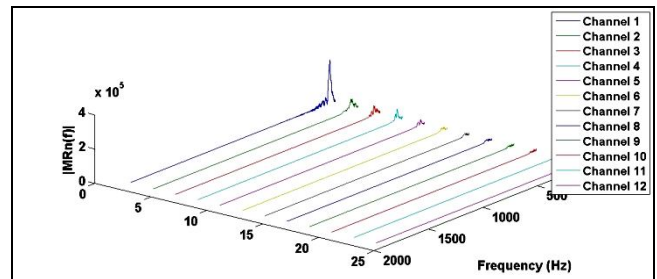


Fig 5(b): Sided amplitude spectrum vs. frequency

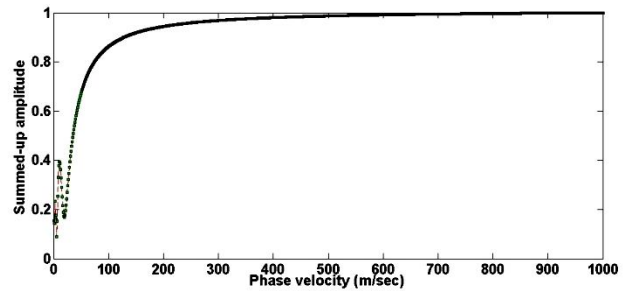


Fig 6a: Summed up amplitude of 12 channels ($\omega = 3.66\text{Hz}$)

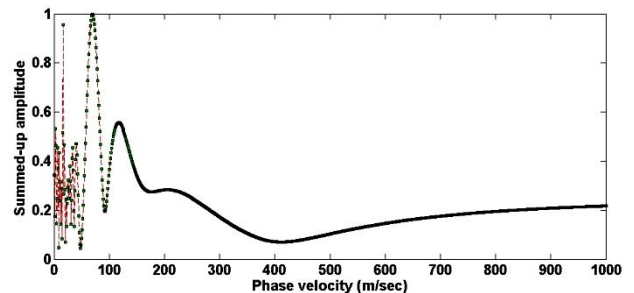
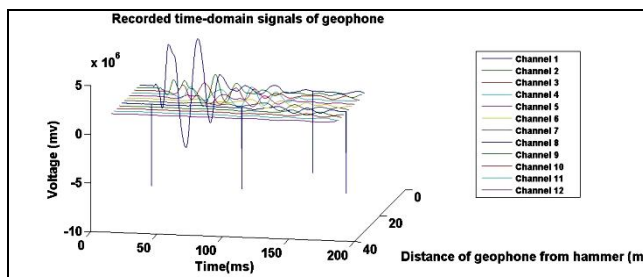


Fig 6b: Summed up amplitude of 12 channels ($\omega = 69.5\text{Hz}$)



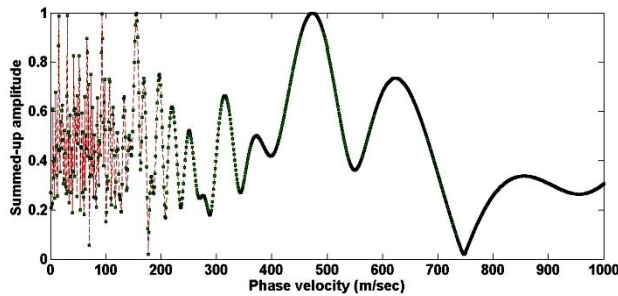


Fig 6a: Summed up amplitude of 12 channels ($\omega = 728\text{Hz}$)

C. Use of EasyMASW Software

EasyMASW is a commercial software available for characterization of the subsurface in terms of shear wave velocity profile. In this software, the wavenumber-frequency and phase velocity-frequency spectra are produced. It determines the shear wave velocity profile only for the top 30m of soil (V_{s-30}) (for both active and passive surveys) and provides the idea about soil type (based on certain specified category inbuilt in the software database), the velocity profile and geotechnical parameters such as shear modulus, elastic and edometric modulus of the soil (again based on the specified category of the soil). Fig. 7 shows a typical set of results for a sampling frequency of 15000 Hz (as collected through the data acquisition system) after post-processing using the EasyMASW software. Fig. 7(a) shows the traces which are imported into the software from the Data acquisition system. These traces are obtained by generating waves at the source and collecting the data (Geophone receiver signals) in the field. Fig. 7(b) is the result obtained after the spectral analysis of the imported traces obtained using phase velocity-frequency spectra. It is known as dispersion spectrum. Fig. 7(c) shows the velocity profile of the soil site and the optimized velocity profile obtained through matching of the experimental and theoretical dispersion curve as well. It is obtained after the inversion process. Fig. 7(d) provides the final velocity profile of the soil site along with the thickness of the soil strata.

effect of the former on the latter. Hence, proper understanding has to be there to carry out a reasonable experiment and post-processing of the data. Any sampling frequency cannot and should not be used for any type of soil. There might be some relationship which can be developed for different soil categories as to which sampling frequency should suit it best.

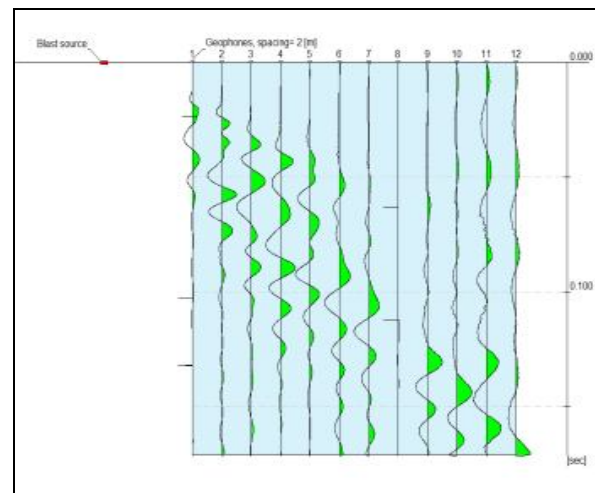


Fig 7a: Traces obtain from the field

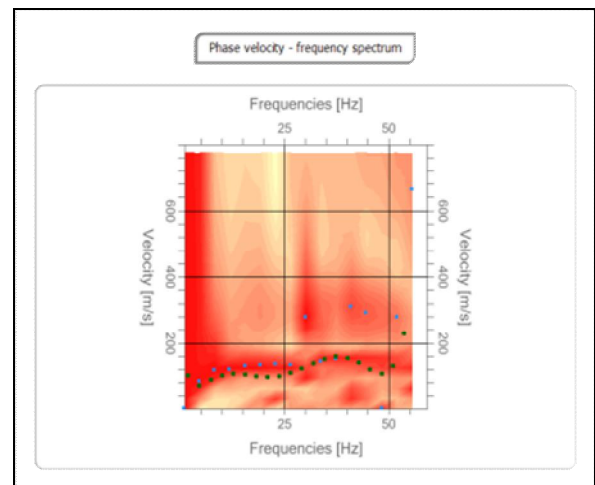


Fig 7b: Dispersion curve

Fig 8 shows that for different sampling frequency the shear wave velocity profile changes, highlighting the

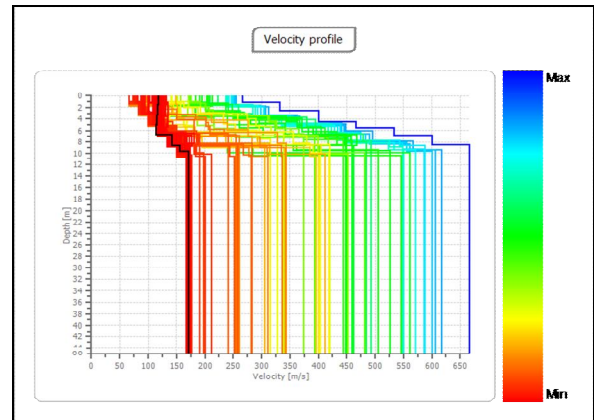
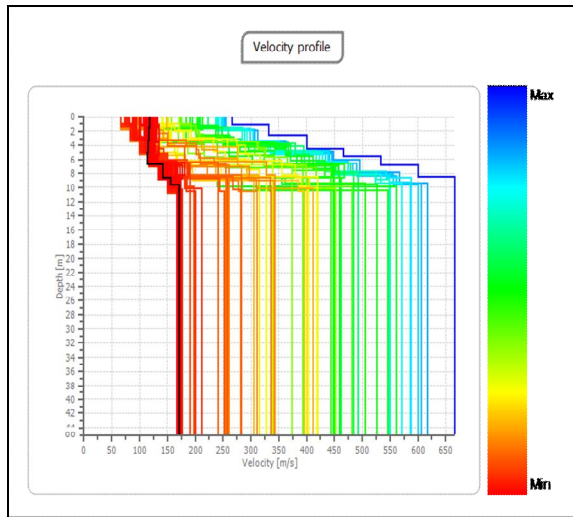


Fig 8(a): Vs profile at 15000Hz

Fig 7c: Velocity profile

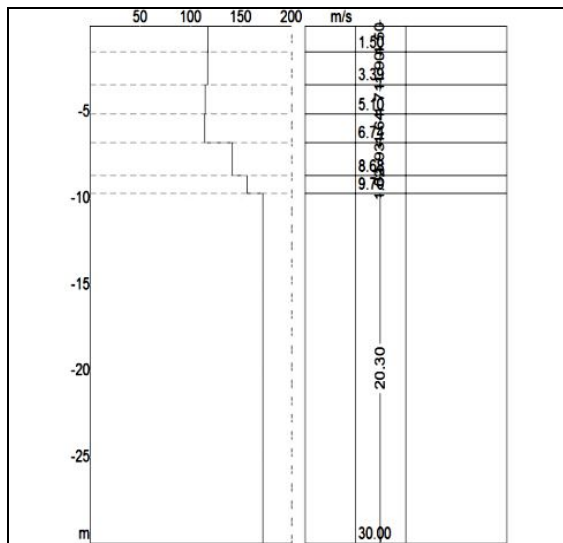


Fig 7d: Soil Stratigraphy

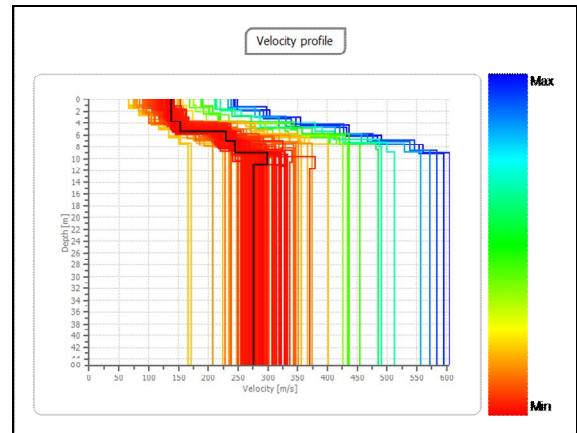


Fig 8(b): Vs profile at 3750Hz

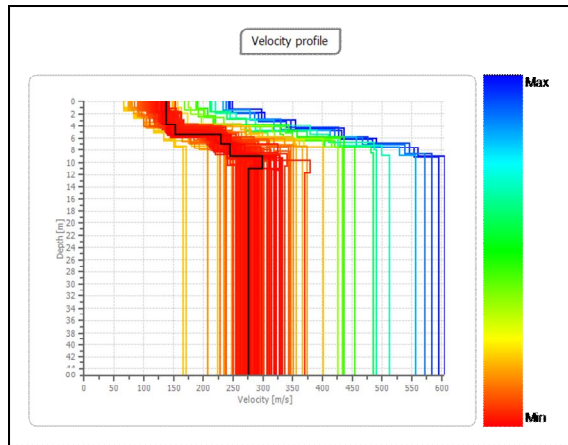


Fig 8(c): Vs profile at 500Hz

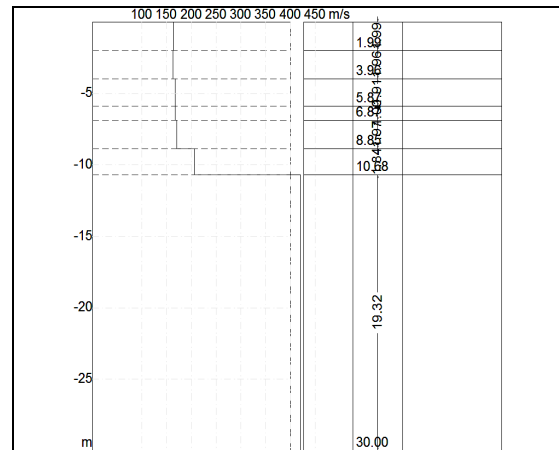


Fig 9a: Soil stratigraphy for sampling frequency of 500Hz (1st test)

For low sampling frequency of 50Hz, the EasyMASW software was unable to analyse the collected signal information; although it is able to import the signal content for analysis, no results are obtained from the stage of dispersion analysis. Maximum frequency sampled by EasyMASW is nearly 60Hz. It has been stated that construction and proper analysis of a signal is possible when the sampling frequency is at least twice the maximum frequency sampled [8], which for this case should be at least higher than 120Hz. Hence, for this reason the signal was not constructed for 50Hz sampling frequency and no further results were provided by EasyMASW.

The reliability of the EasyMASW software is also questionable. The primary issue is that whatever done, the shear wave velocity profile is always provided for a maximum investigation depth of 30m, which is not at all justifiable. Moreover, it assumes the density and Poisson's ratio of the soil to be constant at every layer. The output of the analysis is always adjusted over 6 layers, which is not possible. When verified against the shear wave velocities obtained from the SPT tests carried out at the site, the comparative result of EasyMASW also showed lot of deviation. Moreover, when the results of the repetition experiments were analysed, lot of variation in the shear wave velocity profile was obtained, which is totally illogical as shown in Figures 9(a-f).

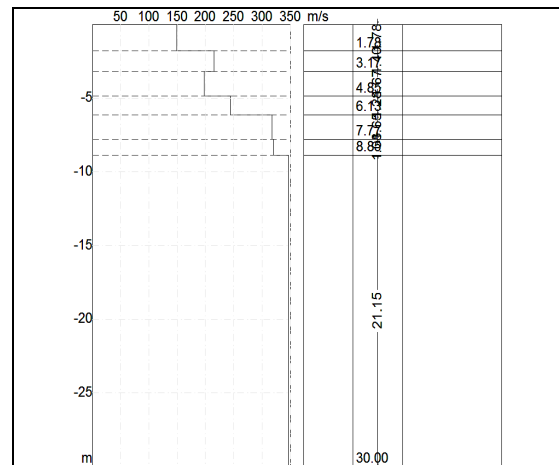


Fig 9b: Soil stratigraphy for sampling frequency of 500 Hz (2nd test)

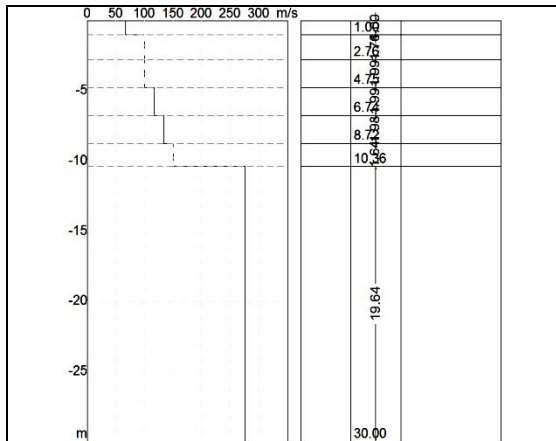


Fig 9c: Soil stratigraphy for sampling frequency of 3750Hz (1st test)

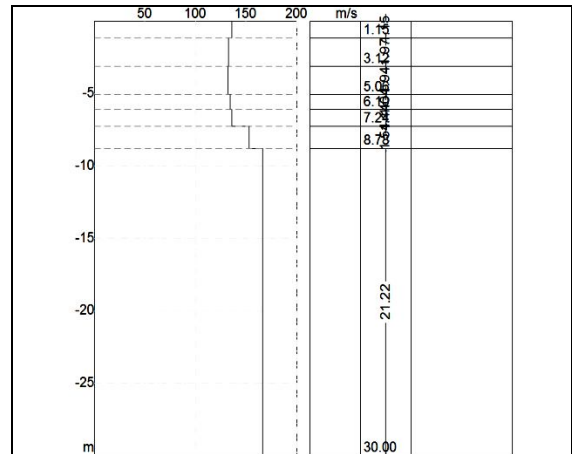


Fig 9e: Soil stratigraphy for sampling frequency of 15000Hz (1st test)

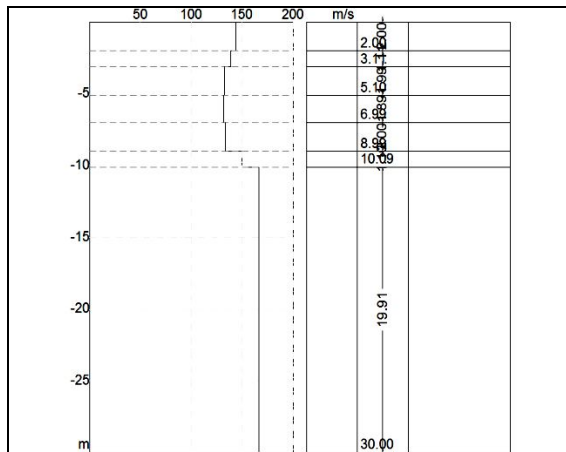


Fig 9d: Soil stratigraphy for sampling frequency of 3750Hz (2nd test)

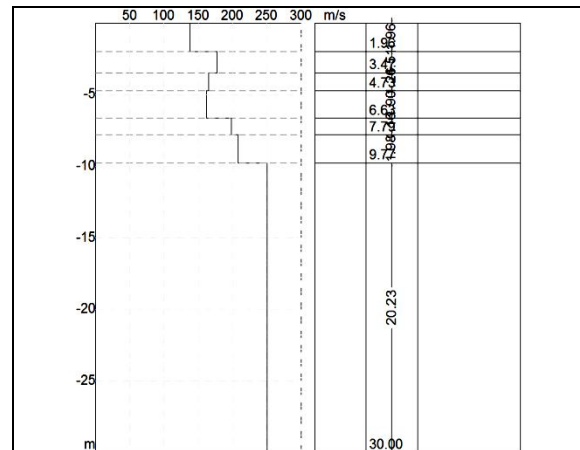


Fig 9f: Soil stratigraphy for sampling frequency of 15000Hz (2nd test)

V. CONCLUSION

This paper reports about the preliminary experimentation conducted at the plane terrain of the Civil Engineering Department, IIT Guwahati, with the aid of MASW for characterization of the subsurface at the site in terms of the shear wave velocity profile. 12 numbers of geophones were placed in a linear array with constant offset and inter-geophone spacing (2m). Input signals were generated with the aid of a sledgehammer impact

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on the striking plate, and the corresponding output signals recorded by the geophones were collected using the Data Acquisition System at various sampling frequencies. Matlab code has been developed and used to obtain the time-domain and frequency-domain curves. A preliminary analysis was also carried out to characterize the subsurface through phase-shift method to obtain the normalized summed-up amplitude. This summed-up amplitude energy accumulation pattern can be studied and a dispersion curve can be obtained. A commercial software EasyMASW has been used to obtain the shear wave velocity profile of the subsurface. The results obtained reveals that the shear wave velocity profile depends on the sampling frequency. The results seem to be ambiguous for the repeated experiments carried out at a specific sampling frequency, and hence, question the reliability of the software.

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