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Evaluating the Efficacy of Combined Active and Passive MASW Techniques for Enhanced Soil Characterization

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Abstract: This paper presents a comprehensive investigation into soil characterization using active, passive, and combined Multichannel Analysis of Surface Waves (MASW) techniques across multiple locations. The study acknowledges the inherent limitations of using active and passive MASW methods independently, particularly their restricted depth of investigation when used alone. The research introduces a combined MASW approach to overcome these limitations, enabling a more extensive subsurface profiling by leveraging a broader range of analyzable frequencies. The methodologyinvolved conducting both active and passive MASW surveys at five critical sites in Itanagar, India. The active MASW survey utilized a controlled source to generate high-frequency waves, providing detailed information for shallow depths (1-25 meters). In contrast, the passive MASW survey employed natural and cultural sources, producing low-frequency waves capable of penetrating deeper into the subsurface (up to 40 m). By combining the data from both approaches, the study achieved a more accurate and continuous shear wave velocity profile, covering a depth range from 1 to 60 m. Key findings of the research include the successful integration of higher modes in the combined MASW survey, leading to improved accuracy in the inverted shear wave velocity profiles. The study also compared the effectiveness of combining raw data versus combining dispersion images from active and passive surveys. Results indicated that the combined approach provided superior resolution and clarity, particularly in identifying the modal nature of dispersion trends and ensuring accurate subsurface characterization across varying depths. This research demonstrates that the combined MASW method is a powerful tool for geotechnical investigations, offering enhanced depth of investigation and improved accuracy in subsurface profiling, which is critical for various engineering and environmental application.

Keywords: Multichannel Analysis of Surface Waves (MASW), Active MASW, Passive MASW, Combined MASW, Subsurface profiling, Shear wave velocity

Introduction

The multichannel analysis of the surface wave method is widely and effectively being used because for its advantages in the field in various geotechnical engineering projects (1) as compared to earlier methods used such as GPR (2), seismic refraction method (3) and NMR (4). MASW has two basic approaches adopted based on the need for exploration depth, i.e., active MASW and passive MASW (5). The active MASW approach uses active sources such as a sledgehammer of 5–10 kg, which produces frequencies in the higher range of 15 to 50 Hz. The higher frequencies lead to an investigation for shallower investigation depths, which are generally less than 30 m (5). The low depth of investigation by the active MASW method is considered to be one of its limitations. A solution that allows for a more in-depth investigation is also highly desired. The deeper investigation depth means a lower frequency of waves needs to be generated. To produce a lower frequency wave-field, i.e., a higher wavelength, the active sources required will be of much greater weight. But such a heavily weighted active source will make the survey exorbitant and non-viable(1, 6, 7, 8).

On the other hand, passive surface waves generated by natural or cultural sources (such as tidal motion and traffic) are typically low-frequency (1-30 Hz) with wavelengths that range from a few kilometres (for natural sources) to a few tens (or hundreds) of meters (for cultural sources). This provides a broad range of penetration depths and a compelling reason to employ them (8, 9). The passive MASW method optimizes the benefits of multichannel recording and processing by employing 24 or more channels (5). It has enhanced the resolution of the investigation of the modal nature and azimuthal aspects of surface waves, as well as the resilience of data processing and the flexibility of field logistics. Depending on the type of $V_s$profiles (1D or 2D) to be obtained or the field logistics, passive MASW surveys can be classified as passive roadside or passive remote MASW surveys. Only passive roadside MASW was conducted in the current case due to space limitations and operational challenges encountered in the field. A linear receiver array positioned parallel to the road is utilized for passive roadside MASW surveys(7, 8, 12). Due to lower frequency range having a longer wavelength corresponding to a deeper depth of investigation, the information related to shallower depth is hazy. Therefore, a combined MASW survey (11)is adopted to overcome the issue encountered in the active and passive MASW survey.

Combining dispersion images from active and passive data sets is frequently advantageous and necessary in order to increase the analyzable frequency (and thus depth) range of dispersion and to more accurately detect the modal nature of dispersion trends, particularly in the dominant modal nature of traffic generated surface waves (5). With the active MASW survey, the dispersion curve in a higher frequency range with a shorter wavelength corresponding to the depth of investigation varying from 1-30 m can be obtained, whereas the passive MASW survey covers the dispersion trend of a lower frequency range having a longer wavelength. The present paper aims at combining the dispersion images of active and passive MASW surveys. The combination of two dispersion images of lower and higher frequency ranges is thought to increase the analyzable frequency range and provide more accurate information from shallower to deeper depths (i.e., 1-100 m approx). However, the combination of raw data from active and passive MASW is also explored and compared to combined MASW obtained from the dispersion images of active and passive. Park et al., (5) has worked on the modal identification of combined MASW. The only use of active MASW leads to mode misidentification. The combined MASW shows clear mode identity. Park et el., (11) has elaborated regarding the modal analysis of combined MASW. In this paper attempt has been made to see the efficacy of combined MASW in terms of modal analysis, depth of investigation, analyzable frequency range, accuracy of the inverted profile. The clarity and accuracy of the inverted shear wave velocity profile is also investigated. Along with the above aspects of combined MASW, the dispersion image obtained after the combination of raw data and combination of dispersion images is also compared.

Location

To evaluate the effectiveness of the combined MASW data, experiments were conducted at five critical locations in Itanagar, the capital of Arunachal Pradesh, India, as depicted in the figure 1. Site-1 is located in the Mai Estate at coordinates 27.126404° N and 93.704415° E, where the MASW test results indicate the presence of relatively soft soil at shallower depths. Borehole test results are available for Site-2, situated in the Thursday Market area of Yupia, at coordinates 27.136441° N and 93.705412° E. Site-3 is located in Midpu II, Doimukh, with coordinates 27.168039° N and 93.761133° E. Site-4 is positioned in Chimpu, Itanagar, at coordinates 27.056296° N and 93.613000° E. Finally, Site-5 is at KV-2, Itanagar, with coordinates 27.072071° N and 93.594505° E. Among these sites, borehole data is available only for Site-2 as illustrated in figure 15, which was used to validate and compare the results obtained from the MASWsurveys.

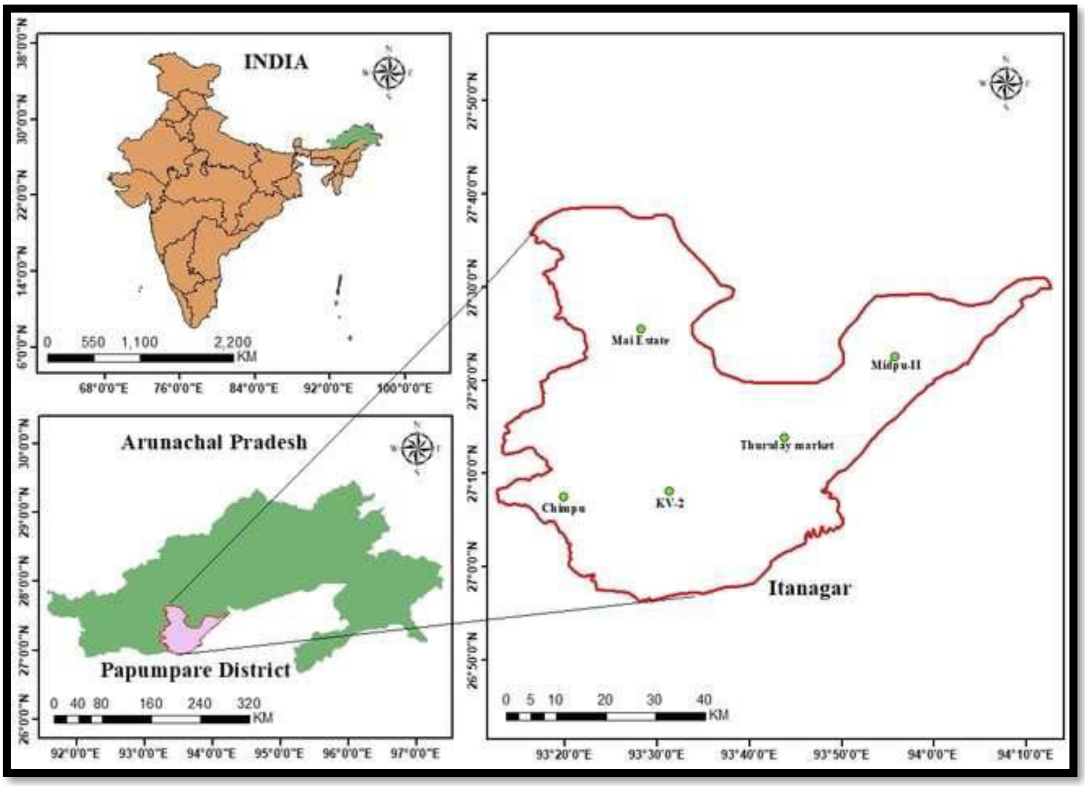


Fig. 1Site Locations of Active and Passive MASW

Methodology

An active and passive MASW survey was conducted in all five locations in Itanagar and Yupia. The Active MASW field survey is shown schematically in Figure 2a, where optimum field parameters were applied (12). The method uses the active source to generate waves that propagate through the soil, collecting insight information or raw data for the analysis to ultimately find out the shear wave velocity V_s. The active source used in the present study is a sledgehammer of 10 kg in a controlled manner. A total of 24 channels were used. These channels were all 4.5 Hz geophones. The offset distance for the Active MASW survey was kept between 3 and 5 m to avoid the undesirable effect of near-field and far-field effects. Acquisition time of 2000 ms at a sampling rate of 1 ms-1000 Hz was set in the data acquisition system, which gave the optimum resolution of the dispersion image.

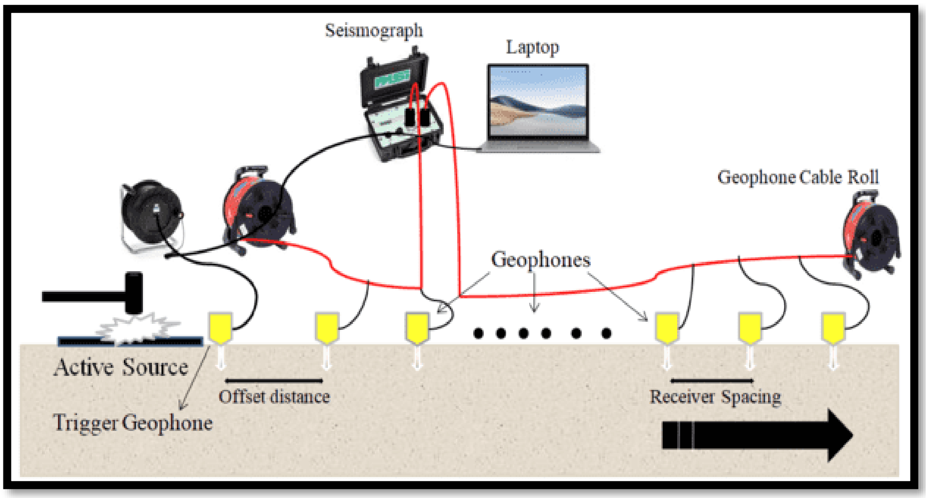


Fig. 2a*Schematic diagram of Active MASW field Survey*

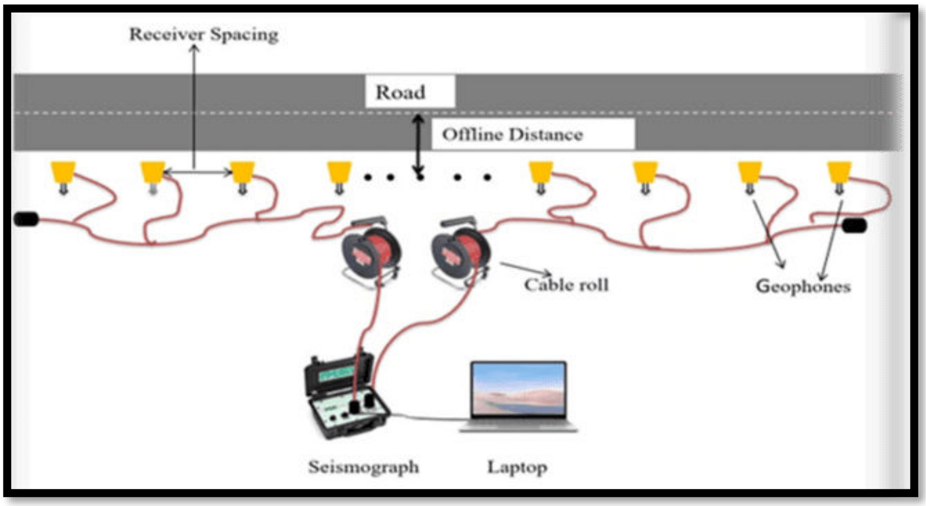


Fig. 2b Schematic diagram of passive roadside MASW

The schematic diagram of a passive roadside MASW survey that was conducted in the field at all sites is illustrated in Figure 2b. The passive MASW approach in the current study employs traffic (13) as passive sources. Additionally, vibrations emanate from unidentified natural sources. The seismic waves generated by traffic as they traverse the earth's substratum are detected by a linear array of geophone receivers. The receiver is connected to a data acquisition system (DAQ) that is equipped with a seismograph. In this investigation, a linear array of 24 geophones with a frequency of 4.5 Hz was arranged at a distance of one to five meters. The offline distance of 4-19 m was maintained in accordance with the availability of space and the feasibility of the project. For the passive roadside MASW survey, the optimal field parameters are a 2 m receiver spacing, a 2000 ms acquisition time, a 2 s delay and interval time, and an offline distance that varies from 5-19 m based on the availability of space at the test sites, all at a sampling rate of 125 Hz.

Data Processing

The collected raw data both from the active and passive MASW surveys were processed. The difference in active and passive MASW survey is mainly due to data acquisition in the field. The data were collected in sg2 format. The raw data is collected in optimum field parameters which will yield the best resolution dispersion image. Optimum field parameters indicate the offset distance, sampling frequency, and total time of sampling. The collected data is allowed to pass through a band pass filter. The primary function of a band-pass filter in MASW surveys is to enhance the quality of the data by allowing only a specific range of frequencies (the band) to pass through while attenuating or eliminating frequencies outside this range. (14). The propagating waves which are out of phase is muted. The top and bottom muting is carried out as mentioned in Taipodia et al., (14). To further improve the quality of the dispersion image, vertical stacking is used as a method in most of the dispersion image processing. Normally, the greater the number of stacks, the higher the resolution of the dispersion image. Figure shows the individual dispersion image and stacked image. Later, active and passive dispersion images are combined for the entire site, where the best resolution dispersion image is chosen out of all the trials(6, 7, 8, 11).The resolution of a dispersion image was defined by Park et al. (15) as the resolvable capabilities along both the velocity axis and the frequency axis. The velocity axis resolution is a good indicator of the capacity to differentiate between a phase velocity and other velocities at a specific frequency, and vice versa. Integrative energy is purported to decrease rapidly as the velocity difference increases, resulting in a well-defined dispersion curve and a relatively narrow bandwidth. Dots per inch (dpi) are used to quantify the resolution of the extracted dispersion band (the white band). An increased dpi of the image indicates a denser concentration of pixels in a unit area, which in turn indicates a higher resolution (14). The image with a fundamental mode dispersion curve that has a wider range of frequency range and a narrow band with high amplitude (SNR~100) is considered to be a good resolution image, according to the definition of dispersion image resolution (14,16). Therefore, it can be concluded that the dispersion images of site-2 and site-3 are satisfactory in the current situation.

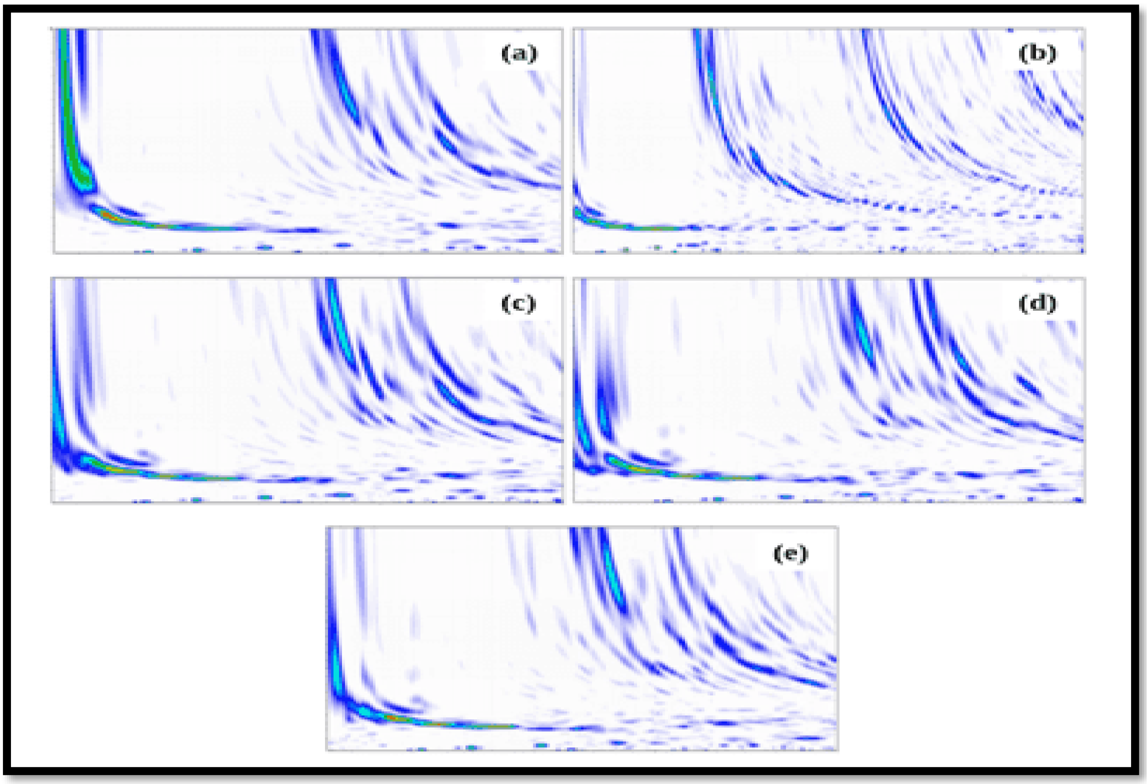
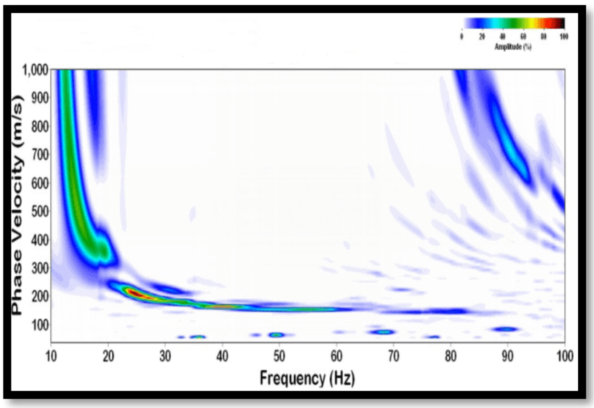
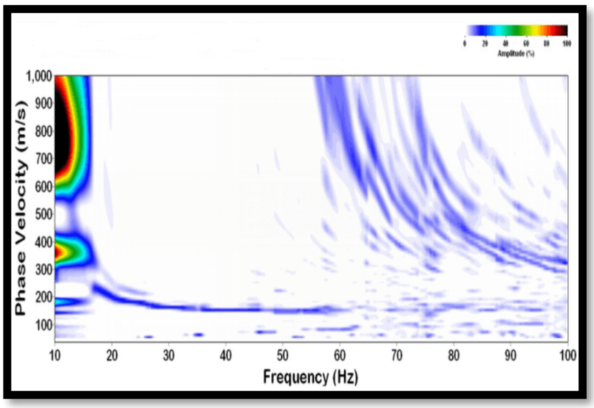


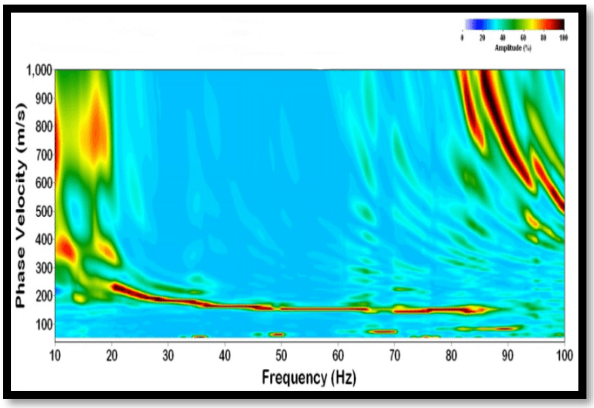
Fig. 3*Dispersion images generated from five hammer blows a) 1st blow b) 2nd blow c) 3rd blow d) 4th blow e) 5th blow*

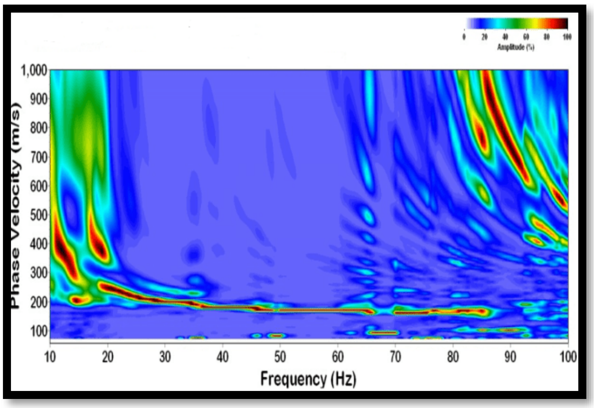
Figure 2 displays individual dispersion images corresponding to a single configuration of five hammer blows at various sites. Each image represents the frequency-velocity relationship as captured during the MASW survey, with the fundamental mode dispersion curve being a critical feature in each plot. The dispersion images shown in Figure 2 reflect the initial data quality before any stacking is applied. The resolution of these images directly affects the ability to accurately interpret the shear wave velocity profile, which is essential for subsurface characterization. In these images, it is observed that the initial clarity of the dispersion curves, prior to stacking, is lacking in distinctness and definition.





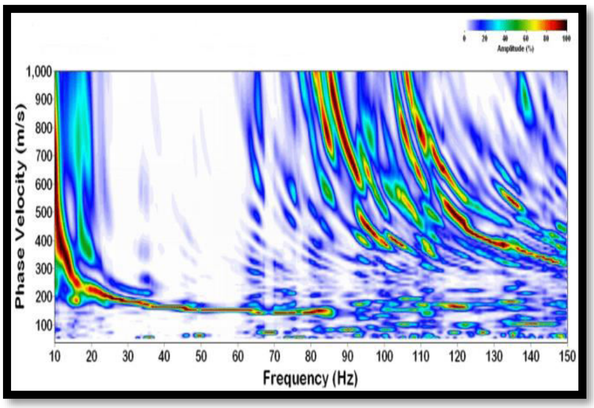
(a)
(b)





(c)

(d)



(e)

Fig. 4*Stacked dispersion images: (a) No stack, (b) One stack, (c) Two stacks, (d) Three stacks, (e) Four stacks.*

In the provided figures, the effect of stacking on the resolution of dispersion images is clearly demonstrated. Figure 3 showcases the stacked dispersion images with varying numbers of stacks: (a) No stack, (b) One stack, (c) Two stacks, (d) Three stacks, and (e) Four stacks. As the number of stacks increases, the images display a progressive enhancement in clarity and resolution. Specifically, the bandwidth of the fundamental mode dispersion curve becomes narrower, and the energy concentration within this band becomes more distinct. This indicates a higher resolution, as the dispersion curve can be more accurately identified and analyzed.

The improvement in resolution with an increased number of stacks is quantified in terms of the capability to discriminate phase velocities at different frequencies. With each additional stack, the ability to discern the correct phase velocity improves, leading to a more precise and reliable subsurface profile.

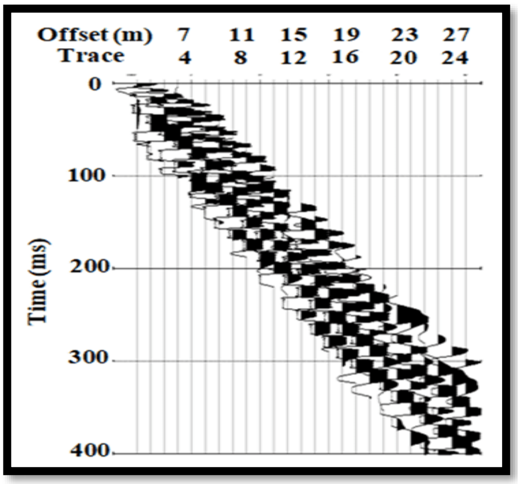
Result and Discussion

Site characterization using active and passive MASW was conducted and the efficacy of combined active and passive MASW survey is explored. The following section shows the test results carried out.

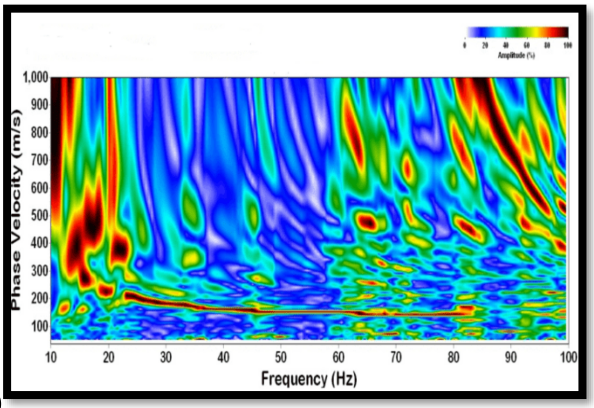
Characterization of site using Active MASW Survey

To evaluate the efficacy of the combined MASW approach, both active and passive MASW were conducted at the five sites mentioned in Section 2. This section focuses on the active MASW performed at all five sites. For Site-1, the receiver spacing was set to 2 meters, with an offset distance of 5 meters. A band-pass filter was applied to allow a specific frequency band of waves to pass through and top and bottom muting was used to eliminate out-of-phase waves (14). As shown in Figure 5a, a proper phase was achieved, and the corresponding dispersion image is presented in Figure 5b.

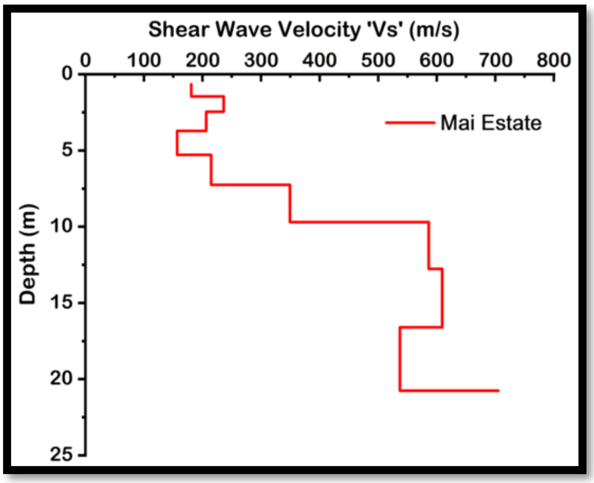
Figure 5b illustrates a robust energy trend up to 38 Hz, with the analysable frequency commencing at approximately 12 Hz. The image's wide analysable frequency range is indicative of its high resolution, as indicated by visual inspections. Inversion analysis was employed to generate the shear wave velocity profile depicted in Figure 5c. In accordance with the inverted profile, the shear wave velocity (Vs) of the soil is approximately 200 m/s to 700 m/s. Furthermore, the inverted shear wave velocity profile in Figure 5c suggests that the depth of exploration is as high as 22 m, with a shear wave velocity of approximately 700 m/s at this depth. The site is classified as soft at shallow depths of up to 10 meters according to the NEHRP site classification (22), which is determined by shear wave velocity.



(a)



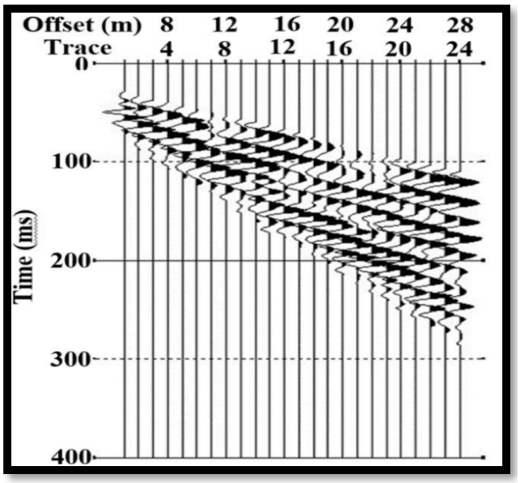
(b)



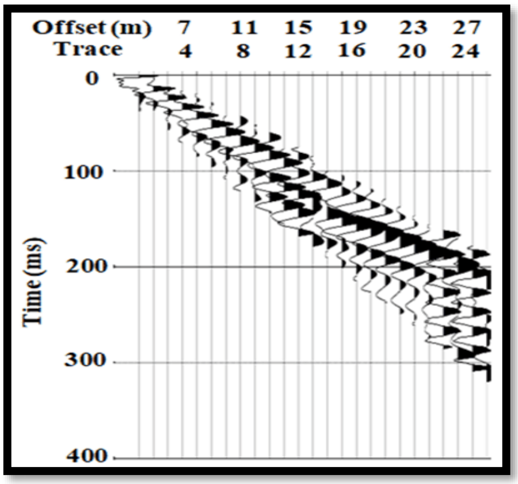
(c)

Fig. 5*(a) Raw Data (b) Dispersion image (c) Shear Wave Velocity for site-1 (Thursday Market)*

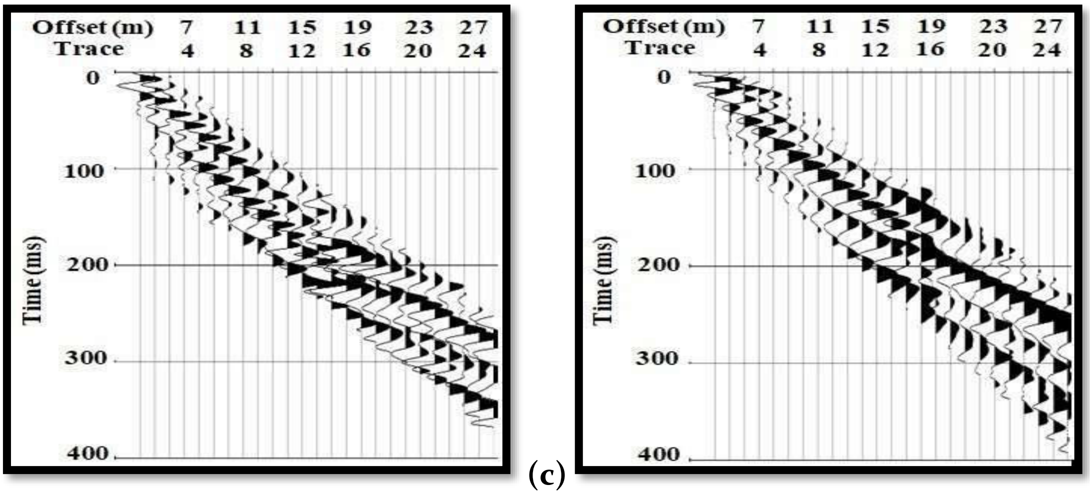
Similarly, the active MASW survey was conducted at Sites 2, 3, 4, and 5. The raw images obtained from these surveys are presented in Figures 6a, 6b, 6c, and 6d. As observed in Figure 5, the raw data from Site 2 requires approximately 280 ms to propagate, whereas the data from Site 3 propagates within 310 ms. The raw images in Figures 6a-d demonstrate that unwanted signals or noise have been effectively filtered, and out-of-phase waves have been muted. Visual inspection reveals that the waves maintain significant energy in phase across all five sites.



(a)



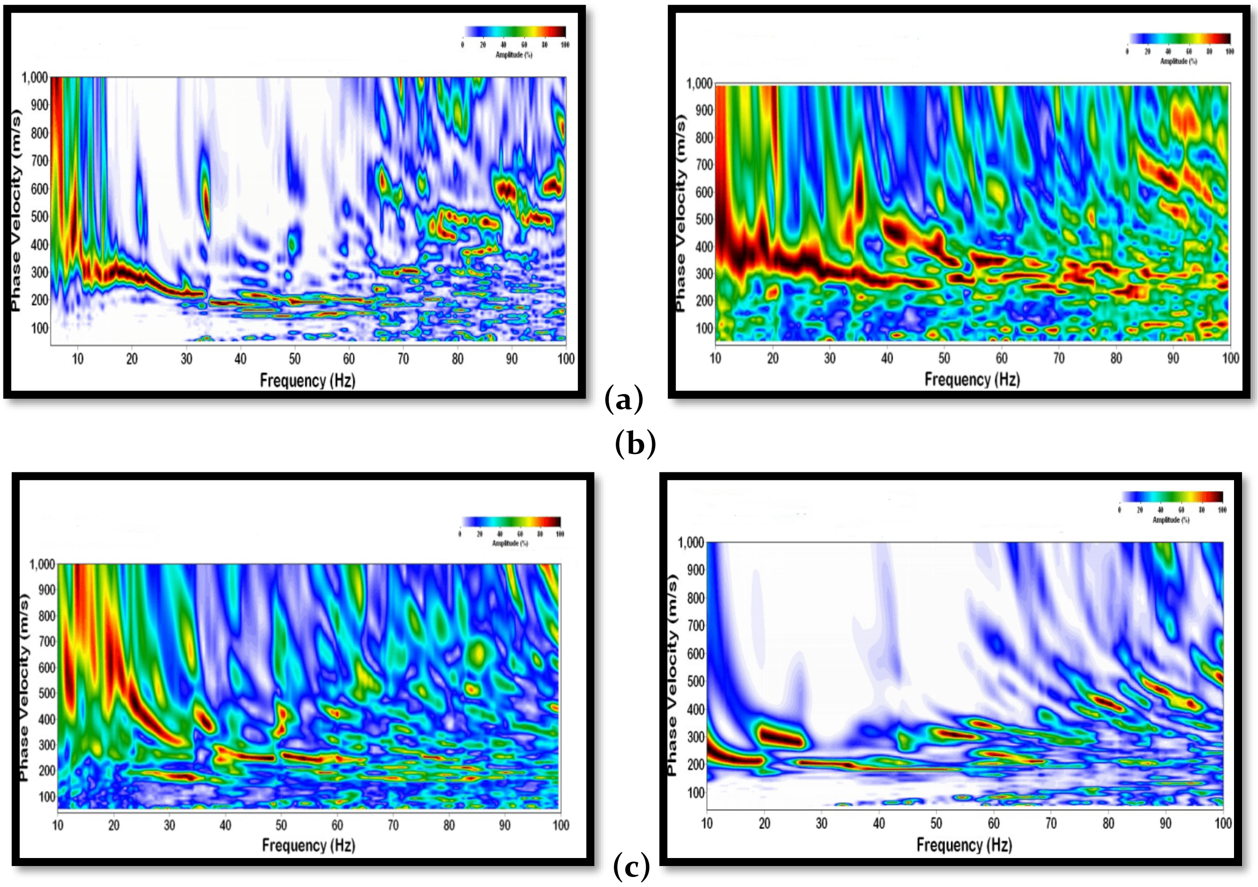
(b)



(c) (d)

Fig. 6*Raw Images of (a) site 2 (b) site 3(c) Site 4 (d) Site 5*

The corresponding dispersion images of site-2, 3, 4 and 5 are shown in figures 7a-d. Figure 7b has more energy and has an energy band in a wider frequency range. Dispersion images of site-4 in figure 7b-d show the presence of higher modes. Though there is huge energy accumulation, there is discontinuity in the energy band in figure 7c-d.



(a)
(b)

(c)
(d)

Fig,7 *Dispersion Images of (a) site 2 (b) site 3 (c) site 4(d) site 5*

Figure 8a-d illustrates the corresponding shear wave velocity profile. A varying shear wave velocity with respect to depth up to 20 m has been found. From figure 8c, it indicates that site-4 has stiffer stratum. The shear wave velocity of the site-2 is varying from the 300 m/s to 500 m/s at 20 m depth which means that site -2 has stiff clay up to depth of 20 m. It can be inferred from figure 8b and figure 8d that the site-5 is very loose soil as it has a shear wave velocity ranging from 200 m/s to 350 m/s which is indication of soft clay. Whereas site-3 has 180-450 m/s up to depth of 20 m depth. According to NEHRP site classification(22), it is soft clay soil.

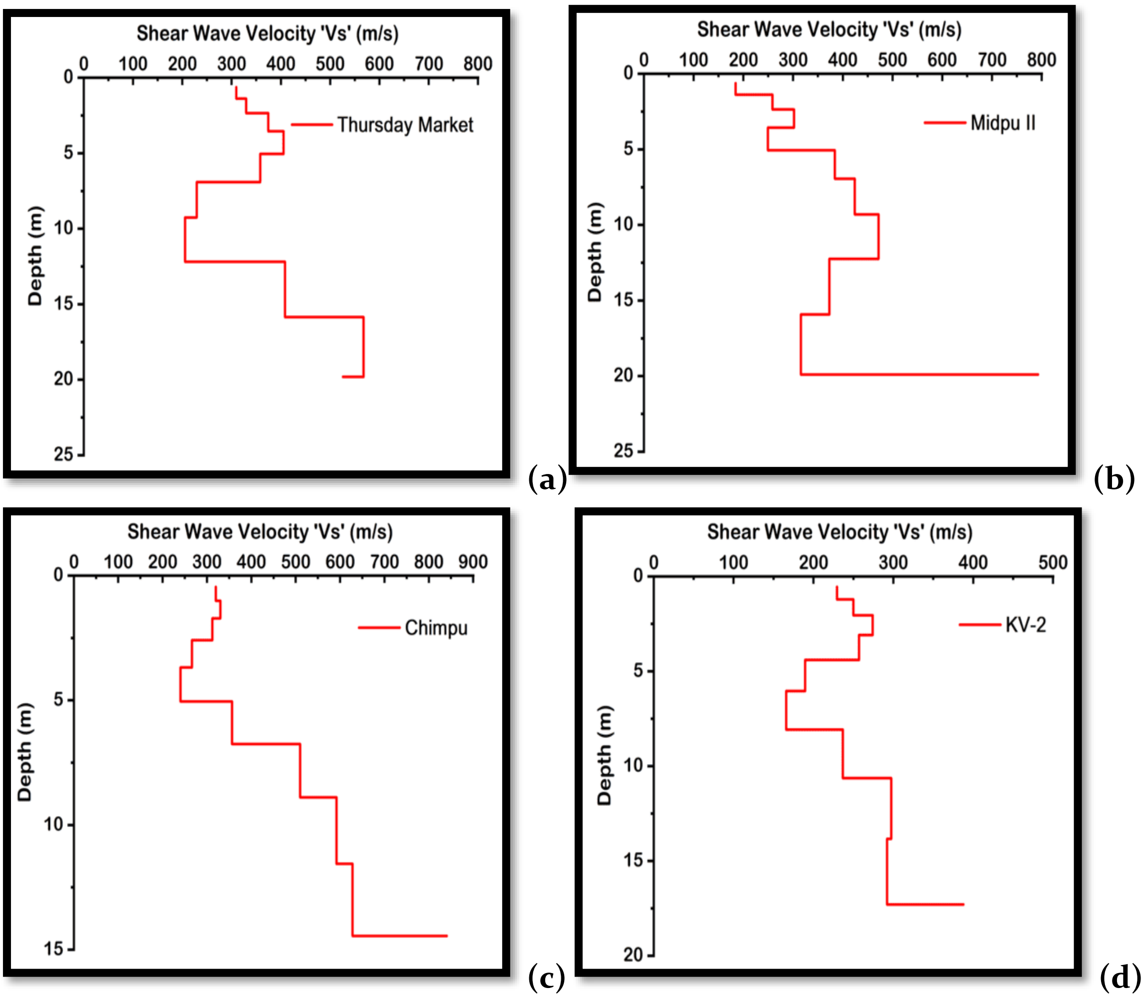


Fig. 8 *Shear wave velocity profile of(a) site 2(b) site 3 (c) site 4 (d) site 5*

Characterization of site using Passive MASW Survey

Passive MASW proves to be efficient in subsurface profiling at deeper depths (11). The method was derived from the ReMi method (17). Passive MASW studies were carried out at sites 1, 2, 3, 4, and 5. We varied the offline distance from 5 m to 19 m based on the availability and feasibility of the selected sites, maintaining a 2 m interval for the entire site. The raw data was collected and processed through a bandpass filter as shown in figure 9a-e. The top and bottom muting was carried out to delineate the waves that are out of phase, as depicted in figures 9a-e. The main source of energy generation is considered to be traffic. Geophones also record energy from a variety of other anthropogenic activities, as shown in dispersion images.

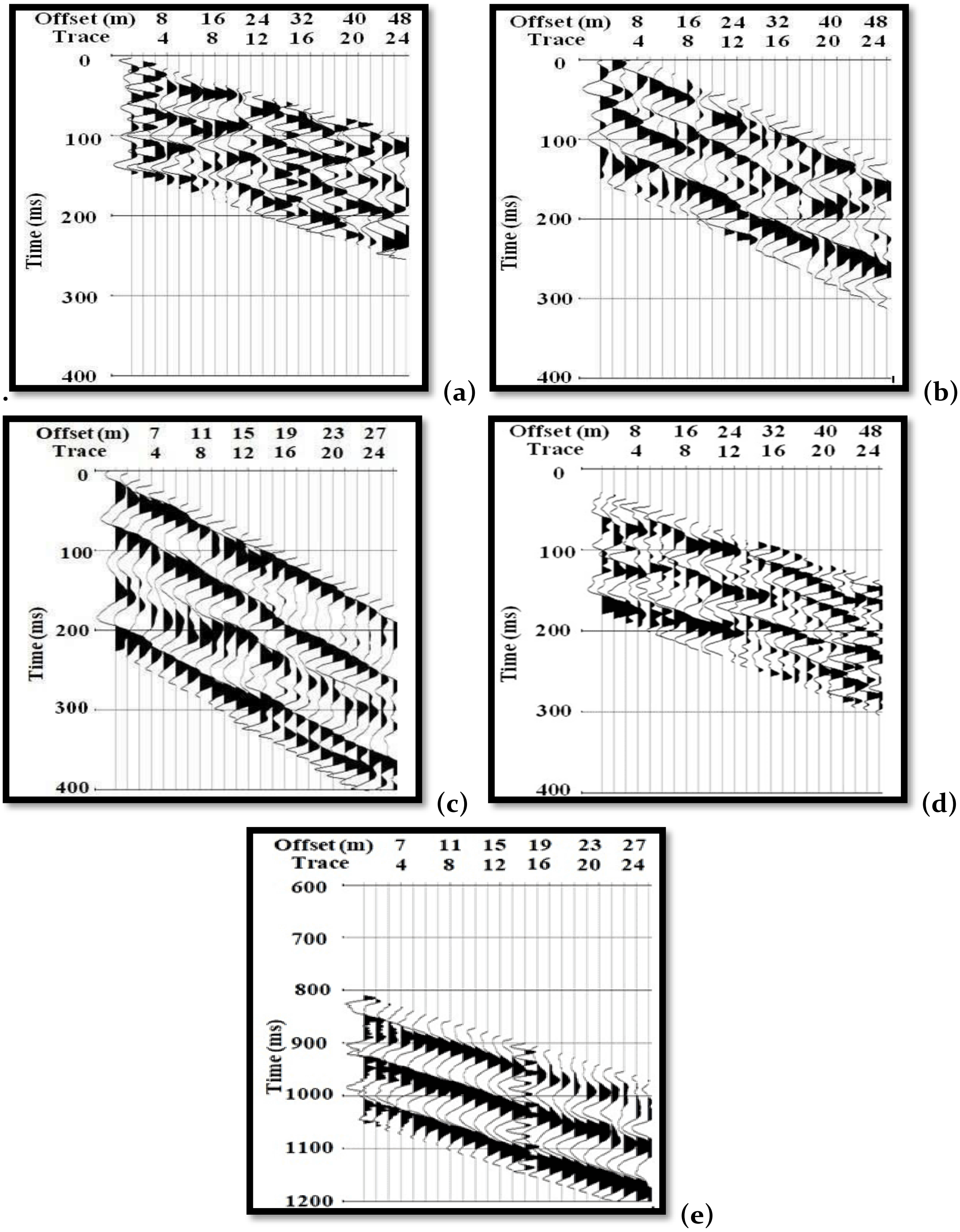
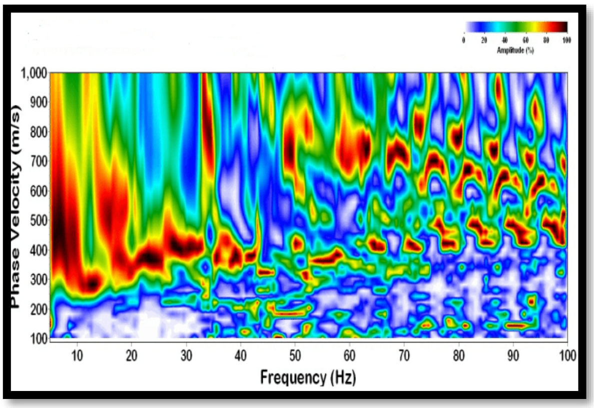
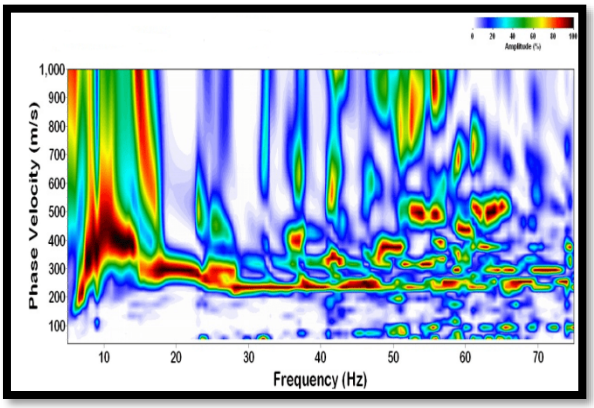


Fig. 9*Raw Images of (a) site 1 (b) site 2 (c) site 3 (d) Site 4 (e) site 5*

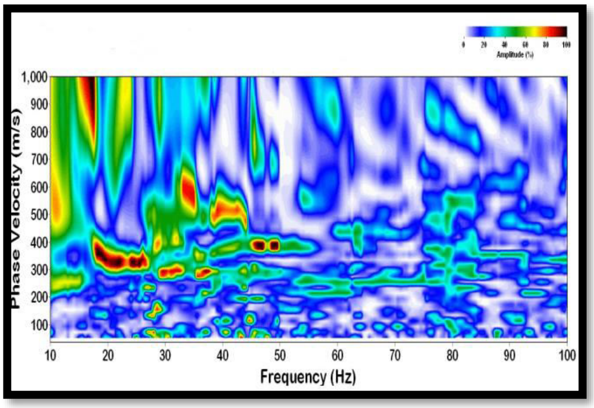
Figure 9 shows that the raw data obtained for the entire site 9a-e is more disturbed as a result of the acquisition of passive wave fields generated by passive sources. For sites 1, 2, and 4, less time is required to propagate (300 ms). However, site-3 raw images propagate slightly higher, i.e., up to 400 ms. For site-5, the propagation of waves begins at 800 ms and continues until 1200 ms. Figure 10 illustrates the continuity and scattering of energy bands in sites 1, 2, 3, and 4. The propagation of energy extends to a wider frequency range.

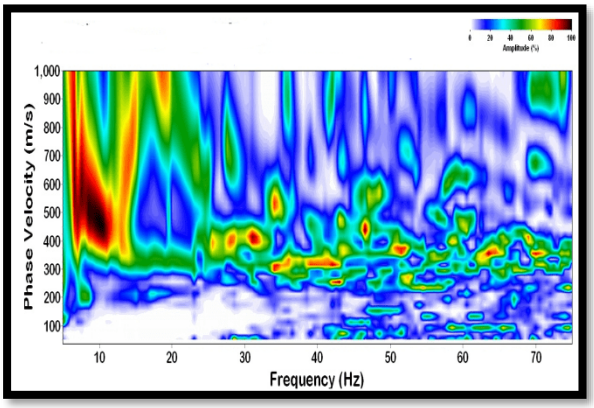




(a)

(b)





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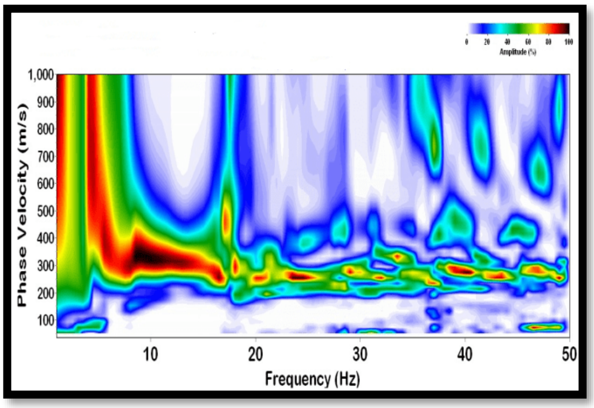
(d)



(e)

Fig. 10*Dispersion Images of (a) site 1 (b) site 2 (c) site 3 (d) Site 4 (e) site 5*

The concentration of energy in the lower frequency range leads to a deeper investigation. Figures 10a, b, and c demonstrate this. Figures 10d and 10e show a higher concentration of energy and discontinuity of the energy band, but energy propagation mostly concentrates on the lower frequency range, indicating a deeper depth of information. Figures 11 a-e display the corresponding shear wave velocity.

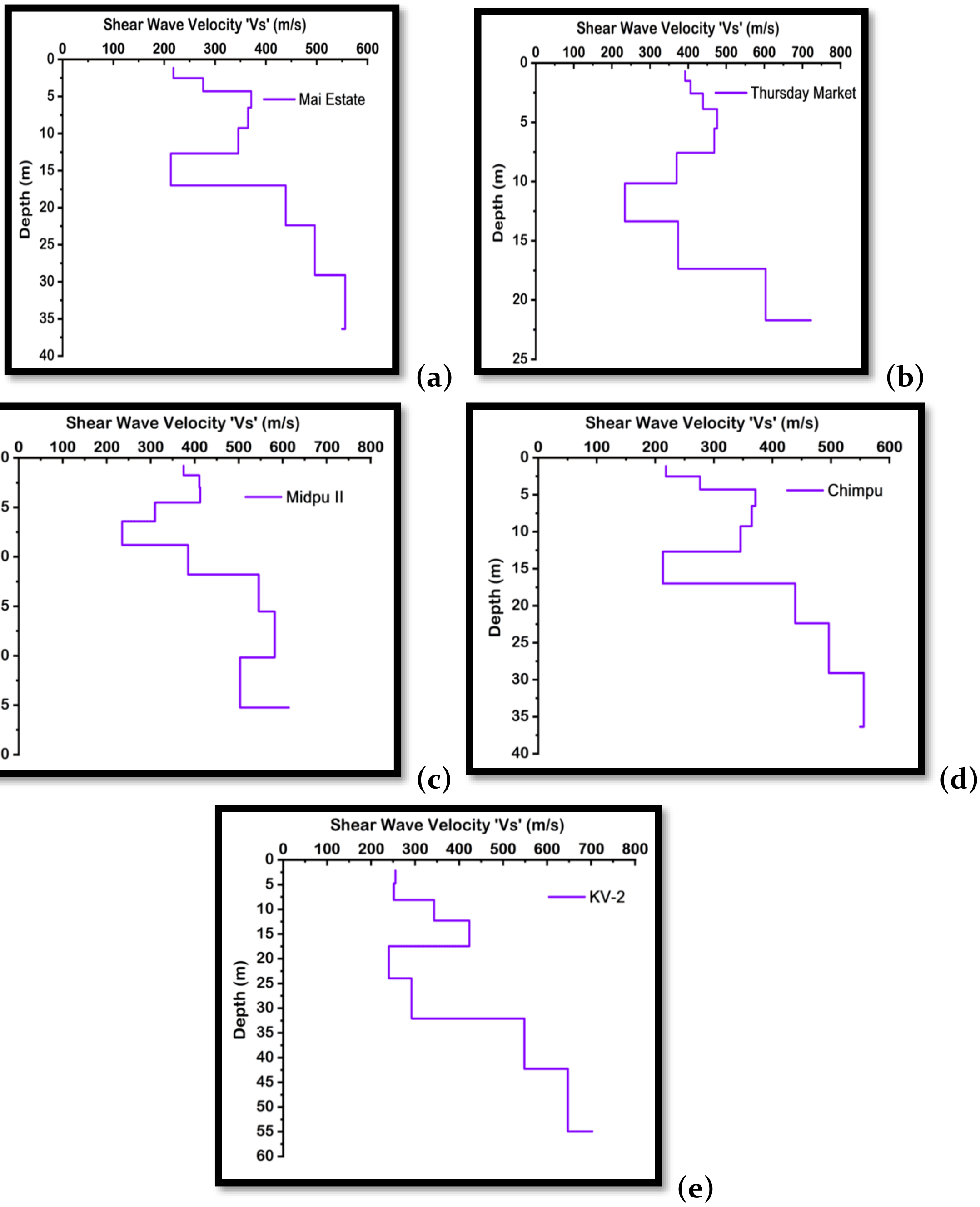
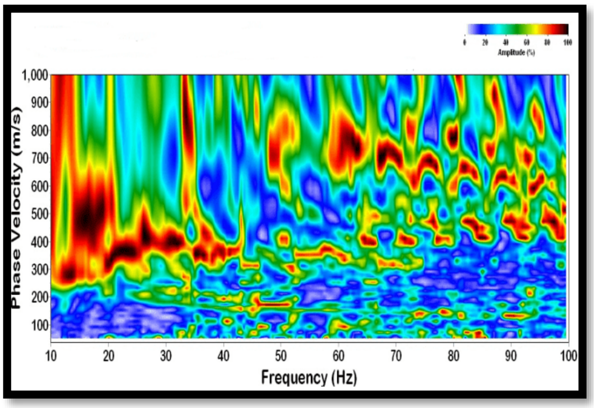


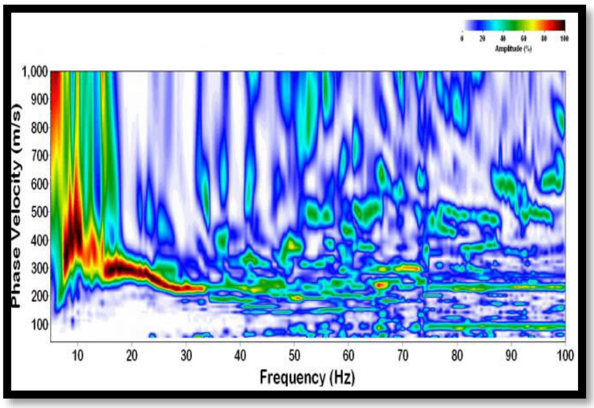
Fig. 11*Shear Wave Velocity profile of (a) site 1 (b) site 2 (c) site 3 (d) Site 4 (e) site 5*

Figure 11a above illustrates the shear wave velocity profile for a passive MASW survey, achieving a depth of over 30 m, which corresponds to a shear wave velocity of 200 to 500 m/s. Depending on the site condition and different compositions of soil strata, the wave propagation and depth achieved vary in different sites. Figure 11a-e shows the shear wave velocity profile for different sites.

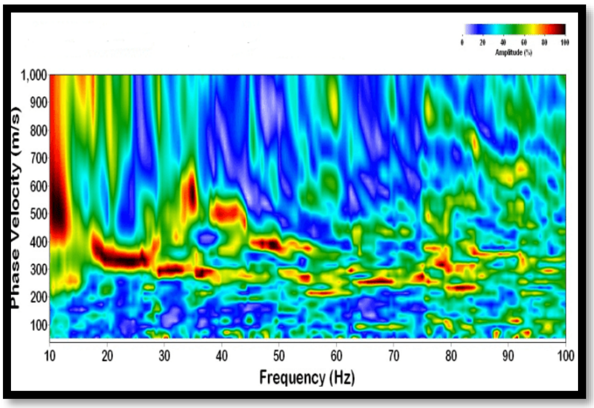
Characterization of site using Combine MASW Survey

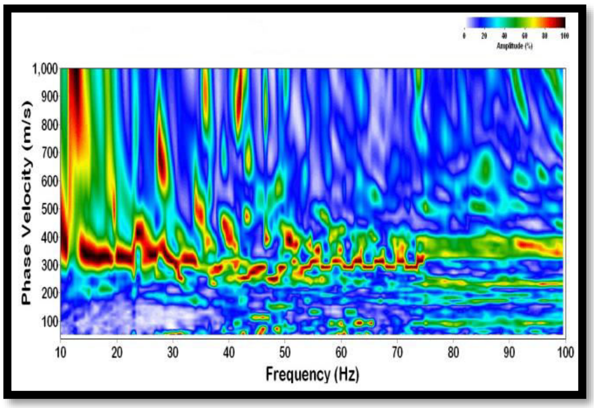
Combining active and passive MASW increases the depth of investigation to a wider analyzable frequency range and also helps to identify the nature of dispersion trend in the form of an energy band more accurately (5, 11). Since the active MASW approach uses shorter wavelength waves, the dispersion curve falls within the higher frequency range, while the passive MASW approach places the dispersion curve in the lower frequency range due to the longer wave length (6, 16). Due to the inverse properties of frequency and wavelength, the depth range varies from 1-25 m in the active MASW approach to 1-60 m in the passive MASW approach. Active and passive MASW tests were implemented at each of the five locations. After the data is collected, it is processed to produce dispersion images for both active and passive MASW surveys. The highest resolution dispersion images obtained from active and passive MASW surveys are subsequently combined. Figure 12a-e shows the combined dispersion images for active and passive tests conducted on all five of the sites mentioned above. Figure 12b shows a continuous dispersion curve trend for site-2. Compared to figures 7a and 10b, the energy accumulation is greater. The dispersion images in figures 12a, 12e, etc. also show better dispersion energy with a wider range of analyzable frequencies. The next section presents a detailed comparison of active, passive, and combined dispersion images.



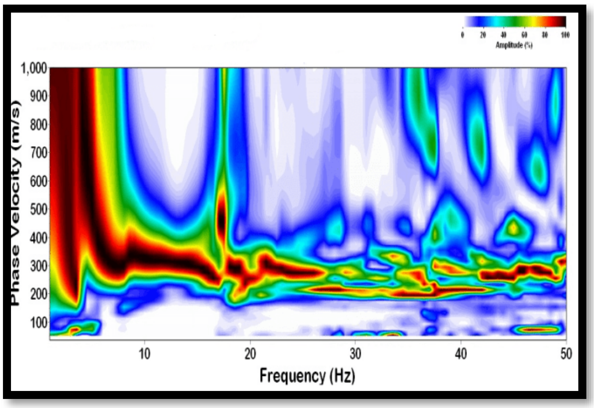


(a)
(b)





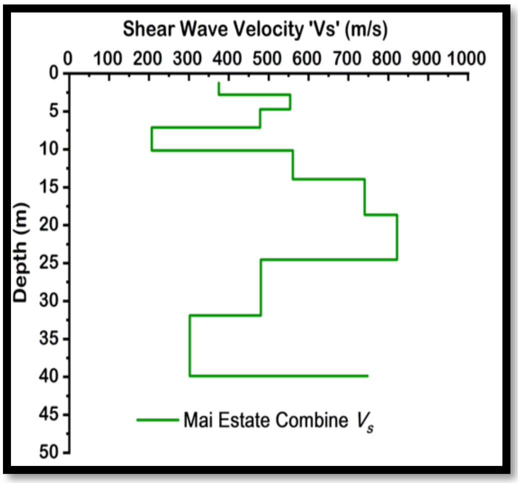
(c)
(d)



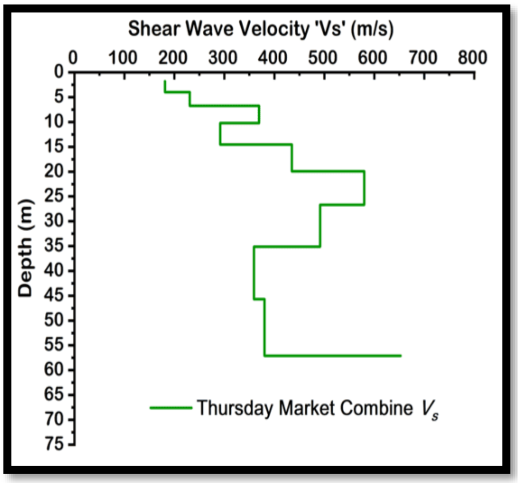
(e)

Fig. 12 *Dispersion Images obtained from combined MASW (a) site 1 (b) site 2 (c) site 3 (d) Site 4 (e) site 5*

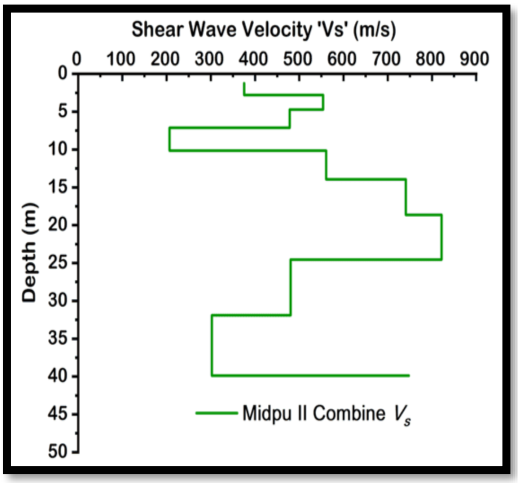
Figure 13a-e depicts the corresponding shear wave velocity profile for all sites. It is observed that the depth achieved for site-1 is 40 m as shown in the figure 13a, it can be seen that the shear wave velocity ranges from 200 m/s to 800 m/s. For site-2 maximum depth of investigation is 55 m. This can be seen in the shear wave velocity profiles in figure 13b. The shear wave velocity profile ranges from 200 m/s to 1000m/s. According to site classification by NEHRP(22), it can be said that the soil site is stiff to dense soil at shallower depth to soft rock at the deeper depth in site-2. Shear wave velocity of site-3, 4 and 5 as shown in figure 12(c-e), also shows a deeper depth of investigation.



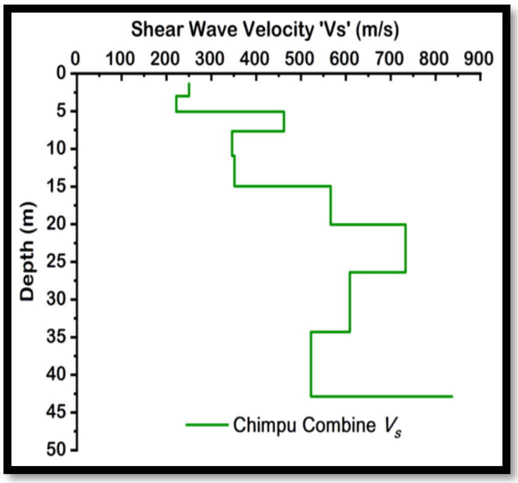
(a)



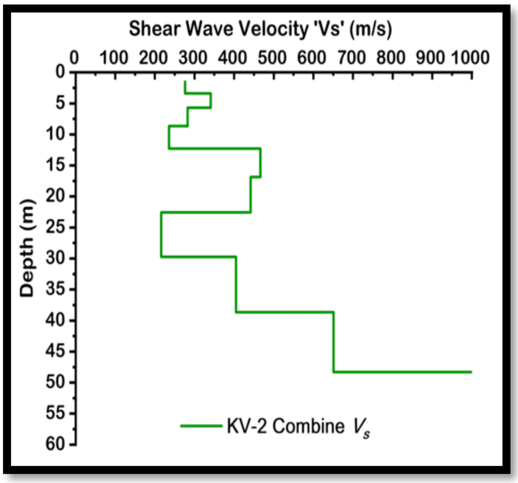
(b)



(c)



(d)



(e)

Fig. 13 *Shear wave velocity profile obtained from combined MASW a) site 1 (b) site 2 (c) site 3 (d) site 4 (e) site 5*

Figure 14 compares the dispersion image data from site-2 once more. Figures 14a and 14b show the dispersion image of active and passive MASW, respectively. Figure 14c shows the combined dispersion image. Figure 14c, when compared to Figures 14a and 14b, exhibits a more continuous, higher concentration, and wider range of energy bands. This indicates that combining active and passive data provides a wider range of analyzed frequencies and aids in identifying the dispersion trend's better modal nature.

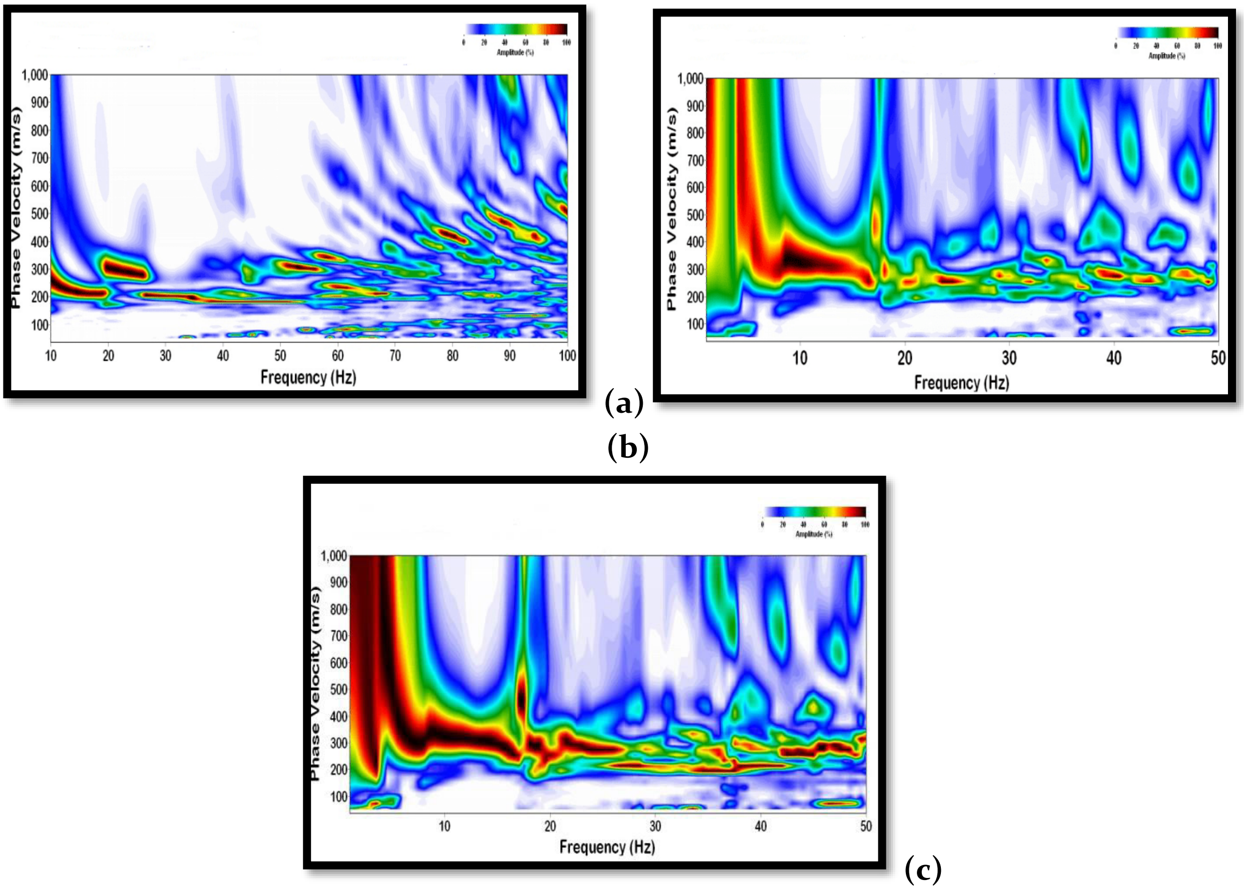


Fig. 14 *Dispersion image of (a) active (b) Passive (c) combined MASW*

Modal Analysis of dispersion image of Combine MASW

Subramaniam et al. (18) have carried out modal analysis of Rayleigh waves based on combined MASW and MAM tests. The sole inversion of the fundamental mode leads to slight inaccuracies and low resolution in the 1D vs. profile. Ivanov et al. (19) show the dominance of higher modes at low frequencies, which can lead to overestimation of invertedV_s results. Karray et al. (20) explicitly designed the MASW (Modal Analysis of Surface Wave) to utilize information from all available modes, rather than minimizing the contribution of higher modes. The MASW system's modal analysis aims to process field dispersion data, generating a dispersion curve for each contributing mode for use in the inversion stage. The separation and use of higher modes greatly influence the collection of dispersion data in the field. All recorded dispersion data undergoes processing and use, without any criteria for discarding specific wavelengths. Park et al. (16) emphasised that the combined MASW survey will lead to better identifying the modal nature of dispersion trends. Figure 14a displays the dispersion images of the combined MASW, revealing the higher mode. Identification of the higher mode is necessary for the accuracy of inverted profiles, and the inverted profile clearly demonstrates this. We later validated the inverted V_s profile of site-2 using the borehole profile (V_s derived from the SPT-N value), as depicted in figure 16a-b. Consequently, figure 15 displays the borehole profile. The borehole profile clearly demonstrates a good match between the shear wave velocity from the combined

MASW and the Vs from the combined MASW survey, particularly up to a depth of 10.5 m, as illustrated in figure 16c.

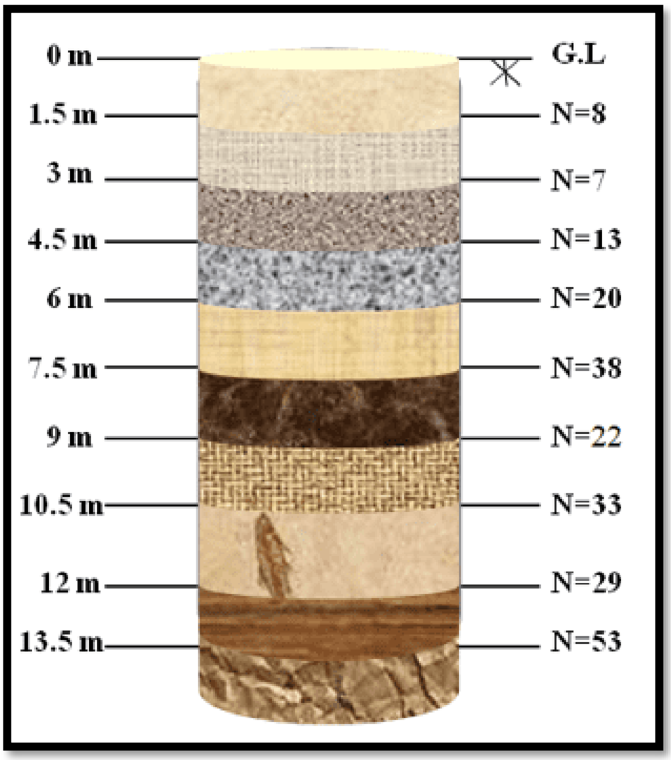
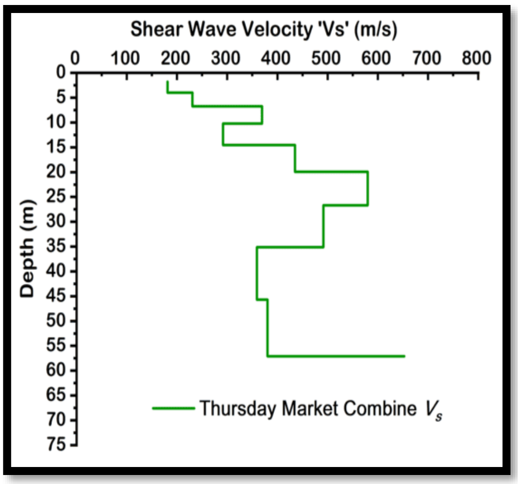
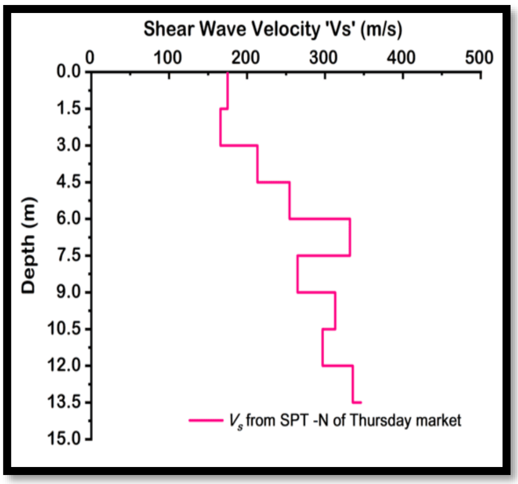


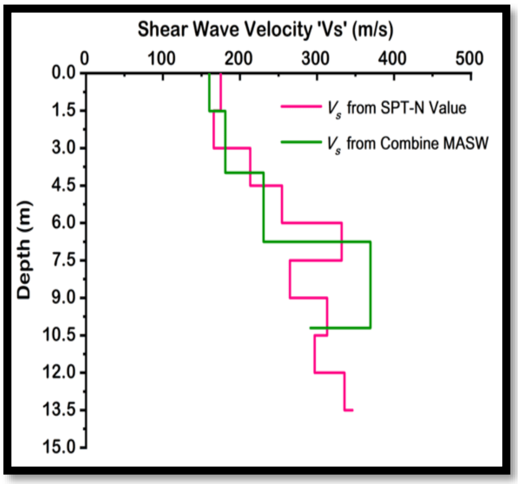
Fig. 15 *Borehole log subsoil profile for site-2 (Thursday Market)*



(a)



(b)



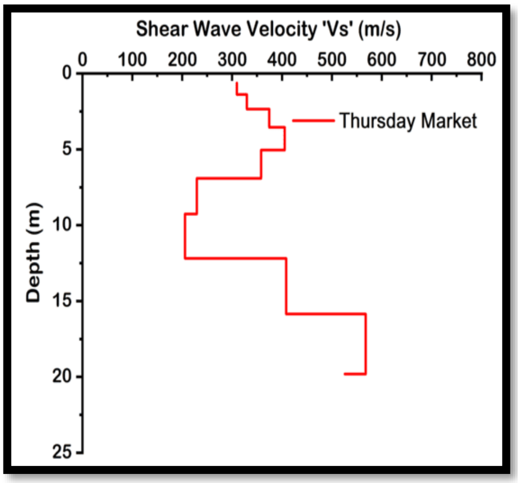
(c)

Fig. 16 *Shear wave velocity profile of site-2 from (a) combined MASW and (b) Borehole (c) Comparative V_s curve*

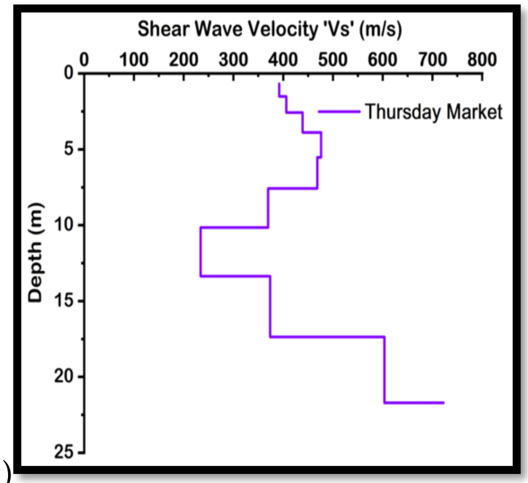
Depth and clarity of exploration

The high frequency of active MASW results in a shallower depth of investigation (Fig. 17a), while the lower frequency of the passive MASW (Fig. 17b) leads to a deeper depth of investigation. The passive MASW obscures the information about shallower depth. The combined MASW has the benefit of clarity in both shallow and deeper depths. As shown in figure 17c, the information becomes clear at both shallow and deeper depths.

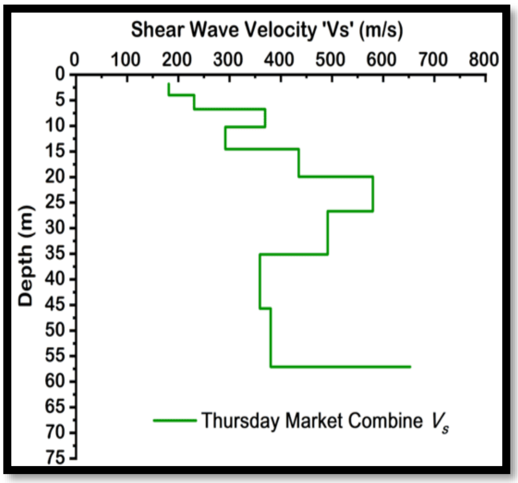
This is because the combination of two active and passive dispersion images from the same site naturally integrates continuous trends over a wider bandwidth (5). These trends contain considerably clearer information about the soil beneath.



(a)



(b)

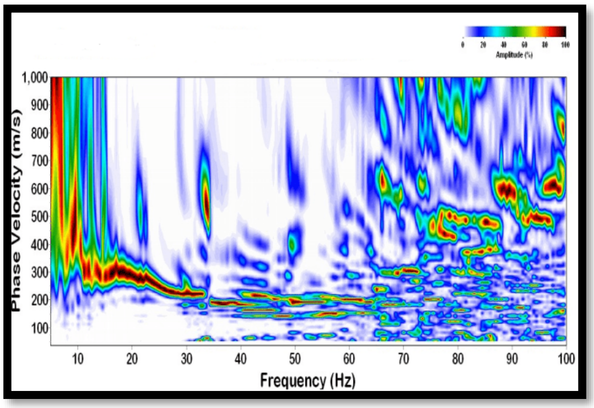


(c)

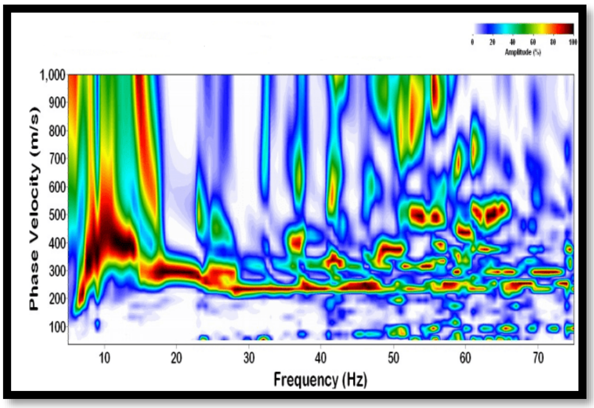
Fig. 17*Shear wave velocity profile of site -2 from (a) Active MASW (b) Passive MASW (c) combined MASW*

Large range of analyzable frequency

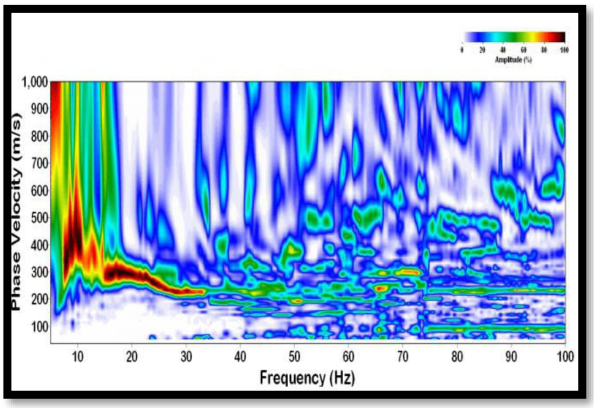
In order to conduct a comparative analysis of the range of analyzable frequencies for active, passive, and combined MASW surveys, a field experiment was conducted at site-2, specifically the Thursday market area of Yupia. The MASW survey was conducted along with the standard penetration test to obtain bore-hole data and validate both results. This site employs an active, passive roadside, and combined MASW survey along the road's length, utilizing 24 geophone arrays with a 2 m receiver spacing and a 5 m offset distance, and adhering to all other optimal data acquisition parameters as recommended by (14). The resulting data undergoes processing to produce a dispersion image with optimal resolution, as illustrated in figure 18. Figure 18(a) reveals a narrower analyzable frequency range between 20 and 30 Hz due to the use of an active source during the experiments, but it also clearly displays a distinct energy concentration. In figure 18(b), which is of passive survey, the analyzable range of frequency is broader and wider but discontinuous because of the longer wavelength wave generated from unknown passive sources. The frequency range starts at 5 Hz and goes up to 50 Hz, but the concentration of energy slowly diminishes. Figure 18(b) reveals the presence of higher modes in the passive dispersion image. Compared to both dispersion images, the dispersion image in figure 18(c), which is the result of combining both active and passive modes, is more advantageous. This is because it enhances the resolution of the dispersion image and provides a wider frequency range, which can be further processed to generate a shear wave velocity profile. A large range of analyzable frequency is essential for a variety of investigations.



(a)



(b)



(c)

Fig. 18 *Dispersion image of site-2: (a) Active MASW Survey (b) Passive MASW Survey (c) Combine MASW Survey*

The dispersion image figure reveals a broad frequency range in the combined MASW survey. A wide frequency range gives a large analyzing frequency, which is directly proportional to the analyzing depth range. Increasing the analyzable frequency range can lead to better and more accurate soil profiling.

Comparative analysis of shear wave velocities

Figure 19 shows the shear wave velocity vs. Active, Passive, Combine, and bore-hole survey, which indicates that the Active MASW survey method can be advisable for characterizing and soil profiling up to 20 m of depth. The depth above 20 m is not advisable in an active survey as the wave's higher frequency is generated by an active source (sledged hammer). In contrast to that, the passive source can generate lower-frequency waves of higher wavelength, which can penetrate deeper into the soil, and hence the information on depth can be obtained, but shallower depth of information is generally unclear in passive surveys because of lower frequency and longer wavelength waves. To overcome the above-mentioned disadvantage, a combined MASW approach is focused on and considered in this research so that information on both shallower and deeper depths can be achieved. Figure 19 (c) shows that higher depth is achieved when a combined approach is considered.

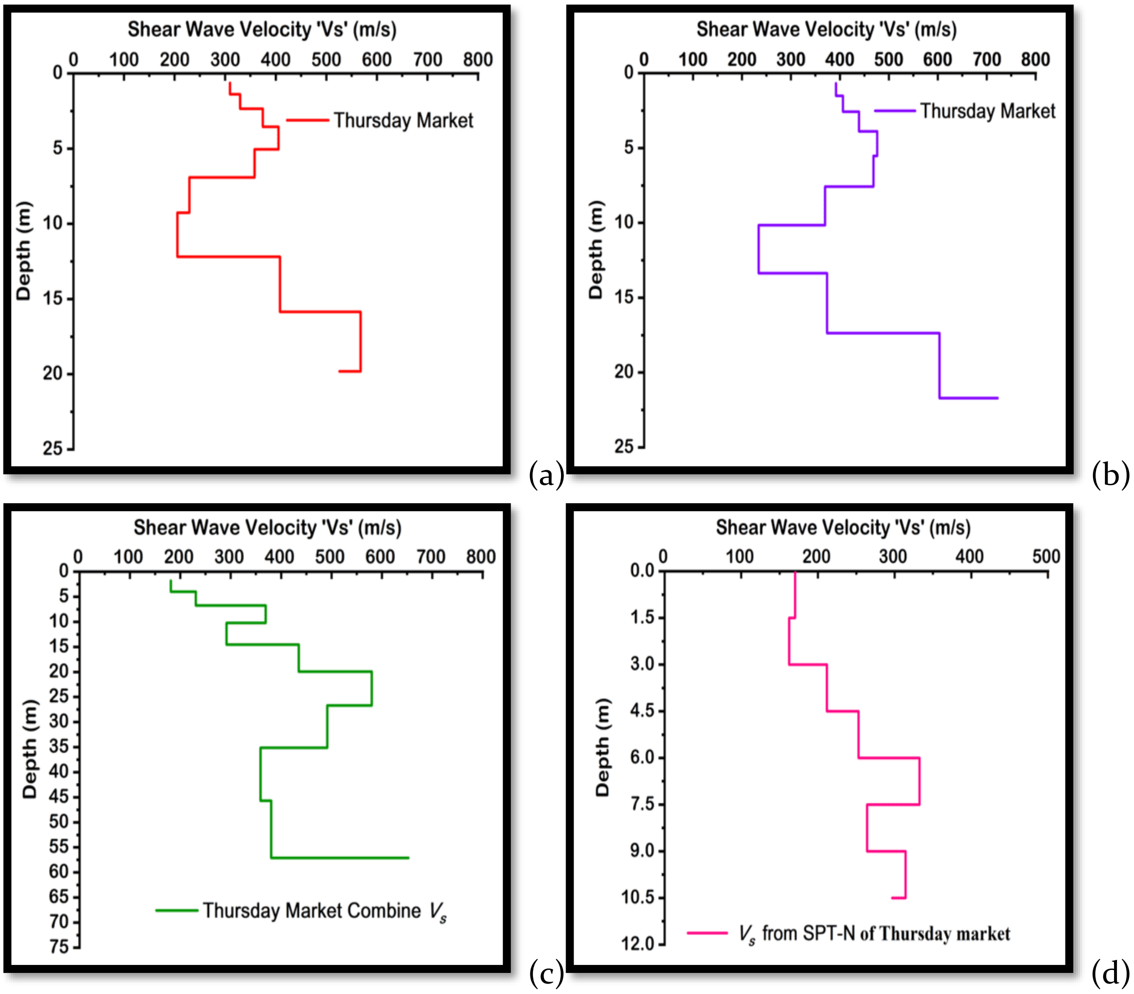


Fig. 19 *Shear Wave velocity profile for site-2 obtained from: (a) Active Survey b) Passive Survey (c) Combine*
Survey (d) Bore-hole Survey

Figure 19(d) shows the shear wave velocity profile obtained from relations using borehole data. The standard penetration test achieved only 10.5 m of depth. Though deeper depth couldn't be achieved due to the presence of rock beneath and economic constraints, the pattern of shear wave velocity vs. depth as seen in figure 19 shows similarity with shear wave velocity vs. depth obtained from MASW approaches.

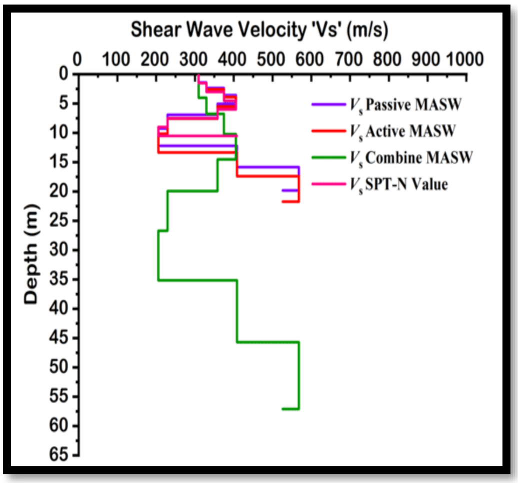


Fig. 20*Comparison of Shear Wave velocities for different approach of survey*

Figure 20 shows the comparative graph of shear wave velocity vs. depth among different methods, such as active, passive, combine, and bore-hole survey. Though investigation depth differs in all the survey methods, the pattern at which shear wave velocity deviates along depth is of a similar nature, which validates the accuracy of the MASW survey approach.

The study provides a brief overview of the active, passive, and combined MASW survey methods, with an emphasis on the combined MASW results. We conducted field tests at various Itanagar and Yupia sites, each with unique physical characteristics. The combined MASW demonstrates greater investigation depth, enhanced modal identification, and a larger analyzable frequency. The data collected were analyzed using a wide range of data acquisition and inversion parameters, and the best resolution dispersion image was generated. This image was then inverted to evaluate the final vs. profile result. The active MASW survey had a depth range of 20 to 30 m, but the passive MASW significantly e

Discussion and Conclusion

The study provides a brief overview of the active, passive, and combined MASW survey methods, with an emphasis on the combined MASW results. We conducted field tests at various Itanagar and Yupia sites, each with unique physical characteristics. The combined MASW demonstrates greater investigation depth, enhanced modal identification, and a larger analyzable frequency. The data collected were analyzed using a wide range of data acquisition and inversion parameters, and the best resolution dispersion image was generated. This image was then inverted to evaluate the final vs. profile result. The active MASW survey had a depth range of 20 to 30 m, but the passive MASW significantly expanded it to 60 m, resulting in a wider Vs. range. The analyzable range of frequency increased during the survey. Combining the best resolution dispersion image from both active and passive methods resulted in an increase in the analyzable range of frequency and a clearer dispersion trend during the dispersion curve extraction process. Conducting a combined active and passive MASW survey increased the investigation's depth to 60 m, providing clarity in the shallow subsurface layers. The experiment shows that combining two sets of higher-resolution dispersion images from active and passive MASW gives more clear and detailed information about the soil at deeper depths. This makes the method very useful for understanding the overall modal nature over a wide range of frequency and phase velocity. Expanded it to 60 m, resulting in a wider Vs. range. The analyzable range of frequency increased during the survey. Combining the best resolution dispersion image from both active and passive methods resulted in an increase in the analyzable range of frequency and a clearer dispersion trend during the dispersion curve extraction process. Conducting a combined active and passive MASW survey increased the investigation's depth to 60 m, providing clarity in the shallow subsurface layers. The experiment shows that combining two sets of higher-resolution dispersion images from active and passive MASW gives more clear and detailed information about the soil at deeper depths. This makes the method very useful for understanding the overall modal nature over a wide range of frequency and phase velocity.

In summary, the combined active and passive MASW method proves to be a powerful tool for soil characterization, offering enhanced depth of investigation, improved resolution, and greater accuracy in subsurface profiling. This makes it an invaluable technique for geotechnical engineering, providing detailed and reliable data for informed decision-making in construction, environmental assessment, and other related fields.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:**Phurba Dorjee Philley; **data collection:**Phurba Dorjee Philley and Tassar Pana; **analysis and interpretation of results:**Phurba Dorjee Philley, Jumrik Taipodia; **draft manuscript preparation:**Phurba Dorjee Philley,Jumrik Taipodia. All authors reviewed the results and approved the final version of the manuscript.

Ethics Approval: Not Applicable

Abbreviation

MASW: Multichannel Analysis of Surface waves, GPR: Ground Penetrating Radar, NMR: Nuclear Magnetic Resonance, SNR: Signal-to-Noise Ratio, NEHRP: National Earthquake Hazards Reduction Program, Dpi: Dots per inch, ReMi: Refraction Microtremor, MAM: Microtremor Array Method, SPT: Standard Penetration Test

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