Guidelines for Minimization of Uncertainties and Estimation of a Reliable Shear Wave Velocity Profile Using MASW Testing: A State-of-the-Art Review

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1 Introduction

Earthquakes are catastrophic phenomena that cause extremely heavy destruction to society. Hence, preparedness against earthquakes is a very crucial task in geotechnical earthquake engineering. To reduce the effects of earthquakes, an essentially important exercise is the seismic hazard analysis of the study area. For carrying out seismic hazard analysis, the shear wave velocity (V_s) profile of the soil serves as a basic input parameter. For the estimation of the V_s profile of the soil, the most preferred technique currently is the multichannel analysis of surface waves (MASW). It is a geophysical method, based on the dispersion phenomenon in seismic surface waves. The MASW method offers several advantages over other conventionally used methods such as cone penetration test (CPT), seismic cross-hole test, and standard penetration test (SPT). It is a non-invasive method and simpler to carry out. It requires less labor, time, and expense compared to the other methods. Also, it can be used for almost all types of soil, unlike many other methods. These characteristics make the MASW test the most common choice to estimate the V_s profile of the soil. The importance of the V_s profile of soil can be understood from the fact that it is a critical input in seismic site characterization (Long & Donohue, 2007; Anbazhagan & Sitharam, 2008; Foti et al., 2011b; Odum et al., 2013; Asten et al., 2014; Taipodia et al., 2014; Rahman et al., 2016; Rehman et al., 2016; Pandey et al., 2016b; Leyton et al., 2018; Noorlandt et al., 2018; Maklad et al., 2020; Yamanaka et al., 2020; Hobiger et al., 2021; Salas-Romero et al., 2021), surface seismic exploration (Socco et al., 2017; Xia et al., 2018), V_{s30} mapping and site classification (Sandikkaya et al., 2010; Yordkayhun

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et al., 2015), studies on local site effects (Rastogi et al., 2011; Panzera et al., 2013; Michel et al., 2014; Pandey et al., 2016a; Stanko et al., 2017; Mugesh et al., 2022), seismic hazard assessment (Ebrahimian et al., 2019; Dwivedi et al., 2020), seismic microzonation (Martínez-Pagán et al., 2014; Khan & Khan, 2018; Caielli et al., 2020), ground motion modeling (Bozorgnia et al., 2014), liquefaction studies (Andrus & Stokoe, 2000; Lin et al., 2004; Kayen et al., 2013; Yokota et al., 2017; Mase et al., 2020), pavement evaluation and road failure investigation (Nazarian et al., 1983; Ayolabi & Adegbola, 2014), earthquake reconnaissance (Cubrinovski et al., 2010), studies on landfills (Suto, 2013; Zekkos et al., 2014), and many others (Watabe & Sassa, 2008; Kim et al., 2010; Omar et al., 2011; Madun et al., 2012; Connolly et al., 2014; Bergamo et al., 2016; Joh et al., 2019; Rahnema et al., 2021).

The procedure of estimating the V_s profile of soil using seismic surface waves started with the steady-state Rayleigh method (Jones, 1958). It comprised a vertical-vibrating sinusoidal vibrator and two receivers. However, it was too time-consuming and was not utilized much. By now, it has become obsolete. Then, the spectral analysis of surface waves (SASW) method was proposed (Heisey et al., 1982; Stokoe & Nazarian, 1983; Stokoe et al., 1988). It consisted of using an impulse source and two receivers to record the traveling waves. The phase difference and time delay of wave arrival between the two receivers were used to estimate the Rayleigh wave phase velocity as a function of frequency. It has been used widely and has also undergone developments (Stokoe et al., 1994; Tokimatsu, 1995). However, it has shortcomings, such as flaws in the identification of higher modes of vibration and separation of noise from the signal and high consumption of time and labor. So, later, a modified method titled MASW (Park et al., 1999; Xia et al., 1999) was developed which uses a higher number of receivers and overcomes the limitations of SASW. Crice (2005), in his editorial *Journal of Environmental and Engineering Geophysics* in 2005, stated that surface wave surveys would bring a paradigm shift in Geophysics because of their higher productivity, large areal coverage at a modest cost, and other advantages. Over the past two decades, the MASW method has emerged as the most popular method for estimation of near-surface soil stiffness and seismic site characterization due to its viability.

Although the MASW is the most preferred surface wave method at present, there are some issues with the method. The presence of body waves in the generated wavefield, the noise present at the site, and the non-uniqueness of the inversion process induce uncertainties in the MASW results. They have been explained in detail in Sect. 2. All these uncertainties pose some questions about the reliability of MASW. Therefore, it has become necessary to employ some techniques to reduce or account for these uncertainties. A lot of research has been carried out on the uncertainties in surface wave methods and their effects on subsequent analyses (Lai et al., 2005; Roy et al., 2013; Jakka et al., 2014; Griffiths et al., 2016; Saifuddin et al., 2018; Roy & Jakka, 2018). A thorough description of the basics of surface wave testing, its associated uncertainties, and the new developments that occurred on the topic is available in the literature (Park & Ryden, 2007; Socco et al., 2010; Nazarian, 2012). The general recommendations for carrying out different types of surface wave tests are provided by Foti et al. (2018), while the basic theory on the topic is reported by Foti et al. (2014).

This paper aims at putting forward practical guidelines, with regards to carrying out MASW and producing reliable results with minimum uncertainties. A huge amount of literature on the topic has been covered in the references and from the inferences from them, and the recommendations to implement have been presented. While carrying out the three steps in MASW, certain criteria are to be followed which are compulsory to get legitimate results. This paper puts focus on all these criteria. From the beginning to the end, all these steps and their peculiarities have immense significance in the MASW test. This paper explores all these steps and puts forth a standardized way to execute all these steps. The guidelines provided in this paper are useful to all the people in academia/industry who would use the MASW test for any study or project or anywhere else.

1.1 Basic Principles of MASW Testing

The MASW method utilizes the dispersive nature of Rayleigh-type surface waves. That is, Rayleigh waves of different frequencies travel at different velocities and penetrate to different depths in a layered medium. Higher frequency (shorter wavelength) Rayleigh waves remain confined to shallow depths and give information about their mechanical properties, whereas lower frequency (longer wavelength) components penetrate up to deeper layers (Fig. 1). This property can be used to infer near-surface soil properties, mainly the shear wave velocity profile and the shear modulus of the soil. These properties can be estimated up to the depths of engineering interest. Earlier, many studies on the MASW method and Rayleigh wave dispersion have been carried out (Zhang et al., 2004; Foti et al., 2011a; Lin & Lin, 2012; Diaz-Segura, 2015; Roy & Jakka, 2017; Roy et al., 2020).

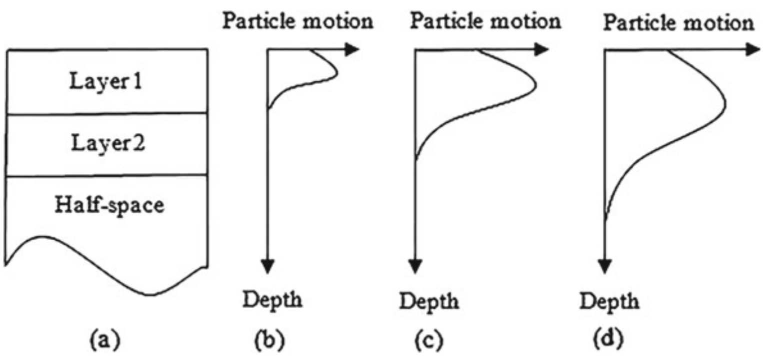


Fig. 1 Rayleigh wave dispersion in a layered media: **a** soil profile, **b** high-frequency wave, **c** intermediate-frequency wave, and **d** low-frequency wave

1.2 MASW Methodology

The MASW test consists of 3 steps: (1) Data acquisition, (2) Data processing and dispersion curve generation, and (3) Inversion (Fig. 2).

Data acquisition involves the deployment of a geophone array, generating waves using a source and its recording (active test), or recording ambient vibrations (passive test). Certain criteria should be followed in this procedure which are elaborated in Sect. 3.

Data processing involves the transformation of the recorded waveform data into a dispersion curve. The dispersion curve is a plot between Rayleigh wave phase velocity and frequency. Some people express it in other terms such as wavelength and slowness. Many methods are available to generate a dispersion curve, which have their own merits or demerits. Detailed information about them is provided in Sect. 4.

Inversion is the procedure of producing the V_s profile of the site from the dispersion curve. For this also, various algorithms are available. A thorough description of the inversion procedure, the considerations in the procedure, and different inversion algorithms have been presented in Sect. 5.

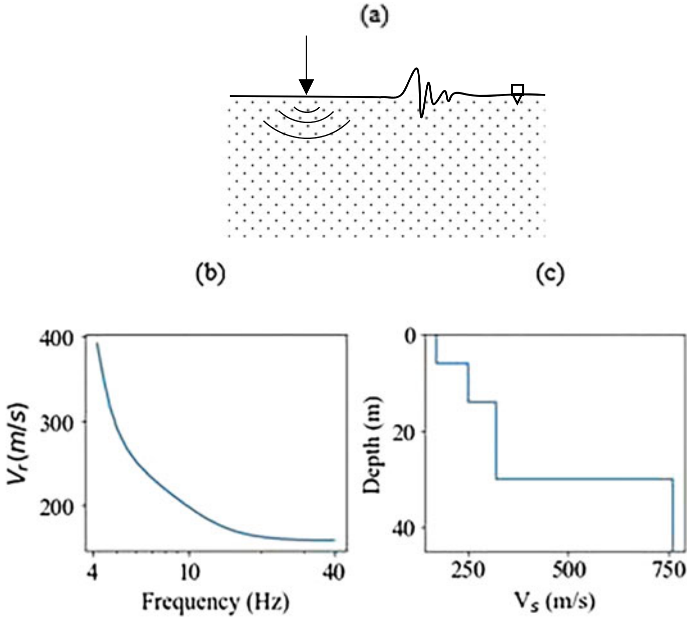


Fig. 2 The three steps of surface wave analysis: **a** Data Acquisition, **b** Processing and dispersion curve generation, and **c** Inversion and retrieval of V_s profile

2 Uncertainties in the MASW Method

The MASW method suffers from several uncertainties during data acquisition and processing. Roy (2015) has provided a thorough description of the types of uncertainties in surface wave analyses. Firstly, while carrying out surface wave analysis, it is assumed that the waves generated by the MASW source are plane Rayleigh waves. However, in reality, the generated wavefield also contains body waves which lead to the underestimation of Rayleigh wave phase velocity. Also, during the MASW testing, the ambient noise and anthropogenic activities such as the passing of vehicles or others interrupt the waves generated by the MASW source during the testing. This noise would be different when the test is conducted at different times at the same location. In addition, the process of retrieving the final V_s profile of soil involves an inversion process that provides a non-unique solution. That means that a single dispersion curve (plot between Rayleigh wave phase velocity and frequency) produced from an MASW test generates numerous V_s profiles equivalent to it. This phenomenon gives rise to ambiguities regarding the actual V_s profile of the soil. The uncertainties associated with surface wave testing can be broadly classified into three main categories and various other categories as shown in Fig. 3.

2.1 Model-Based Uncertainty

Model-based uncertainty is primarily associated with the phenomena known as the near-field effects. The MASW processing assumes the plane Rayleigh wave propagation, i.e., only Rayleigh waves are present and recorded on the receivers. However, in the real scenario, other waves such as P and S waves are also generated from the impact of the MASW source. These waves contaminate the Rayleigh waves and therefore, the Rayleigh wave phase velocity (V_r) is underestimated at lower frequencies, and the underestimation increases as the frequency decreases. Earlier, it has been found that near-field effects lead to the underestimation of phase velocity at wavelengths greater than half the length of the linear geophone array (Bodet et al., 2009) or wavelengths greater than the mean source to geophone distance (Yoon & Rix, 2009). Various factors can influence the near-field effects such as the source type, its height of fall, its contact mechanism with the ground, source to first receiver distance, array length, dispersion (data processing) method, subsurface soil profile, etc.

Many studies have been carried out on the near-field effects and the ways to mitigate them (Zywicki & Rix, 2005; Xu et al., 2006; Li & Rosenblad, 2011; Roy & Jakka, 2017). One way to reduce the near-field effects is to keep the distance between the MASW source and the first receiver as much as possible. However, it should be ensured that the generated wave-train is properly captured at all the receivers, especially the high-frequency components because they attenuate more with distance. Also, the use of the cylindrical beamformer method to generate the dispersion curve

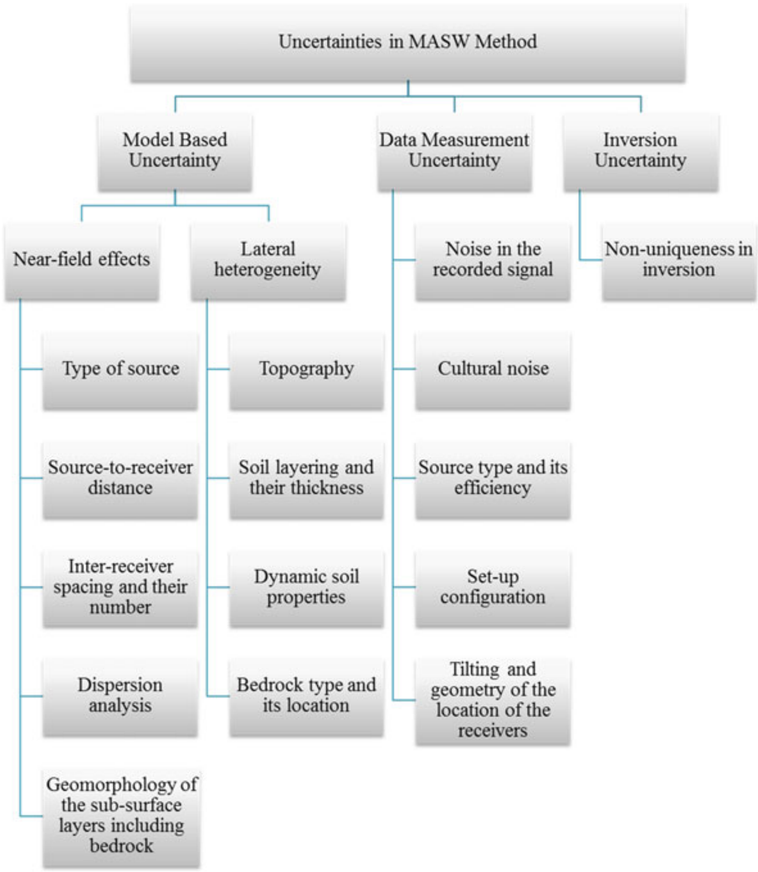


Fig. 3 Types of the uncertainties in the MASW method (Roy, 2015)

from the MASW data was found to be reducing the near-field effects (Tran & Hiltunen, 2011). However, some studies found that this method does not completely serve the purpose (Li, 2008; Jiang et al., 2015).

Another way to tackle the near-field effects is the use of combined active and passive MASW tests. The 2D passive array can be circular, triangular, L-shaped, etc. The passive test uses the wavefield coming from far distances. So, because the body waves attenuate faster with distance than surface waves, at far distances, surface waves become dominant. Hence, the passive MASW test acquisition can be approximated as the plane Rayleigh wave condition which would demonstrate negligible near-field effects. So, the underestimation of V_r at lower frequencies due to near-field effects can be avoided. On the other hand, the active MASW test can provide better resolution at higher frequencies. Hence, the active and passive MASW data complement each other to generate good quality, broadband dispersion curves. By comparing the individual dispersion curves from the active and passive tests, the

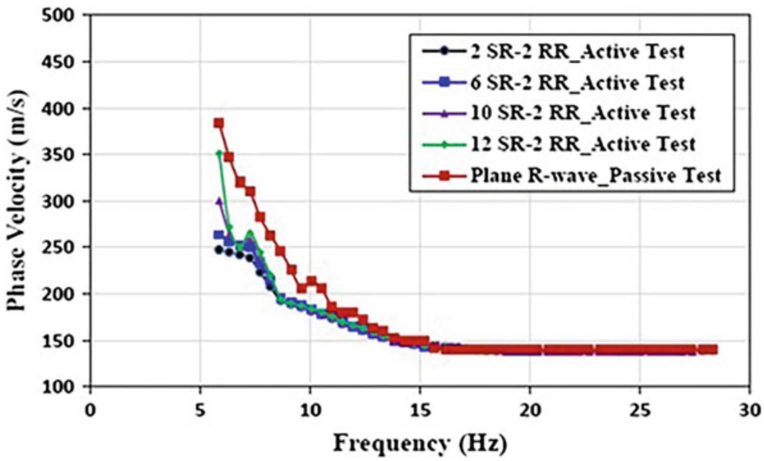


Fig. 4 Comparison of dispersion curves using different source offsets in active MASW test and a passive MASW test (SR: Source to first receiver distance; RR: Receiver to receiver distance) (Roy, 2015)

frequencies at which near-field effects are prominent can be identified and should be removed. For example, Fig. 4 shows the underestimation of V_r at lower frequencies in active test results. Such a portion should be removed from that particular dispersion curve and the remaining portion should be used to prepare a combined dispersion curve to be used for further analyses. Also, for passive MASW acquisition, it is strongly suggested to use the 2D arrays and avoid the linear arrays by many researchers because of a lot of discrepancies in the latter case.

Another source of the model-based uncertainty is the lateral heterogeneity present in the soil. The MASW test is carried out assuming that the soil is laterally homogeneous, i.e., the soil properties do not change in the horizontal direction at the site. However, some locations may exhibit changes, i.e., there may be material boundaries that are not perfectly horizontal. This would affect the test results and the results would have errors. Lateral heterogeneity may depend on the topography of the site, soil layering and their thicknesses, dynamic soil properties, bedrock type, its location, etc.

2.2 Data Measurement Uncertainty

The waveforms recorded in the MASW test invariably contain the ambient noise present at the site. It may be due to the passing of people, vehicles, earth's vibrations, wind, sea waves, instrumental self-noise, etc. This can produce scatter in the dispersion curve. Also, such a type of noise would be different during different acquisitions carried out at the same site. This produces ambiguity about the actual

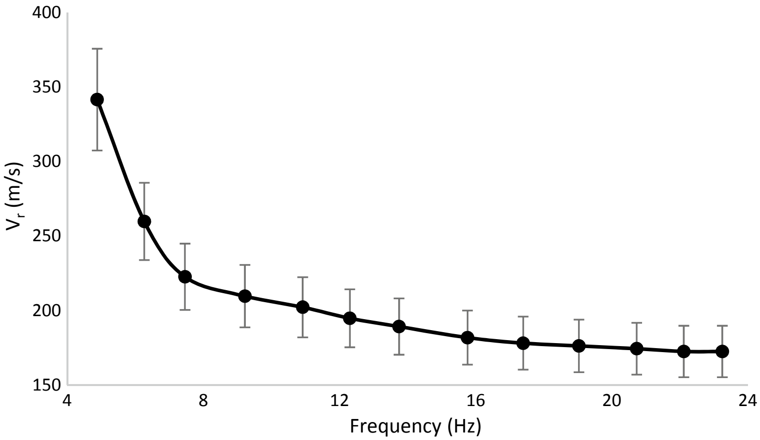


Fig. 5 Representation of dispersion curve with data measurement uncertainty: Curve displaying the Rayleigh wave phase velocity mean value and its standard deviation using several dispersion curves at the same location

dispersion curve at the site. This is termed the data measurement uncertainty. It can get affected by the source type and its efficiency, MASW setup, the alignment, and tilting of the receivers. Many researchers have worked on the data measurement uncertainty and its impact on further analyses (Marosi & Hiltunen, 2004a, b; Lai et al., 2005; Jakka et al., 2014). The data measurement uncertainty increases when the signal-to-noise ratio (SNR) decreases. It is generally suggested to be very careful in using data that has SNR < 10 dB. When the low SNR produces bad quality data or when the COVs of the measured dispersion curves using different source offsets are significantly high, that data should not be used for the analysis (Wood & Cox, 2012). To prevent the data from getting affected by the noise, the test should be carried out when the traffic due to vehicles can be avoided.

One way to deal with this uncertainty is to take multiple shots of the MASW at the same location and generate multiple dispersion curves. Then, using all these curves, the final dispersion curve can be presented as a mean curve and its standard deviation (Fig. 5). This would provide the dispersion curve along with its data measurement uncertainty. Also, taking multiple shots and stacking them together improves the SNR which is very much needed to get good quality data.

2.3 Inversion Uncertainty

The process of inversion involves the generation of the final V_s model of the site using the experimental dispersion curve. However, the inversion process is non-unique, i.e., for a single dispersion curve, several V_s profiles are generated whose theoretical dispersion curves have remarkably similar misfit values. Misfit is the measure of the

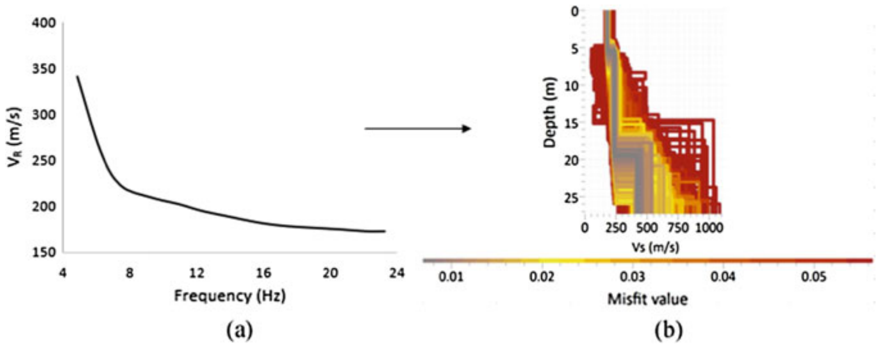


Fig. 6 Concept of inversion uncertainty: A single dispersion curve giving numerous V_s profiles with similar misfit values: **a** Dispersion curve and **b** V_s profiles

difference between the experimental dispersion curve of the site and the theoretical dispersion curve of the generated V_s profiles from inversion (Wathelet, 2008). This creates uncertainty about the actual V_s profile of the site. The inversion procedure is such that a single, true V_s profile of soil cannot be ascertained. This is called inversion uncertainty. The inversion uncertainty or inversion non-uniqueness has been a topic of research for many authors (Foti et al., 2009; Boaga et al., 2011; Roy et al., 2013; Teague & Cox, 2016; Lei et al., 2018; Roy & Jakka, 2020). Figure 6 shows the concept of inversion uncertainty. The inversion process was carried out using the DINVER framework of Geopsy software based on an improved neighborhood algorithm (Wathelet, 2008).

3 Data Acquisition

Data acquisition is the first step in an MASW test. An MASW test can be carried out in the field in two ways: (1) Active test or (2) Passive test. The active test involves the use of a source to generate Rayleigh waves. In the passive test, the waves from the ambient vibrations are recorded.

3.1 Active Test

A typical field MASW setup is shown in Fig. 7. It includes a source to generate waves, a receiver array (geophones), and equipment for data processing. The seismic waves in an MASW test are usually generated using either a hammer, electro-mechanical vibrator, or blasting, etc. Vertical component geophones are used for recording the particle motion at the surface. It is assumed that the maximum energy in the recorded

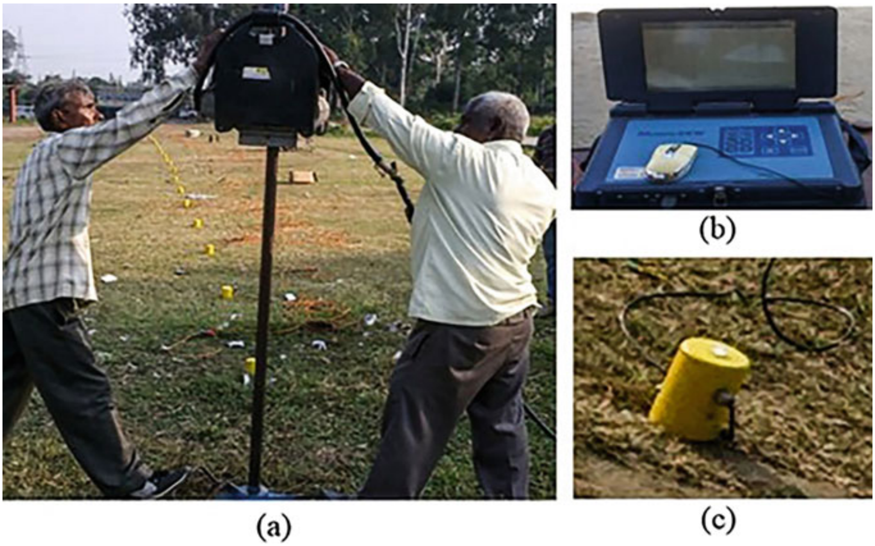


Fig. 7 MASW test setup: **a** Drop weight arrangement and receiver array, **b** A sample recording device: McSeis-SXW 24 channel seismograph, and **c** A sample vertical component geophone (Roy & Jakka, 2018)

motion is from the Rayleigh waves. The recorded signals are then processed to get the dispersion curve and the V_s profile.

Selection of test parameters and their effects on the uncertainties

In the MASW testing, the choice of the data acquisition parameters plays a huge role in the final results. The parameters can influence the uncertainties during all three steps of the test. Consequently, it can affect the resolution, quality, and correct identification of the dispersion curve and also the depth of investigation. A description of different test parameters and their role in MASW testing has been provided below.

Source type

The type of source influences the frequencies that are generated in the wavefield. There are two common active source types: Impact sources such as a sledgehammer/drop weight or a harmonic source such as an electro-mechanical or a servo-hydraulic (Vibroseis) shaker. These different sources have their own merits and demerits and would generate different surface wave energy of different frequencies. Wood and Cox (2012) compared the impact and harmonic sources in which the harmonic source was found to produce better quality data, particularly at lower frequencies.

A major benefit of active source testing is that the generation and measurement of Rayleigh waves can be carried out in a controlled way. It allows a band of frequencies to be measured altogether. The sledgehammer is by far the cheapest and most common impact source. Usually, the hammer used as the seismic source should be of a minimum of 5 kg (Foti et al., 2018). It can generate frequencies as low as 10–15 Hz. These frequencies may enable the user to obtain a V_s profile up to 30 m depth if the site is stiff, but the uncertainties in generating the dispersion curve would remarkably increase and need to be accounted for in the inversion analyses (Cox & Wood, 2011). Usually, when the sledgehammer is used as the MASW source, the depth of V_s profile obtained is less than 30 m (Park & Carnevale, 2010; Tran & Hiltunen, 2011). In soft soils, it can be substantially less than 30 m. Therefore, a challenge is faced by those who want to estimate V_{s30} (time-averaged V_s of top 30 m soil) at a site. Therefore, to generate low-frequency data to obtain V_s profile at higher depths, heavy sources such as large weight drop systems, Vibroseis, and bulldozers can be used. Efforts have been made to use specific sources to generate low-frequency data and generate V_s profile up to higher depths (Rosenblad et al., 2008; Rosenblad & Li, 2009b). They facilitate the analysis to be focused on a narrow band of frequencies, thereby decreasing the disturbance due to noise (Hebeler & Rix, 2001). Harmonic sources (i.e., Vibroseis) have been used for deep V_s profiling using SASW (Kayen et al., 2005; Wong et al., 2011). Stokoe et al. (2004) developed a low-frequency shaker that can actively generate surface wave energy even at frequencies less than 1 Hz. A description of the large-scale mobile shakers for generating such low-frequency data can be found in Stokoe et al. (2020). However, for MASW, they have been used quite less, because of the cost, difficulty in mobilization, and time-consuming data acquisition and analysis (Rix et al., 2002; Rosenblad & Li, 2009a; Cox & Wood, 2010). Overall, the type of source to be used should be decided based on the desired depth of investigation, portability, available space for the testing, availability of the equipment, and financial considerations.

Array length

The length of the receiver array (L) is associated with the wavenumber (k) resolution (and therefore the investigation depth) and the separation of modes. If the frequency–wavenumber (f–k) method is used for the processing of MASW data, a longer array would yield better wavenumber resolution, i.e., a lower value of minimum wavenumber k_{min}. Therefore, higher λ_{max} and higher depth of V_s profile can be achieved. Usually, as a thumb rule, if the V_s profile is desired up to a depth of D, it is recommended to keep the array length at least equal to 2D; and to be more conservative, it should be 3D. However, it also depends on the stiffness of the soil. If the processing method used is other than f–k, this condition may not be followed exactly. Still, a higher array length would enable to get a higher value of $\lambda_{max.}$ However, to make the array length larger, the inter-receiver spacing should not be kept too high, which would adversely affect the V_s resolution at shallow depths.

The second feature is mode separation. If the array length is less, a lower resolution in the wavenumber domain hampers the identification of higher modes. The operation of zero padding can help up to some extent, but it cannot compensate for the loss of data due to the lower array length (Socco & Strobbia, 2004). Therefore, a longer array is suggested especially for soils having high impedance contrast or inversely dispersive V_s profile in which higher modes may become dominant. However, in the case of a longer array, the waves may get affected by the attenuation of high-frequency components, lateral variations, and noise at the site. Therefore, an optimum value of array length should be selected, which can provide good quality data, by visual inspection of the acquired data after using different array lengths. Also, the chances of occurrence of lateral heterogeneity are more in longer arrays. So, if long arrays are to be used, it should be ensured before the test that lateral heterogeneities are not present (e.g., considering local geology).

Inter-receiver spacing

The spacing between adjacent geophones (denoted as Δx) should be such that waves of short wavelengths are sufficiently sampled, which is required for a good resolution at shallow depths. As per the Shannon–Nyquist sampling theorem, aliasing will occur for the waves having a wavelength less than $2^*\Delta x$. Aliasing might obscure the correct identification of the high-frequency portion in the dispersion curves, especially when higher modes are excited. Therefore, the spacing should be chosen based on the minimum expected wavelength in the signal, which primarily is a function of the MASW source and the stiffness of the site. The choice of inter-receiver spacing can also depend on the desired investigation depth. If the required data is only up to shallow depths, then receiver spacing can be kept smaller. Considering a given number of receivers, a small receiver spacing would help in getting good resolution at shallow depths. The requirement of a higher investigation depth automatically prompts the user to choose large receiver spacing to get a longer array length. The suggested values of inter-receiver spacing for near-surface characterization range from 0.5 to 4 m. Some researchers demonstrated that non-uniform spacing of the receivers can help in producing good experimental dispersion curves (Zywicki, 1999; Hebeler & Rix, 2001; Yoon, 2005). However, the practice of using a non-uniform spacing of receivers has not been adopted widely by now.

Source to first receiver distance (Source offset)

The source offset should be selected keeping in mind the minimization of the near-field effects, which require large offsets, and the adequate capture of high-frequency waves, which undergo high attenuation with distance (far-field effects). The near-field effects contaminate the Rayleigh waves and lead to the underestimation of Rayleigh wave phase velocity. On the other hand, the far-field effects cause a considerable reduction in SNR at traces recorded far from the source. Earlier, a lot of research has been carried out on the near-field effects but still, there is no single rule to entirely eliminate them. Bodet et al. (2009) reported that for linear arrays, the underestimation of phase velocity occurs at wavelengths greater than half of the receiver array length. Yoon and Rix (2009) suggested that the maximum resolvable wavelength to make the near-field effects less than 10–15% is equal to the array center distance (distance from the source to the mid-point of the array). However, Wood and Cox (2012) found that this criterion is not always valid, and it can be site-specific. A study using multiple values of source offsets should be done at the site to understand and minimize the near-field effects. Generally, the source offset can be as taken three to five times the geophone spacing, provided that the signal-to-noise ratio is adequate even at the farthest geophone (Foti et al., 2018). Usually, the range in which the source offset value should be chosen is suggested as 5–20 m. However, it may depend on the site conditions. Stiff soils require a large source offset value compared to soft soils as presented later in Table 2. Overall, the source offset should be selected as an optimum value such that both the near-field effects and the far-field effects (attenuation of waves at far receivers) are minimized.

Number of receivers

The number of receivers in an MASW test can influence the quality of the dispersion image because a higher number of receivers can reduce the uncertainties in the results (Socco & Strobbia, 2004). It also impacts the depth of investigation because it is connected to the array length. Ideally, based on the required depth of investigation and the resolution at shallow depths, the array length and receiver spacing should be decided and that would fix the number of receivers required. Generally, it is suggested to use 24 or 48 receivers. A large value such as 48 would allow getting V_s profile up to large depths and by allowing for less receiver spacing, and provide higher resolution at shallow depths. However, many times in the field, the number of available receivers is less, or the space is limited. In such cases, multiple shots with different source offsets and receiver spacing should be taken to improve confidence in the results and get more reliable data.

Alignment of the receiver array

The receivers must be in a straight line. Also, they must be placed perfectly vertical and not tilted at all. The slope along the geophone array also affects the MASW results. In an ideal condition, the MASW test must be carried out on the flat ground. The maximum allowed difference in the elevations of the receivers is 0.1*array length, beyond which the MASW results would get significantly altered. Zeng et al. (2012) presented that when the slope along the receiver array is less than 10°, the error in the estimated dispersion characteristics would be within 4%.

Receiver specifications

In MASW, mostly, vertical component geophones are used as the receivers. The natural frequency of the geophones determines the lowest frequency of surface waves that can be recorded and consequently, the maximum depth of V_s profile that can be obtained. A low value of the natural frequency of geophones enables to get deep V_s profiles (Park et al., 2002). If it is required to resolve an extremely thin layer at the top of the soil, high-frequency geophones may be useful. However, as it is obvious, the investigation depth would be comparatively less in the case of high-frequency geophones. Usually, 4.5 Hz geophones are used which can generate V_s profiles up to a maximum of approximately 30 m. If the geophones of about 10–14 Hz frequency are used, the maximum V_s profile can be obtained up to a maximum of 10–15 m approximately (Foti et al., 2018).

Coupling between the source and the base plate

The use of a base plate for taking the shots in MASW can affect the energy transferred to the soil. Using a base plate rather than a direct impact on soil can enhance the transformation of impact energy into seismic wave energy (Mereu et al., 1963). Kumar and Rakaraddi (2013) found that the use of a base plate increases the maximum wavelength (λ_{max}) that can be extracted, consequently providing higher investigation depth. It was also found that (1) If the height of fall of the MASW source is increased, a higher value of λ_{max} can be obtained. (2) Stiffer soils provide higher λ_{max} compared to softer soils.

Regarding the base plate material, many studies have produced several results. Plates of steel and aluminum generated waves of similar amplitude and frequency content (Keiswetter & Steeples, 1994). A different result by Kim and Lee (2011) stated that polyethylene and steel plates transferred higher energy to the ground compared to the aluminum plate. The use of embedded plates improved the amplitude, but the frequency content was found to be the same (Keiswetter & Steeples, 1995). Larger base plates enabled to get higher seismic energy but an increase in mass without any change in the base plate area did not enhance the spectral content (Keiswetter & Steeples, 1994, 1995). Jeong and Kim (2012) found that compared to a circular plate, a rectangular plate having an aspect ratio of 1–2 increased energy by 10–20%. Also, when the longer side of the rectangular plate is put perpendicular to the array, the frequency bandwidth and power would be maximum. Mahvelati (2019) found that compared to the aluminum plate, Al/EPDM (aluminum/ethylene propylene diene monomer) and polyethylene (PE) plates generated 15–20% larger signal amplitudes, transmitted more energy into the soil, provided more low-frequency energy, and enhanced the SNR. However, although they seem a better option, these plastic/rubber plates undergo more tear. Many times, the benefit compared to metallic plates are not significant and in soft soils; they may have some negative effects. Therefore, the choice of the base plate material should be made very carefully considering the durability and portability of the material and the expected noise at the site (Mahvelati et al., 2020).

Duration of the load

Numerical modeling has been carried out by researchers to study the effect of the duration of load on MASW results. Mahvelati (2019) compared the impact duration of Al and PE base plates. It was found that the PE base plate, which is comparatively softer, ended up transferring the stresses to the soil for a longer time. Because of this, the soil below the PE plate underwent overall higher stresses compared to that below the Al plate, even though the stresses inside the Al plate were larger than the PE plate. It is obvious that when higher stresses (energy) are transferred to the soil, higher λ_{max} can be obtained. In another work, Desai et al. (2019) found that as the duration of load increases, the uncertainty due to the near-field effects decreases.

Sampling frequency

As per the Nyquist criterion, the sampling frequency should have a minimum value of twice the maximum frequency of the propagating signal. However, for the surface wave analyses, usually, sampling frequencies of 500–2000 Hz are considered reasonable. If refraction/reflection analysis is desired to be carried out, higher values of sampling frequencies should be used. The refraction/reflection analyses are sometimes carried out additionally to be used as a priori information during the inversion procedure. The choice of the sampling frequency can influence the frequency bandwidth that can be extracted.

Recording time

The time to record the waves due to a hammer blow in MASW should be selected such that each receiver captures the full-wave-train passing through it. A check should be made by visually observing in the raw recorded waveform that no wave-train is cut at any receiver. Usually, a recording time of 2 s is sufficient. However, it also depends on the V_s structure of the site (softer soils require higher recording time compared to stiffer soils). Also, a longer receiver array requires a longer recording time. Also, a pre-trigger time of 0.1–0.2 s should be kept so that leakage of waves is avoided and the operations during the signal processing in the frequency domain are not affected.

Filtering and muting of the field data

The field data acquired in an MASW test might be containing the wavefield due to higher modes. However, the surface wave analysis is often based on only the fundamental mode surface waves. The presence of unwanted noise in the data may limit the frequency band of the required dispersion curve or may lead to erroneous results. Therefore, filtering and muting can be applied to the time-offset data before generating the dispersion image. Also, in the recorded data, the portion other than the signal can be muted to avoid the noise in the signal.

Various researchers have implemented different ways of filtering and muting and got good results. Park et al. (2002) presented two methods for the removal of the higher mode data. They are the bow-slice method implemented in the f–k domain and the frequency variant linear move out (FV-LMO) correction. The use of a conventionally used method known as the pie-slice f–k filtering was discouraged because it can also remove parts of the main signal. Ivanov et al. (2005) demonstrated the way of the muting of the portions of the higher modes from the raw waveform, which can improve the bandwidth and resolution of the fundamental mode dispersion curve. However, it generates artificially high velocities at low frequencies. So, the unmuted data should be used at low frequencies while employing this method. Morton et al. (2015) suggested a modified f–k filter, implementing multiple passes of the filter to get better information about the fundamental mode energy. Overall, if implemented properly, the operations of filtering and muting on the MASW field data can enhance the generation of the dispersion image. However, it must be taken care that these operations are applied only to unnecessary noise without hindering the main signal to be used for dispersion image generation. Also, care must be taken because insufficient spatial resolution may cause insufficient mode separation. In this case, an effective/apparent velocity is obtained and filtering cannot be applied.

Forward and backward shots

The shots in the MASW test are suggested to be taken on both sides of the receiver array (forward and reverse shots). If the dispersion curves are the same in both cases, it ensures that the medium is laterally homogeneous which is the basic assumption in surface wave analysis. If any lateral heterogeneity is present, the changes in energy distribution over the frequency band and in attenuation pattern from both the locations would finally lead to different dispersion curves.

Checking results using parts of the array

Another task to be considered for checking the lateral heterogeneity is the generation of dispersion curves using different portions of the receiver array. For example, in case the data has been acquired with 48 receivers, the dispersion curves can be constructed for receiver numbers 1–24 and then for 25–48. If the dispersion curves are quite similar for both cases, it ensures that lateral homogeneity is there at the location of the data acquisition. If they are quite different, it implies that the medium has lateral heterogeneity (Foti et al., 2018).

Multiple shots and stacking together

A single MASW shot contains a remarkably high amount of noise and adequate resolution cannot be achieved in the required frequency band. If multiple shots are taken and then stacked together, it can significantly improve the signal-to-noise ratio (SNR). Vertical stacking can improve the SNR by the square root of the number of shots (Foti et al., 2014). Therefore, in MASW, it is suggested to take multiple shots and then stack them together for use in the analysis, especially at high noise locations. Also, vertical stacking in the f–k domain is suggested instead of the time domain (Foti et al., 2018). If the length of the receiver array increases, and/or the ambient noise increases, a higher number of shots should be used for stacking. The number of shots to be stacked together can be selected when the SNR remains the same even after adding more shots for stacking (Ivanov & Brohammer, 2008). Another thing to be considered is that after taking each shot, its waveform should be observed visually and the shots containing very high noise or having abnormal waveforms should be removed. Also, to prevent the data from getting affected by the noise, the test should be carried out when the traffic due to vehicles can be avoided.

Multiple shots and mean and standard deviation curve to curb data measurement uncertainty

The experimental dispersion curve of an MASW test suffers from uncertainty due to the noise present at the site. Therefore, rather than using a single dispersion curve to represent a site, it is suggested to generate multiple dispersion curves at the same location and prepare an ensemble of a mean and $\pm$ standard deviation curve. This would take care of the data measurement uncertainty. Section 2.2 provides more details about this.

Overview of the parameters of data acquisition for active MASW test

The parameters discussed above for the active MASW data acquisition have been presented in a tabular format in Tables 1 and 2. Table 1 provides guidelines for any general condition. Table 2 gives guidelines depending on the stiffness of the site (Vs30 value). It is suggested to use Table 1 guideline initially, carry out MASW test,

Table 1 Parameters for data acquisition: active MASW (Foti et al., 2018)

Parameter	Notation	Suggested values	Theoretical implications
Geophone spacing	Δx	1–4 m	Aliasing: usual minimum measurable wavelength $\lambda_{min} = 2\Delta x$ Minimum near-surface layer thickness/resolved depth $P_{min} = \lambda_{min}/3$ to $\lambda_{min}/2$
Array length	L	23–96 m	Maximum wavelength $\lambda_{max} = L$ Expected maximum investigation depth $P_{max} = \lambda_{max}/3$ to $\lambda_{max}/2$
Number of geophones	N	24 or 48	Quality of dispersion image
Distance between source and first geophone	X_1	5–20 m	Near-field and far-field effects Multiple shot locations strongly recommended
Sampling interval	Δt	0.5 ms	Nyquist/Shannon frequency $f_{max} = 1/2\Delta t = 1000$ Hz
Sampling Frequency	$f_s = 1/\Delta t$	2000 Hz	Nyquist/Shannon frequency $f_{max} = f_s/2 = 1000$ Hz
Post-trigger recording length (time window)	T	2 s	Record the whole surface wave-train
Pre-trigger recording length		0.1–0.2 s	Mitigating leakage during processing

Table 2 Parameters for data acquisition: active MASW (Penumadu & Park, 2005)

Vs30 (m/s)	X_1(m)	Δx(m)	L(m)	Optimum geophone (Hz)	Optimum source* (kg)	Recording time (s)	Sampling interval (ms)
<100	1–5	0.25–0.5	≤ 20	4.5	≥ 5	1	1
100–300	5–10	0.5–1	≤ 30	4.5	≥ 5	1	1
200–500	10–20	1–2	≤ 50	4.5–10	≥ 5	0.5	0.5
>500	20–40	2–5	≤ 100	4.5–40	≥ 5	0.5	0.5

*Weight of sledgehammer

and make a preliminary assessment of the stiffness (V_s profile) of the site. Then, based on the stiffness of the site, the guidelines provided in Table 2 can be used. However, still, these guidelines are just to give an overall idea of how to carry out the test. Based on site-specific conditions and the purpose of the test, adapted values of the parameters should be selected.

In Table 1, X_1, Δx, and L refer to the distance between the source and the first geophone, inter-geophone spacing, and the array length, respectively.

3.2 Passive Test

In the passive tests, the ambient vibrations are recorded and used for V_s profiling rather than the use of active sources. The ambient vibrations can be due to natural phenomena such as the earth's vibrations, sea waves, wind, or anthropogenic activities such as traffic and machinery. Usually, the natural phenomena generate lower frequency waves and human activities produce higher frequency waves. The advantage of passive tests over the active test is that they allow getting the dispersion curve data at lower frequencies compared to the active test. Thus, they help in obtaining V_s profiles up to higher depths. Typically, dispersion curve data from the lower (0.2–5 Hz) to intermediate (10–30 Hz) range of frequencies can be obtained using passive surveys. This range depends on factors such as the shape and size of the array, V_s and attenuation properties of the site, and the equipment used (Foti et al., 2018). Also, the passive sources have the advantage of being cheaper and no requirement of deployment and mobilization of a heavy source such as the active sources.

Selection of test parameters and their effects on the uncertainties

Similar to active testing, passive MASW testing is also highly dependent on the selection of the data acquisition parameters. The various test parameters and their influence on the passive MASW testing have been explained below.

Array setup

The passive tests can be carried out using a linear receiver array or 2D arrays. The method using a 1D linear array is called refraction microtremor (ReMi), proposed by Louie (2001). In this, the geophones are set up in the same way as the active MASW test, but the ambient vibrations are recorded and processed rather than those from an active source. The guidelines and pitfalls of the ReMi method have also been provided by Louie et al. (2021). The 2D receiver arrays can be deployed in various configurations such as circular, triangular, L-shape, and T-shape (Foti et al., 2018). Zywicki (1999) provided an in-depth discussion on passive surface wave testing using 2D arrays and found that the uniformly spaced circular arrays can give the best results under a majority of the circumstances. However, in the passive surface wave measurements using linear arrays, the wavefield comes from several directions, which makes the whole analysis extremely complicated and significantly increases the uncertainties in the results (Cox & Beekman, 2011). Therefore, it is highly suggested to avoid the use of a 1D linear array for passive surface wave measurements and to use only the 2D array for the passive test (Foti et al., 2018). However, these arrays require larger areas and are challenging to be placed. Also, there should be sufficient passive surface wave energy in the required frequency range near the array.

Depth of investigation

The maximum depth of investigation is controlled by the maximum retrieved wavelength (λ_{max}) and the resolution at shallow depths is controlled by the minimum retrieved wavelength (λ_{min}). λ_{max} and λ_{min} primarily depend on the array aperture (maximum distance between 2 receivers) and the minimum spacing between 2 receivers, respectively. The V_s structure of the site and the processing technique can also affect them. Approximately, it is suggested to keep the minimum receiver spacing equal to the desired minimum thickness of the topmost layer and the array aperture at least equal to or 2 times the desired depth of investigation (Foti et al., 2018). Wathelet et al. (2008) provide another criterion, viz., theoretical array resolution limit ($k_{min}/2$) and aliasing limit (k_{max}) to define the frequency limits of the dispersion curve obtained from the passive test array, where k is the wavenumber. Also, when it is important to resolve the shallow layers properly, the passive surveys should be accompanied by the active test to get good high-frequency data.

Number of sensors

The choice of the number of sensors depends on the desired investigation depth. Even though only 4 receivers can provide results, a higher number of receivers would be required to produce better results. A smaller array may cause an overestimation of phase velocity due to poor wavenumber resolution (Yoon, 2005; Jiang et al., 2015). Therefore, it is suggested to keep the number of receivers as high as possible, especially at locations having low ambient vibrations. However, they are generally limited by the available equipment and space.

Recording duration and sampling frequency

The recording time of passive tests is usually suggested as 30–120 min. When the level of ambient vibrations is low, it is suggested to keep a long recording time. Sometimes, if the required frequency band is high, several hours of recordings may be required. After that, these recordings are divided into different time windows which may range from 1 to 5 min approximately. The average of all these time windows is calculated and then used for further processing. The sampling frequency in passive tests is kept lower than in the active tests. This is because the recording time is longer in passive tests. Usually, the sampling frequency is kept at 100–200 Hz.

Natural frequency of sensors

Regarding the natural frequency of the geophones, if the data is required only up to the upper tens of meters of soil, 4.5 Hz geophones are sufficient. If it is required to unravel the deeper soil layers, velocimeters/seismometers having natural periods of 1, 5, or 30 s should be used whose sensitivity is higher compared to geophones. The vertical component geophones provide the data to generate Rayleigh wave dispersion curves. If 3-component sensors are used, they help in generating a horizontal-to-vertical spectral ratio (HVSR) curve, which can help in generating an even deeper V_s profile. More details about the HVSR methods have been provided in Sect. 5.4. All the types of geophones and velocimeters/seismometers require proper installation, coupling with the soil, and leveling while putting them for the recording. Foti et al. (2018) have provided in-depth information about the specifications for the setup/installation of the geophones/velocimeters/seismometers in the field.

Check on the recorded ambient vibrations

To evaluate the ambient vibration level at the site, the models of reference levels of ambient vibrations are available: (1) Low noise model (NLNM); (2) High noise model (NHNM) (Peterson, 1993) which also includes instrumental self-noise. By comparing the recorded waveforms with these models, the user can verify whether the ambient vibration level at the site of acquisition is adequate or not. If the ambient vibration level at the site is not sufficient, it is required to increase the number of sensors, increase the recording time, make sure that the sensors are installed and leveled properly, and not affected by rain, wind, or temperature fluctuations.

3.3 Combined Active and Passive Test

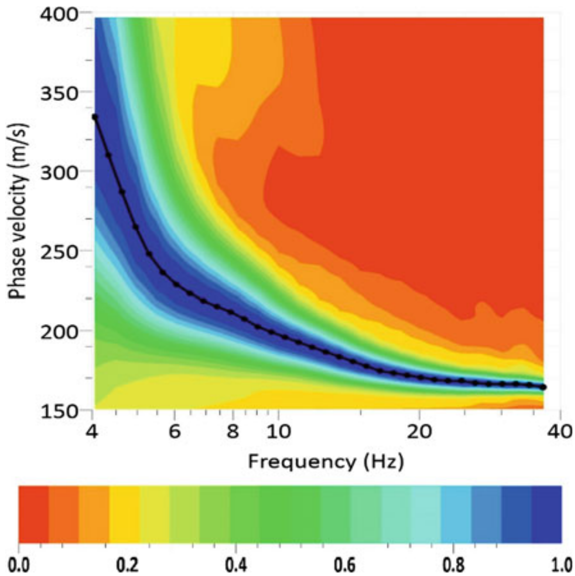
As mentioned earlier, in the active MASW test, the waves generated contain more high-frequency content and lack sufficient low-frequency data. On the other hand, the passive MASW provides good low-frequency data because the ambient wavefield used in it contains primarily low-frequency waves. Therefore, it is imperative that if both of them are used collectively, a dispersion curve with a wide band of frequencies can be obtained. This serves two purposes: (1) Estimation of V_s profile up to higher depths, and (2) Getting high resolution at shallow depths. Also, taking such multiple acquisitions (active and passive) at a single site reaffirms the extraction of fundamental mode data (Martin et al., 2017) and thus improves confidence in the obtained results. It is quite common practice among researchers to use concentric circles as 2D arrays along with the active test to get good results (Wood et al., 2014; Foti et al., 2018). If 3-component seismometers are available, they can also provide a horizontal to vertical spectral ratio (HVSR) curve, which would help in V_s profile estimation at even deeper depths. More information about the HVSR curve and joint inversion using MASW and HVSR has been provided in Sect. 5.4. While carrying out combined active and passive tests, the arrays of both active and passive data acquisition should be placed at nearby locations. However, both the acquisitions must not be carried out together, because the wavefields of both would interfere with each other.

The use of combined active and passive data has been suggested and implemented by many researchers (Park et al., 2005; Tokimatsu 2005; Richwalski et al., 2007; Mahajan et al., 2011; Lontsi et al., 2016; Pamuk et al., 2017; Foti et al., 2018; Kamai et al., 2018; Senkaya et al., 2020). It can aid in getting data on a wide band of frequencies and help in understanding the modal nature of dispersion trends (Park et al., 2007).

4 Data Processing (Estimation of the Experimental Dispersion Curve)

The recorded data on the geophones in the time-offset domain (seismograms) are typically transformed into a dispersion image. Various algorithms/methods are available for this transformation which are discussed later in this section. From the dispersion image, by picking the energy peak at various values of frequencies (sampling), a dispersion curve is extracted. Usually, the dispersion curve is presented as a plot between Rayleigh wave phase velocity and frequency. There are also some other ways to present a dispersion curve, i.e., frequency–slowness and phase velocity–wavelength. Figure 8 shows a typical dispersion image along with the picked dispersion curve in which the X-axis data is on a logarithmic scale. The image generation and dispersion curve extraction were carried out using the software Geopsy (Wathelet, 2008) based on the frequency–wavenumber algorithm. Although the curve can be plotted on either a linear or a logarithmic scale, the logarithmic scale would present the data with better clarity, especially at lower frequencies. Also, before carrying out the inversion, it is suggested to sample the dispersion curve at equal logarithmic frequencies or wavelengths (Foti et al., 2018). The picking of the dispersion curve from a dispersion image may be automated or manual. However, it should be done with utmost care. The lower and upper bounds of the frequencies in the dispersion curve should be decided based on maximum and minimum wavelengths available (λ_{max} and λ_{min}), respectively. These are dependent on the length of the receiver array and inter-receiver spacing, respectively. Suppose the array length is L, then $\lambda_{max} =$ L. If the inter-receiver spacing is Δx, then $\lambda_{min} = 2\Delta x$. Based on these values, the

Fig. 8 Typical dispersion image and picked dispersion curve



range of frequencies in the dispersion curve to be extracted is decided. A dispersion curve showing data beyond this range becomes unreliable.

4.1 Methods of MASW Data Processing

Active MASW

There are many signal processing techniques for the active MASW, which include the frequency–wavenumber (f–k) (Capon, 1969; Lacoss et al., 1969; Nolet & Panza, 1976; Horike, 1985; Yilmaz, 1987), high-resolution f–k (Capon, 1969), frequency–slowness (f–p) (also referred as p–ω or τ–p) (McMechan & Yedlin, 1981), phase shift transform (Park et al., 1998), conventional frequency domain beamformer (Johnson & Dudgeon, 1993), cylindrical frequency domain beamformer (Zywicki, 1999), multi-offset phase analysis (MOPA) (Strobbia & Foti, 2006), multichannel nonlinear signal comparison (MNLSC) (Hu et al., 2019), etc.

Conventionally, the f–k and f–p methods have been utilized quite frequently by researchers (Foti, 2000; O'Neill, 2003). The f–k method is based on the 2D Fourier transform of the input time-offset data. The f–p method performs the slant stack transform and then the Fourier transform of the data. However, it was found that these methods underperform in getting adequate resolution dispersion curves when the number of receivers is small (Park et al., 1998). The phase shift method and cylindrical beamformer method were found to provide better resolution comparatively. The phase shift method involves Fourier transformation, amplitude normalization, and then retrieving of dispersion curve. It is quite effective in the decomposition of various modes and noise. The cylindrical beamformer uses the cylindrical wavefield as opposed to plane wavefield in other methods, which becomes handy in dealing with the near-field effects. Tran (2008) provides a detailed description of these four methods.

Various researchers have worked to assess the variability in results due to using different signal processing methods on common experimental data (Cornou et al., 2006a; Tran & Hiltunen, 2011; Cox et al., 2014; Garofalo et al., 2016). When the study location has a simple, normally dispersive V_s profile, these methods would yield reasonably matching results. However, for complex sites, the results of different methods can be different (Cox & Wood, 2011). Dal Moro et al. (2003) examined the three methods: f–k, τ–p, and phase shift methods. They found that the phase shift method can provide better results even with less number of geophones under most circumstances. On the other hand, the other two methods showed aliasing and reduction in quality, especially in the case of a smaller number of geophones. Tran (2015) found that cylindrical beamformer and phase shift transform better imaged the dispersion curve at lower frequencies (<15 Hz) compared to f–k and f–p methods. In a study by Tran and Hiltunen (2011), the spectrum obtained from the cylindrical beamformer provided the best resolution. This can be attributed to the fact that the f–k, f–p, and phase shift transforms treat the signal as a plane wavefield, while the cylindrical beamformer uses the cylindrical wave equations to transform and identify Rayleigh waves. The assumption of the plane wavefield induces a near-field model incompatibility that may lead to problems in phase velocity estimation at low frequencies (Zywicki, 1999). Hence, a major advantage of the cylindrical beamformer is that it thwarts near-field effects because of using the cylindrical wave equations (no assumption of plane wavefield required). However, some studies have found that the cylindrical beamformer method showed lower phase velocities compared to the passive 2D arrays at lower frequencies. Therefore, the cylindrical beamformer is also not a completely effective method (Li, 2008; Jiang et al., 2015).

Passive MASW

1D geophone array

Louie (2001) developed the method termed refraction microtremor (ReMi) which uses ambient vibrations with a linear array. A 2D slowness–frequency (p–f) transform is applied to collect the Rayleigh waves and identify the true phase velocity. In active MASW tests, the waves have a specific propagation direction, i.e., along the geophone array, whereas passive waves arrive from any direction. ReMi was utilized by Pancha and Pullammanappallil (2011) and it was found that the higher modes of Rayleigh wave dispersion can be identified using this method. Spatial autocorrelation (SPAC) (and its modified versions MSPAC, ESPAC) (Aki, 1957; Ling, 1993; Bettig et al., 2001; Zhao & Li, 2010) has also been suggested to process passive surface waves' data recorded using a 1D linear array. Zhao (2011) has provided a brief explanation of the SPAC and f–k methods. The disadvantage of ReMi is that it requires manual picking, as this depends on subjective judgment, and sometimes influences the results. Also, this method assumes that passive source distribution is homogeneous and isotropic at the site or they are in line with the direction of the receiver array. This condition cannot be satisfied in the field most of the time. Overall, it is suggested to avoid the use of ReMi by many researchers because of a lot of shortcomings (Zywicki, 2007; Rosenblad & Li, 2009a, b; Foti et al., 2018). Instead, the use of 2D geophone arrays is encouraged for passive surface wave analysis.

2D geophone array

Park et al. (2004) introduced a data processing scheme, which is extended from the phase shift method (Park et al., 1998) applied for active MASW tests. Spatial autocorrelation (SPAC) and modified spatial autocorrelation (MSPAC) methods can also be employed for this. It was found that at lower frequencies, SPAC methods perform better than the f–k methods due to the limited resolution capability of f–k methods in treating wavefields coming from different directions (Horike, 1985; Okada, 2003; Cornou et al., 2006b; Wathelet et al., 2008). Zywicki (1999) provides detailed information about passive surface wave analysis using 2D arrays. Three different processing algorithms have been described there which are frequency domain beamformer (FDBF) for 2D arrays (Lacoss et al., 1969), minimum variance distortionless look (MVDL) (Capon, 1969), and multiple signal classification (MUSIC) (Schmidt & Franks, 1986). However, Jiang et al. (2015) found that FDBF and MUSIC provided reasonably good results, but MVDL could not. The FBDF for 2D arrays is an extension of the beamformer method for the 1D linear receiver arrays. MVDL is a high-resolution method, which decreases the impact of waves coming from directions other than the active look direction. MVDL is also a high-resolution method, having its power estimate similar to the MVDL method.

5 Inversion

Inversion is the process of estimating the V_s profile of the site from the experimental dispersion curve. The process of inversion is not straightforward; it is non-unique and ill-posed, which induces inversion uncertainty. More information about the inversion uncertainty is provided in Sect. 2.3. Various algorithms/methods are available to carry out the inversion process. They are primarily of two types (Foti et al., 2018):

1. Local search algorithms: In this, in the beginning, an initial V_s profile is assumed, and its corresponding theoretical dispersion curve is generated. The misfit between this theoretical dispersion curve and the experimental dispersion curve is calculated. Then, in the next iteration, a modified V_s profile is generated such that the misfit value gets decreased. In this way, several iterations are carried out one after the other. When a point is reached when no noticeable change in the misfit occurs with more iterations (convergence), the process is stopped, and the V_s profile obtained at that time is considered as the final V_s profile. This whole process can be automated. In some software, it must be done manually, where the user can choose the V_s profile iteratively till he finds the best one (trial and error procedure).
2. Global search algorithms: In this, several V_s profiles are generated having an equivalent match with the experimental dispersion curve. The user is supposed to choose the parameterization, i.e., the expected values of the number of layers and the ranges of thickness, V_s, V_p, density, and Poisson's ratio of the layers.

Due to the various uncertainties associated with the MASW testing and its interpretations, the choice of a single V_s profile, i.e., the use of local search algorithms can involve significant errors. Also, in the local search algorithms, there is a possibility of getting caught in some local minima. The selection of the initial model also heavily affects the finally generated V_s profile. On the other hand, the consideration of a suite of V_s profiles, i.e., the use of global search algorithms would allow accounting for the uncertainties during the further analysis. Therefore, the use of global search algorithms is usually recommended for the inversion process. Poggi et al. (2012) have suggested a combined use of global and local search algorithms in which model space is searched and then the solution corresponding to the minimum value of misfit is picked out.

For carrying out the inversion, several methods are available, such as trial and error method (Stokoe et al., 1994), Occam's algorithm (Constable et al., 1987), least-squares technique (Xia et al., 1999), simulated annealing (Sen & Stoffa, 1991;

Martínez et al., 2000), genetic algorithm (Lomax & Snieder, 1994; Hunaidi, 1998), Monte Carlo method (Socco & Boiero, 2008), neighborhood algorithm (Sambridge, 1999; Wathelet, 2008), and mutation particle swarm optimization (MPSO) (Zarean et al., 2015). Some research has been carried out on how the use of different inversion methods by different analysts would influence the final V_s profile (Cox et al., 2014; Garofalo et al., 2016). Pelekis and Athanasopoulos (2011) provide a good description of the methods used for inversion and also propose a simplified inversion method (SIM).

While carrying out inversion, a theoretical dispersion curve has to be generated for each V_s profile from inversion, which is termed forward modeling. This theoretical dispersion is then compared with the experimental dispersion curve using the misfit value. For the forward modeling, various methods are available which are (a) Transfer matrix method proposed by Thomson (1950) and Haskell (1953), and subsequently modified by Knopoff (1964), Dunkin (1965), and Herrmann (1994). (b) Dynamic stiffness matrix method (Kausel & Roesset, 1981). (c) Propagator matrix method (Gilbert & Backus, 1966; Aki & Richards, 1980), etc.

5.1 Choice of the Depth of V_s Profile While Doing Inversion

The maximum depth of the V_s profile obtained from an MASW test is constrained due to various factors. It cannot be chosen randomly. It is unreliable if the software provides a V_s profile up to exceedingly high depth when the dispersion curve does not contain sufficient data at low frequencies (high wavelengths). Several researchers have found that the intra-analyst and inter-analyst uncertainties in the V_s profiles at large depths are much significant than those at shallow depths (Tran & Hiltunen, 2011; Cox et al., 2014; Garofalo et al., 2016). This implies that utmost care needs to be taken in deciding the maximum depth of V_s profile obtained from an MASW test. The maximum investigation depth is a function of the maximum available wavelength which mainly depends on these factors (Foti et al., 2018):

- The length/aperture of the receivers' array used for the test.
- The frequency content of the generated signals (depending upon the source and site attenuation).
- V_s profile of the soil.
- The receivers' frequency bandwidth.

Michaels (2011) presented a way to estimate the maximum frequency up to which the fundamental mode is dominant, based on Karl (1989). He also used eigenfunctions of frequencies to demonstrate how deep each frequency wave is penetrating which can be useful in knowing the usable frequency band for the MASW analysis.

Once the dispersion curve is generated from an MASW test, the values of the maximum wavelength (λ_{max}) and the minimum wavelength (λ_{min}) to be used for V_s profile generation must be fixed. It can be decided based on the minimum and

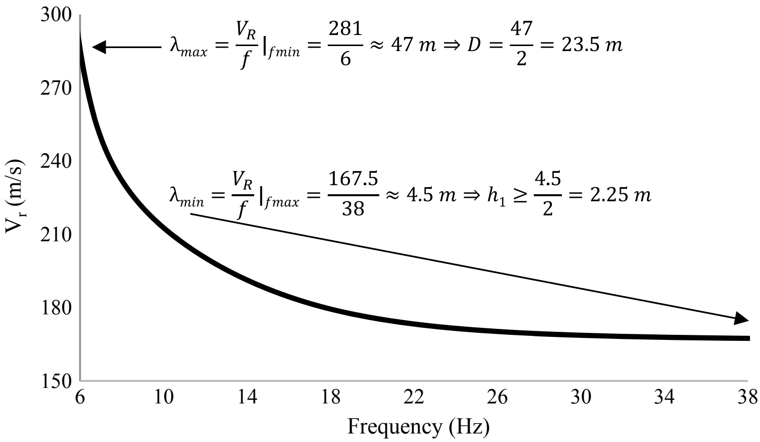


Fig. 9 Determination of maximum and minimum wavelengths available from the MASW test, which fixes the maximum depth of V_s profile and the minimum thickness of the top layer of the V_s profile that can be resolved, respectively

maximum frequencies obtained in the dispersion curve. This has been demonstrated in Fig. 9.

Figure 9 is a typical example of an experimental dispersion curve. As it is evident, λ_{max} is approximately 47 m. So, the maximum depth D up to which the V_s profile can be generated using this curve is $\lambda_{max}/2 = 23.5$ m. However, when it is required to be more conservative, this depth D should be kept limited to $\lambda_{max}/3$. Also, $\lambda_{min} = 4.5$ m indicates that the thickness of the topmost layer in the retrieved V_s profile should be at least 2.25 m. This means that, at this particular site, if there is a thin layer of less than 2.25 m thickness at the top, it is not possible to identify it using this experimental dispersion curve. In that case, another MASW test would be required to get the dispersion curve data at frequencies higher than 38 Hz which would help to resolve wavelengths less than 4.5 m.

5.2 Parameterization During Inversion

While carrying out the inversion process, it is required to choose a possible range of the parameters related to inversion. These parameters to be selected for each layer are the V_s, thickness (H) (except the half-space), V_p (compressional wave velocity), or Poisson's ratio (ν) and density (ρ). In some cases, the damping ratio (D) is also incorporated in the parameterization in case the attenuation is also considered in the model. Out of these parameters, V_s and H are the parameters having the highest impact on the dispersion curve. The values of ν and ρ can be given as a constant usually because they have negligible influence on the dispersion (Socco & Strobbia, 2004). They are chosen based on some available a priori data or some standard values from the literature. However, the V_p is connected to V_s through ν. So, it is a good practice to give a range of ν which would allow a broad range of V_p and prevent it from getting trapped into unrealistic values. Also, in some cases, the water table can be present in the subsoil, due to which the values of ν and V_p become extremely high and subsequently affect the dispersion curve. In such cases, in inversion, if parameterization is given without the consideration of the water table, it can give substantially erroneous results. Therefore, it is required to have an estimate of the water table at the testing location and its consideration during inversion by providing a quite high value of ν and V_p (Foti & Strobbia, 2002). Regarding ρ, its increasing values with depth can provide results with better accuracy (Ivanov et al., 2009). The usually occurring values of ν and ρ for different soil conditions have been given by Foti et al. (2018).

The number of layers should be selected such that it is not too high which can be unrealistic. Also, it should be sufficient to properly resolve the soil profile. Di Giulio et al. (2012) have provided a method using multiple-model parameterization and Akaike's information criterion that can help in finding the adequate number of soil layers, and selecting the best class of models. Also, it is required to carry out multiple inversions with different parameterizations to find out the most appropriate V_s models. Methods to select appropriate parameterizations for different trials in the absence of any a priori data have been proposed by Cox and Teague (2016), and Vantassel and Cox (2021).

5.3 Special Considerations During Inversion: Inversely Dispersive Layers and Higher Modes

Before carrying out the inversion process, the experimental dispersion curve should be thoroughly perceived, which would hint at the V_s profile. If the V_r is continuously increasing with the decrease in the frequency, it is most likely that the profile has continuously increasing V_s with depth. If a kink is visible at some place in the dispersion curve, or the V_r remains constant with a change of frequency in a certain range, it can be a likely indication of a softer layer below a stiffer layer (Foti et al., 2018). Figure 10 shows an example where there is an unusual feature of a trough in the dispersion curve (approximately from 8 to 20 Hz). This type of shape is an indicative of inverse layering pattern (soft layer trapped between two stiff layers or stiffer layer trapped between two softer layers) in the V_s profile. In the InterPACIFIC project involving several analysts working on the same experimental dataset, a lower velocity layer in the top 50 m soil at a site at Mirandola was identified by only 5 of the total 12 teams (Garofalo et al., 2016). This clearly indicates that extra care should be taken in the visualization and interpretation of the dispersion curve before inversion, especially in the case of an inversely dispersive V_s profile.

In some cases, due to high impedance contrast between two layers or inverse layering, higher modes become dominant and the extracted dispersion curve from

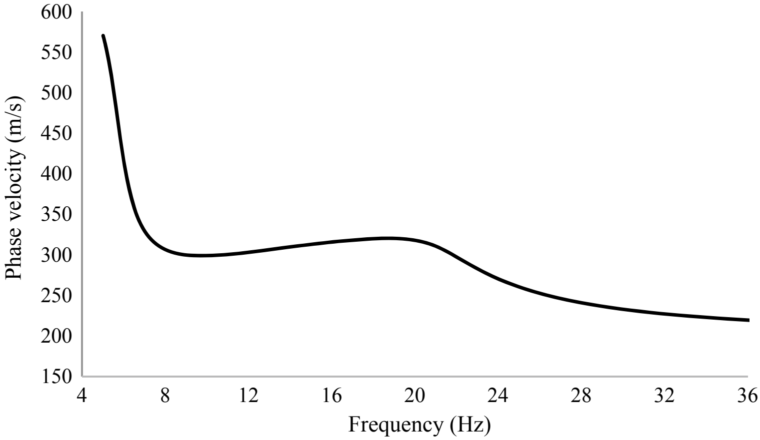


Fig. 10 A typical example of dispersion curve showing a trough between 8 and 20 Hz, indicating the presence of a softer layer below a stiffer layer at some depth

the dispersion image may be an apparent dispersion curve because of mode jumping. Figure 11 explains this phenomenon in which higher modes impede the extraction of the fundamental mode dispersion curve. If such an apparent curve is considered for further analysis, it would lead to completely different results from the real scenario. Therefore, dealing with higher modes requires some more effort compared to the normal analyses. Maraschini and Foti (2010) have proposed a way to deal with higher modes. Wood et al. (2014) have also shown a way to identify and deal with higher modes.

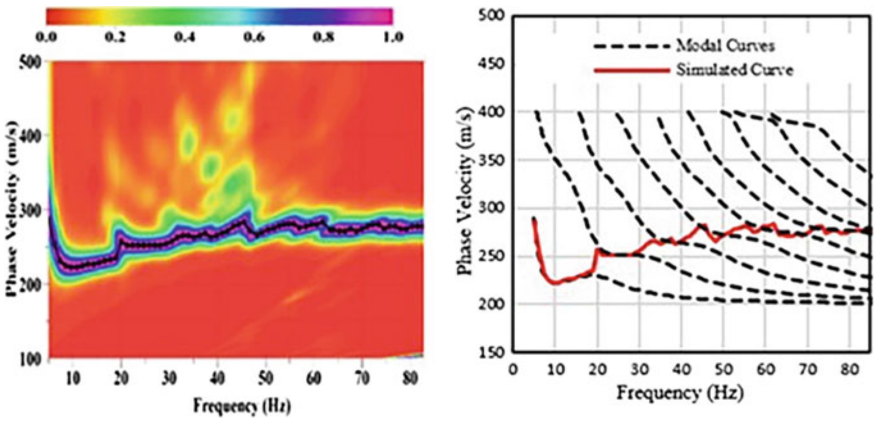


Fig. 11 A typical example of dispersion curve extraction affected by mode jumps, resulting in an apparent dispersion curve in place of the fundamental mode dispersion curve (Roy & Jakka, 2020)

5.4 *Use of Horizontal to Vertical Spectral Ratio (HVSR) and Joint Inversion*

The depth of investigation in an active MASW test using a sledgehammer can reach up to a maximum of 20–30 m approximately, as discussed earlier. In many cases, the data at a higher depth would be required. For that, the horizontal to vertical spectral ratio (HVSR) can become useful. The HVSR is the ratio of the Fourier spectra of horizontal and vertical velocity components of the ambient vibration recordings at a site. The horizontal one is the root mean square of the two orthogonal horizontal components. The technique which uses this ratio to estimate the V_s profile of soil is called the H/V technique, popularized by Nakamura (1989). The ambient vibrations may be due to the earth's vibrations, sea waves, wind, or human activities such as walking and driving vehicles. As these ambient vibrations are of low frequency, the HVSR method provides the data of higher depths of a V_s profile. The method is based on obtaining the curve between the H/V ratio and frequency at a site.

The field instrument used for this can be a single station 3-component sensor or an array of 3-component geophones which may be in the shape of a triangle, circle, L-shape, or any other. Figure 12 shows a single station 3-component sensor (Micromed, 2012). The signals are recorded for a particular duration and then divided into separate time windows. The H/V ratio is the average value obtained from all the time windows considered. The computed Fourier amplitude spectra can be smoothened using different ways. The method proposed by Konno and Ohmachi (1998) is a popular method for that currently. The peaks in any H/V curve correspond to an impedance contrast between 2 soil layers. Sometimes, a peak may be due to a velocity inversion or higher modes. To get a deeper and more accurate V_s profile at a site, the use of joint inversion using both the MASW and HVSR data has proven

Fig. 12 A single station 3-component ambient vibration recording sensor to obtain H/V spectral ratio curve

to be a particularly good technique (Scherbaum et al., 2003; Parolai et al., 2005; Arai & Tokimatsu, 2005; Castellaro & Mulargia, 2009). So, currently, such type of joint inversion is widely used worldwide. An important parameter obtained using the HVSR method is the fundamental frequency of the site (Haghshenas et al., 2008). Due to that, an advantage of HVSR is that it can help in constraining the bedrock depth (Wood et al., 2014). It is suggested to carry out HVSR investigations as per the guidelines provided by the SESAME project (SESAME Team, 2004). A thorough review of the application of the HVSR method has been presented by Molnar et al. (Molnar et al., 2018). The advantage of the joint inversion using the combined active MASW and HVSR is that the former provides good high-frequency data, enabling to get good resolution at shallow depths; and the latter provides good low-frequency data, enabling to get data up to deeper depths.

5.5 Use of a Priori Information

A lot of investigations by various researchers have been carried out to investigate how a priori information can help to produce better results in surface wave analysis. Cox and Wood (2011) compared the results of SASW, MASW, and ReMi methods. It was found that when a priori information about the water table (from P-wave refraction data) was used, the inter-method uncertainty reduced from 20–30% to less than 10%. Garofalo et al. (2016) found that a priori data in the form of borehole logs, P-wave refraction analysis, local geology, Rayleigh wave ellipticity, and HVSR can help in generating better results. Wood et al. (2015) found that for finding the V_s profile that reflects the actual soil layering, detailed subsurface investigations help in constraining the surface wave inversions. This becomes especially important for soils having high impedance contrasts and/or velocity reversals. The MASW results are typically used for seismic site response analysis which requires the knowledge of modulus reduction and damping ratio curves which depend on the soil type. The lack of knowledge of soil type can induce substantial uncertainties in the site response analysis results (Desai & Jakka, 2017). On the other hand, the availability of a priori data which includes the soil type from borehole logs can reduce the uncertainties in site response analysis significantly (Desai & Jakka, 2021; Desai et al., 2022). Overall, it is imperative that any a priori information in the form of borehole logs, water table estimation, etc. should be used as complementary data along with the MASW test to produce results with higher confidence and fewer uncertainties. A typical example of how a priori information can affect the results of MASW inversion has been shown in Fig. 13. The a priori information that has been included during the inversion is the thickness of the soil layers and the number of soil layers. While going from Fig. 13a to Fig. 13b, it is visible that V_s profiles are becoming highly constrained with the use of a priori information. Also, Fig. 13c shows that the standard deviation of the natural logarithm of V_s ($\sigma_{\ln V_s}$) is significantly decreased in the case of inversion with the a priori information.

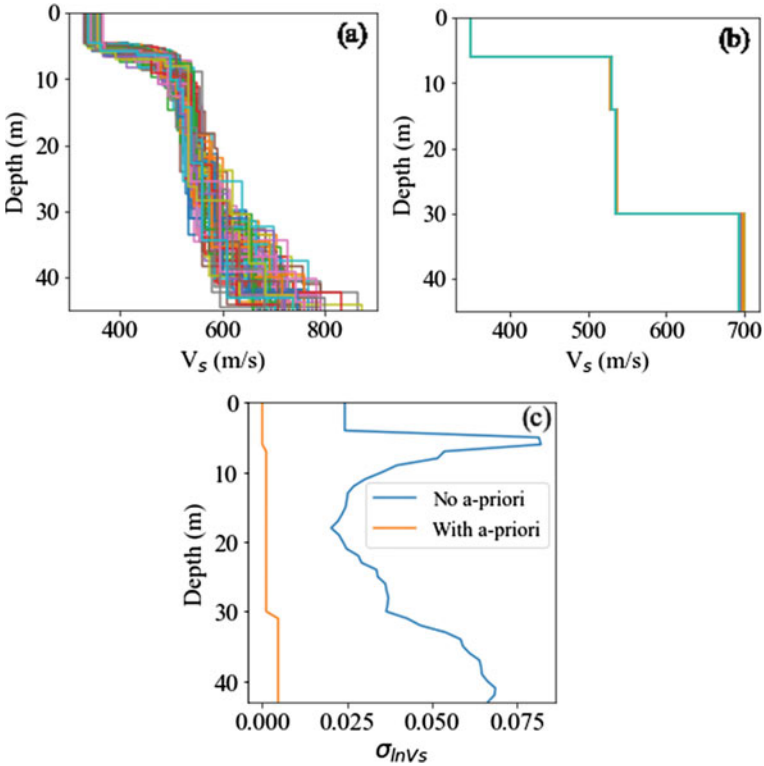


Fig. 13 V_S profiles after inversion considering **a** No a priori information; **b** a priori information; and **c** Influence of a priori information on the variability of V_S

6 Concluding Remarks

The MASW is the most common test currently for seismic site characterization and subsequent applications. Although its usage is quite extensive across the globe, the meticulous specifications associated with the complete method are not known to many practitioners. Due to the lack of awareness about the uncertainties in MASW, the practice of using MASW without following necessary rules is still prevalent. To explain these rules, on the whole, a comprehensive list of references has been presented in this article. Also, some results from the work carried out by us have been presented and used for necessary inferences. This also enabled us to cover all the different aspects of the MASW testing in depth. Subsequently, an attempt has been made to assemble and present a set of recommendations that are to be followed for a reliable practice of MASW testing. There are specifications for all three steps of the MASW, i.e., data acquisition, processing, and inversion. Primarily, the specifications are related to the source to first receiver distance, inter-receiver spacing, receiver array length, sampling frequency, choice of MASW source, boundaries of the generated dispersion curve and the maximum depth of V_s profile that can be extracted, use of a priori information, joint inversion with HVSR method, etc. Discussions are also made on how the choice of these parameters influences the uncertainties in the MASW test and how these uncertainties can be minimized. Because the MASW method suffers from several uncertainties, while using this method, there must be a goal to restrict these uncertainties to the minimum level and/or account for them in further analyses. The suggestions presented in this study come from a large set of references. So, they would be helpful for people working in academics/industry in the fields of geophysical investigations, seismic hazard assessment, and many others as the MASW test has plenty of applications in various domains. Also, there is a dire need for a code that deals with the specifications for seismic surface wave testing because of its popularity and wide usage across the world. The summary of this article in the form of guidelines is presented below, which would help to minimize the uncertainties and increase the reliability of MASW testing.

Guidelines at a glance for a reliable estimation of shear wave velocity profile:

- The distance between the source and the first geophone (source offset) should be kept at approximately 5–20 m. However, if a source such as Vibroseis is used, the source offset can be kept higher.
- The inter-geophone spacing should be kept at approximately 1–4 m.
- The length of the geophone array should be kept at approximately 23–96 m.
- The number of geophones should be kept 24 or 48. If fewer geophones are used, the test should be repeated with different inter-geophone spacing to get good resolution.
- The sampling frequency should be kept at 500–2000 Hz. A higher sampling frequency would enable better resolution for very stiff top layers (e.g., pavement systems).
- The recording time and pre-trigger time are suggested as 2 s and 0.1–0.2 s, respectively. Also, the raw recorded waveform should be observed visually, and it should be made sure that full wave-train is captured on each geophone.
- The natural frequency of geophones is usually recommended as 4.5 Hz. If the depth of investigation required is quite shallow and/or high resolution is required at extremely shallow depths, then geophones of higher natural frequency can be used. If the information up to very high depth is required, then geophones of lower natural frequency should be used.
- The mass of the sledgehammer should be at least 5 kg. However, a heavier sledgehammer enables the acquisition of V_s profiles up to higher depths.
- With a single acquisition layout, around 5–20 shots should be taken (till the signal-to-noise ratio becomes acceptable), stacked, and then used to generate a dispersion curve.
- Taking forward and reverse shots (keeping the source on either side of the array) is recommended to tackle the effect of lateral heterogeneity.
- If any a priori information from some other test is used, the MASW test location should be kept near the location of the other test. Also, the V_s profile from MASW should correlate with the other field tests.

- The dispersion curves obtained from the MASW testing should be further analyzed along with the HVSR curves obtained from ambient vibrations or small earthquakes using the joint inversion technique, which enables to extend the shear wave velocity profiles up to bedrock and also helps in the estimation of bedrock depth, bedrock velocity, and site fundamental frequency.
- Whenever a researcher is carrying out the MASW test for the first time or a new methodology for the interpretation of MASW is suggested, it is suggested to validate their results using a comprehensive surface wave database by Passeri et al. (2021) which is an excellent source to be used as a reference benchmark.

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