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Shear Wave Velocity Profiling: Comparing MASW and SPT for NEHRP Site Classification

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Abstract - Discrepancies between shear wave velocity (Vs) profiles derived from Multichannel Analysis of Surface Waves (MASW) and the Standard Penetration Test (SPT) pose significant challenges for seismic site classification under the National Earthquake Hazards Reduction Program (NEHRP) standards. This study investigates the effects of velocity contrasts and irregular subsurface stratification on the alignment of MASW and SPT Vs profiles. A MASW survey was conducted using an active seismic source and an array of geophones, with data processing involving preprocessing, dispersion curve extraction, and shear-wave velocity inversion using a Monte Carlo approach. The extracted dispersion curve spans frequencies from 25 Hz to 80 Hz, with phase velocities ranging between 200 m/s and 500 m/s. The inverted Vs profile indicates a progressive increase in shear wave velocity with depth, suggesting a compacting sedimentary sequence transitioning into bedrock at greater depths. The computed Vs30 value of 541.7 m/s classifies the site as NEHRP Site Class C (very stiff soil or soft rock). The correlation with regional borehole data confirms the presence of clay and silty deposits in the upper layers, followed by claystones and sandstones at depth. Despite the reliability of the MASW for seismic site characterization, discrepancies with SPT-derived Vs profiles highlight the challenges posed by velocity contrasts, irregular stratification, and higher-mode Rayleigh waves. Refining inversion techniques and integrating multiple geophysical methods are crucial for improving subsurface characterization and seismic hazard assessments. These findings emphasize the importance of considering seismic design regulations for infrastructure development in Site Class C soils, which can exhibit moderate ground motion amplification.

Keywords: Vs30; velocity contrasts, irregular stratification, surface waves; Rayleigh waves

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Introduction

Shear wave velocity (Vs) is widely recognized as an essential parameter for diverse applications, ranging from subsurface characterization and CO_2 storage evaluation to fundamental seismic site characterization and site-specific seismic hazard assessments (Dhaifullah *et al*., 2026; Abbas *et al*., 2024; Poggi *et al*., 2017; Toro, 2022; Muktaf *et al*., 2022). Multiple geophysical techniques are employed to evaluate near-surface Vs, notably including Multichannel Analysis of Surface Waves (MASW) and borehole methods (Park and Carnevale, 2010; Xia *et al*., 1999), such as The

Standard Penetration Test (SPT) in conjunction with seismic measurements. By using surface waves, the MASW Method generates Vs profiles through Rayleigh wave dispersion characteristics (Olafsdottir, 2016; Park *et al*., 1999). This approach allows for effective data collection across wide distances (Xia *et al*., 2000). Conversely, drilling techniques such as the SPT provide high-resolution insights through localized, discrete Vs measurements along the vertical axis. However, this approach often involves higher costs and logistical challenges (Ghanbari *et al*., 2018; Stephenson *et al*., 2005). The two methods function as complementary strategies, each possessing distinct strengths and weaknesses in addressing the intricacies of subsurface heterogeneity.

The significance of acquiring precise Vs profiles is highlighted by seismic site characterization frameworks like The National Earthquake Hazards Reduction Program (NEHRP), which relies on the Vs30 parameter and denotes the time-averaged shear wave velocity in the upper 30 m of the subsurface as a crucial metric for site classification (Ghanbari *et al*., 2018; Mulargia and Castellaro, 2009). Vs30 is critical for assessing soil amplifications that influence ground motion during earthquakes, which form a cornerstone of seismic hazard assessment. Discrepancies between the Vs profiles derived from the MASW and borehole techniques have been extensively documented and are particularly significant in geologically complex environments, including those characterized by sharp velocity contrasts or irregular subsurface stratification (Ivanov *et al.*, 2006, 2013; Roma and Tononi, 2011). These discrepancies are attributed to differences in the spatial resolution of the methods: MASW provides horizontally averaged profiles over the geophone spread, whereas borehole techniques offer localized point-specific measurements (Ivanov *et al*., 2011).

Geological phenomena such as strong velocity contrasts (*e.g.* a low-velocity layer beneath a high-velocity layer) and irregular subsurface stratification (*e.g.* dipping layers or channel infill deposits) further complicate the alignment of Vs profiles derived from the MASW and borehole methods (Sanuade *et al*., 2023). Sites with velocity inversions or strong contrasts tend to produce dominant higher-mode Rayleigh waves, whose effects can distort the MASW dispersion curves if not properly accounted for during inversion processes (Ivanov *et al*., 2011; Roma and Tononi, 2011). In such cases, relying solely on the MASW fundamental-mode dispersion analysis can yield erroneous Vs profiles that deviate significantly from borehole measurements (Casto *et al*., 2008; Roma and Tononi, 2011). Similarly, the lateral averaging of subsurface properties during MASW inversions systematically masks small-scale heterogeneities that borehole methods, which are vertically discrete, is better equipped to detect (Ghanbari *et al*., 2018).

Practical uses depend heavily on the differences between the MASW and borehole-derived Vs profiles, particularly in the precise calculation of Vs30 values for NEHRP site categorization (Sanuade *et al*., 2023). Minor changes in the Vs profiles could lead to significant differences in the computed Vs30, thus influencing NEHRP classifications, engineering design criteria, seismic hazard models, and structural performance evaluations during seismic events (Ghanbari *et al*., 2018; Mulargia and Castellaro, 2009; Stephenson *et al*., 2005). Efforts to understand and to mitigate these discrepancies have received increased attention, as addressing them is vital for enhancing the accuracy of seismic site characterization.

Several methods for addressing such problems have been investigated recently: analysis of higher-mode Rayleigh wave dispersion, joint inversions integrating MASW and borehole data, and advanced computational techniques including full-waveform inversion (Ivanov *et al*., 2011; Roma and Tononi, 2011). Although these methods have shown promise, challenges remain in reliably reconciling MASW and borehole measurements in areas of significant subsurface complexity. Thus, the interplay of geological factors (*e.g.* velocity contrasts and irregular stratification) and methodological considerations (*e.g.* sensitivity to higher modes and horizontal averaging in MASW) calls for further investigation to achieve greater alignment of the Vs profiles derived from these methods. This study seeks to contribute to this evolving area

of research by addressing the impact of contrasting layer velocities and irregular subsurface stratification on the alignment of MASW and borehole Vs profiles, with a particular emphasis on seismic site characterization under the NEHRP standards.

Methods and Materials

Data Acquisition

A Multichannel Analysis of Surface Waves (MASW) investigation was undertaken at the Archery Field of Hasanuddin University (Figure 1), employing an active seismic source and a geophone array to capture Rayleigh wave propagation. The main purpose was to calculate the shear wave velocity (Vs) profile for site categorization, facilitating future construction development on the campus. The acquisition configuration consisted of a WZG-24C Engineering Seismograph, a 10 kg sledgehammer as the active source, and twenty-four vertical-component geophones with a natural frequency of 4.5 Hz. The geophones were positioned at 3 m intervals, with a 5 m offset, producing a total spread length of 69 m. To maximize energy coupling with the subsurface, a 10 kg steel plate was inserted at the impact location.

To ensure high-quality data acquisition, multiple hammer strikes were stacked to improve the signal-to-noise ratio (SNR). The recording system was configured with a sampling frequency of 2000 Hz and recording duration of 1.024 s per shot (Table 1). These parameters were selected to capture the full waveform of the surface waves while adhering to Nyquist's sampling theorem, which dictates that the sampling frequency should be at least twice the highest frequency of interest. The recorded seismic traces were stored in the SEG2 format for further processing.

The first evaluation of seismic record quality was conducted after collecting field data. Figure 2 illustrates a shot-collect recording of the waveforms captured by the geophones. This image enables a preliminary analysis of wave arrivals, energy distribution, and potential noise contamination. By recording wave arrivals along a linear geophone array, the seismic waveforms correspond to shot collects from seismic refraction or MASW surveys. The y-axis represents time (s), while the x-axis indicates distance (m) along the

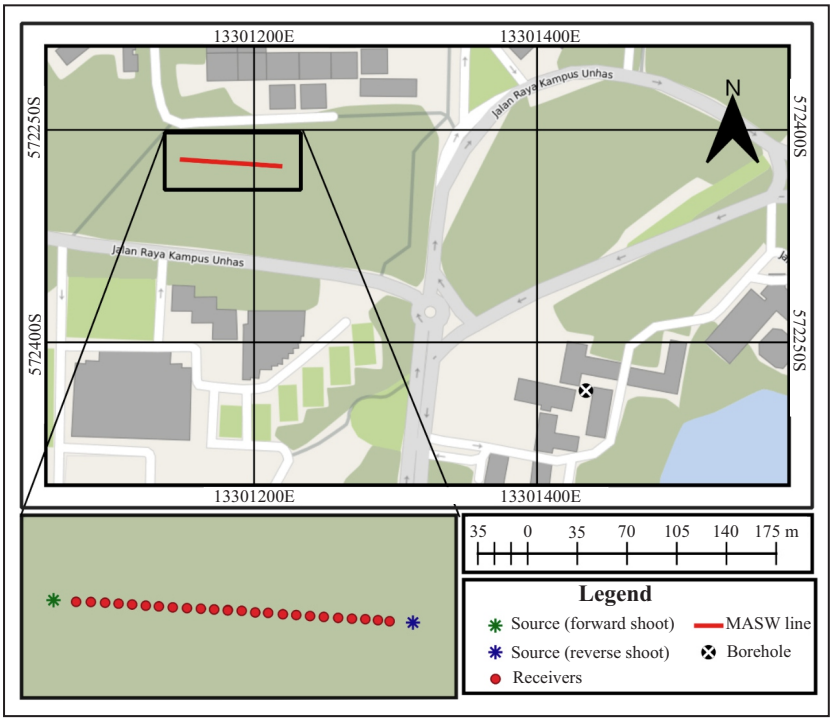

Figure 1. MASW data acquisition at The Archery Field, Hasanuddin University.

Table 1. MASW Data Acquisition Parameters

Parameter	Value
Receiver Spacing (Δx)	3 m
Number of Geophones	24
Offset Distance	5 m
Total Spread Length	69 m
Seismic Source	Sledgehammer (10 kg plate)
Sampling Frequency	2000 Hz
Recording Time	1.024 s

survey line. Despite being oriented oppositely, the left panel (a) and right panel (b) display identical wave propagation patterns, showcasing forward and backward shot recordings.

The initial arrivals in both Figures 2 were observed near the top, suggesting the propagation of the fastest wavefronts, probably including P-waves. The curvature of the arrivals indicates structural heterogeneities or layering, which induce changes in the subsurface velocity. The strong, coherent, and downward-arching energy of the later arrivals suggests surface or refracted waves at varying depths. The asymmetry in the two pictures may indicate anisotropic geological structures, lateral velocity changes, or underground sinking layers. Based on this data, a thorough velocity inversion could provide insights into potentially weak zones, lithological boundaries, and subsurface stiffness.

Data Processing

First arranged and then sequentially processed, the MASW data was used to extract and invert the dispersion curve, hence producing the shear wave velocity (Vs) profile. The computation process was built up using Python-based tools like Obspy, Scipy, and Maswavespy, known for their efficiency in signal analysis and inversion. This approach assures the earlier study (Ivanov *et al*., 2011; Xia *et al*., 1999) document by using standard MASW data-processing criteria and assuring correct data management. Three key stages of the research included preprocessing, dispersion curve extraction, and shear-wave velocity inversion (Casto *et al*., 2008, 2009). Every movement was deliberately planned to enhance the accuracy and data integrity in subsurface velocity structure determination.

The first steps in data processing are format conversion and filtering, which help to improve the quality of recorded seismic signals. Originally stored in the SEG2 format, the raw MASW data were converted into the ASCII format to ensure

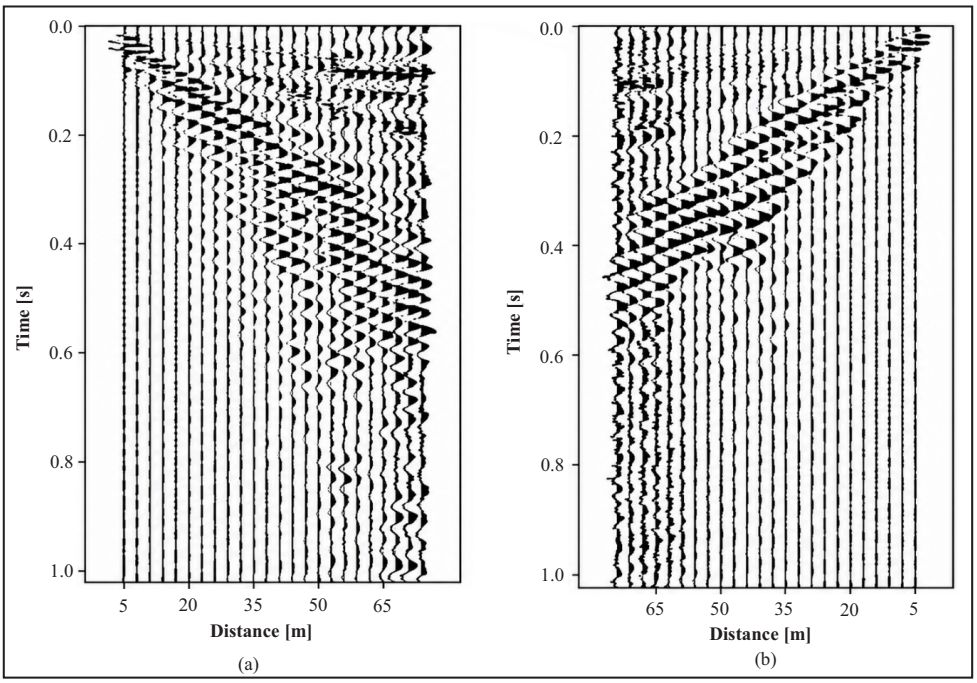

Figure 2. MASW shot gather for shooting in two directions: (a) forward and (b) backward.

complete compatibility with upcoming analytic approaches. Following format conversion was performed using bandpass filtering to eliminate frequency components beyond the specified range of Rayleigh wave propagation, and hence lower undesirable noise. Largely depending on this filtering step, ensuring that the processed data largely consist of dispersive surface waves-which are fundamental for an accurate velocity estimation. As shown in other works (Ivanov *et al.*, 2011; Xia *et al.*, 2000), such methods complement the accepted MASW data-processing techniques. Early step refinement of the seismic signals improves the dependability of the derived dispersion curve, and finally increases the correctness of the inverted Vs profile.

Dispersion Curve Extraction

The frequency-dependent velocity (Stokoe and Nazarian, 1985) fluctuations of the surface waves were investigated using Fast Fourier Transform (FFT) after preprocessing. Phase velocity information at different frequencies may be extracted using the FFT, converting time-domain seismic data into the frequency domain. As explained in another research, this method is basic in MASW analysis for producing the dispersion curves needed for shear wave velocity inversion (Ivanov *et al.*, 2011; Xia *et al.*, 2000). This transformation is mathematically represented in Equation (1) (Lunedei and Albarello, 2010):

$$U(x,\omega) = \int_{-\infty}^{\infty} u\,(x,t)e^{i\omega t}\,\mathrm{d}t. \quad .....(1)$$

where $U(x,\omega)$s the frequency-domain representation of the trace recorded at position x; $u(x,t)$ is the recorded trace in the time domain at time t; and ω is angular frequency.

The next step involved applying a frequency–wavenumber (f-k) transformation, which facilitated the identification of the phase velocities for various frequency components (Yaede *et al.*, 2015). The dispersion curve, representing the variation in the phase velocity as a function of frequency, was extracted by tracking the highest-energy trend in the frequency-phase velocity domain (Ivanov *et al.*, 2011; Xia *et al.*, 1999, 2000). This process is crucial because it enables identification of the fundamental mode of Rayleigh waves, which is required for estimating shear-wave velocity (Ivanov *et al.*, 2011; Roma and Tononi, 2011).

The dispersion curve provides critical insights into subsurface layering, because higher-frequency components are associated with shallower depths, whereas lower-frequency components correspond to deeper layers. This relationship allows the dispersion curve to serve as a key input for the inversion process, during which a shear-wave velocity (Vs) model is derived (Ivanov et al., 2011; Roma and Tononi, 2011; Xia et al., 1999, 2000). As illustrated in Figure 3, the dispersion curves obtained from the MASW measurements capture these characteristics for both (a) forward and (b) reverse directions.

Shear Wave Velocity (Vs) Inversion

A basic procedure in geophysical site characterization, shear wave velocity (Vs) inversion allows the estimation of subsurface Vs structures from observable surface wave dispersion data. The main objective is to match theoretical and actual dispersion curves (Ivanov *et al.*, 2011; Roma and Tononi, 2011; Xia *et al.*, 1999), thereby deriving a Vs profile that precisely depicts the velocity distribution with depth. This paper explored a wide spectrum of possible subsurface models using an iterative Monte Carlo inversion technique, therefore providing a probabilistic framework. The Monte Carlo Method encourages a more complete investigation of model space, unlike deterministic inversion methods, which could converge to limited minima. This guarantees a strong estimate of subsurface features by considering observed data uncertainty (Ivanov *et al.*, 2011; Xia *et al.*, 2000).

The first set of velocity models produced, each reflecting a possible subsurface structure depending on geological limitations, started the inversion process. These models use past geological information, including expected layer

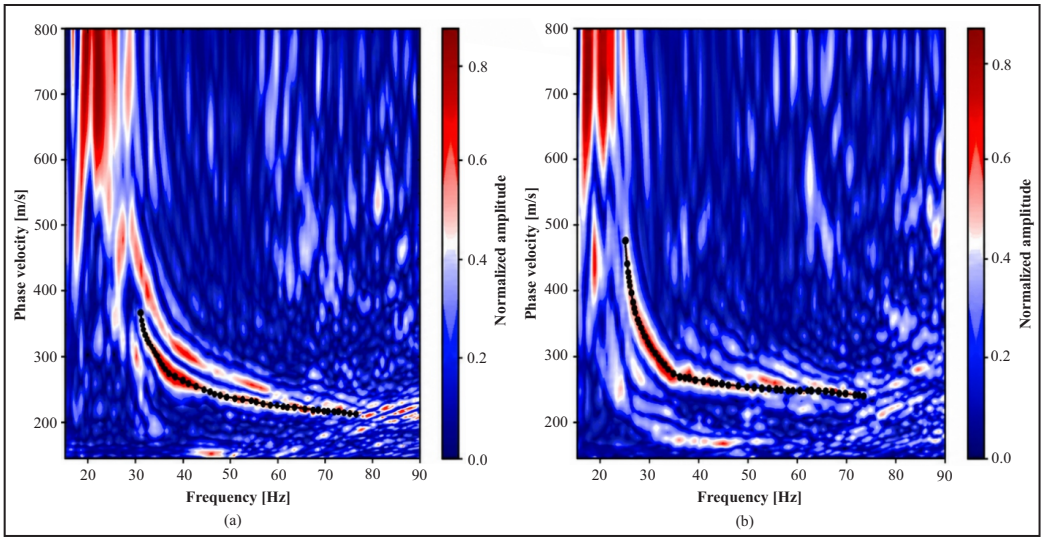

Figure 3. Dispersion Curve of the MASW measurements for (a) forward direction and (b) reverse direction.

velocities and thicknesses, therefore including variability. Including such constraints is absolutely essential since studies on initial modeling assumptions, including the number of layers and velocity values, show clearly how MASW inversion outcomes are influenced, especially in the presence of conflicting layer velocities and irregular stratification (Casto *et al*., 2008; Ivanov *et al*., 2011). Previous geological data may aid in reducing nonuniqueness in inversion findings and enhance alignment with borehole-derived profiles (Stephenson *et al*., 2005; Xia *et al*., 2000). Every velocity model was disturbed with the following Equation 2 to guarantee enough investigation of the model space:

$$Vs_{test,j} = Vs_j + X_j \quad \text{.....(2)}$$

where Vs_j is base shear wave velocity at a given layer j; X_j is a random uniform perturbation applied within a predefined range to introduce variability; $Vs_{test,j}$ is the perturbed velocity for the layer j

This stochastic variation allows the algorithm to explore a broad range of potential Vs structures, reducing bias and improving the reliability of the final solution (Luo *et al*., 2007; Xia *et al*., 1999).

Following model initialization, each candidate velocity model was used to compute a theoretical dispersion curve that describes how Rayleigh waves propagate through the subsurface. This computation was performed using the fast delta matrix method, which numerically solved the Rayleigh wave equation governing surface wave dispersion. Comparative theoretical predictions with observed field data depend on synthetic dispersion curves, particularly in cases involving conflicting layer velocities or velocity inversions where higher-mode Rayleigh waves can dominate and complicate the interpretation (Ivanov *et al*., 2011; Roma and Tononi, 2011). This procedure helps to improve subsurface models, so that they match the observed dispersion patterns, therefore guaranteeing more accuracy in the Vs structure (Xia *et al*., 2000). Given that the basic condition for Rayleigh wave propagation is Equation 3:

$$D(c,k) = \det[U'TV] = 0 \quad \text{.....(3)}$$

where D(c,k) is determinant of the boundary matrix; U'TV which must be equal to zero for the theoretical dispersion relationship to hold true; U and V are the boundary matrices that depend on the elastic properties and geometry of the true subsurface layers.

Wave propagation qualities depend on k, the wavenumber, and c, the phase velocity (Buchen, 1996; Keil *et al*., 2022).

By calculating this equation, one produces a theoretical dispersion curve matching any velocity model. This phase ensures that any proposed subsurface model can accurately reproduce the surface wave propagation, therefore enabling a valid comparison between synthetic and observed dispersion data (Foti *et al*., 2014; Xia *et al*., 1999). In the inversion process, evaluating the accuracy of every theoretical dispersion curve by means of real-world dispersion data comes last. Calculated using The Error Dispersion Coefficient (EDC), the degree of mismatch was found (Equation 4):

$$\mathrm{EDC} = \frac{100\%}{Q}\sum_{q=1}^{Q}\frac{\sqrt{\left(V_{R,t,q} - V_{R,e,q}\right)^2}}{V_{R,e,q}}. \quad .....(4)$$

Where Q is the number of sampled frequencies; $V_{R,t,q}$ is the theoretical Rayleigh-wave phase velocity at frequency index q; and $V_{R,t,q}$ is the observed phase velocity at the same frequency.

The Monte Carlo method repeatedly creates fresh random perturbations Xj, iteratively refines the velocity models, and performs misfit assessment once again. The method chooses models that gradually reduce the EDC with each iteration, hence enhancing the agreement between the theoretical and actual dispersion curves (Arai and Tokimatsu, 2004, 2005). Until convergence is reached, the inversion process keeps on producing one or more reasonable Vs profiles that best capture the subsurface velocity structure.

Results and Discussion

Dispersion Curve Analysis

The obtained phase velocities, ranging from 200 to 500 m/s, provide a dispersion curve spanning frequencies 25 to 80 Hz. A fundamental aspect of surface-wave propagation, the frequency-dependent phase-velocity change ensures Rayleigh wave dispersive quality. Higher frequency waves fit lesser depths, whereas lower-frequency components reach deeper subsurface layers, and provide an insightful study of stratigraphic changes. Figure 4 shows the extracted dispersion curve, thereby highlighting the change in phase velocity with frequency. The dominating wave mode was found to be the basic mode; higher-order modes were less evident due to the energy properties of the active source employed in this study.

Using The Monte Carlo Method, dispersion curve inversion was accomplished by repeatedly modifying subsurface velocity models to get the best alignment with observed data. This approach essentially reduces the inherent nonunicity of

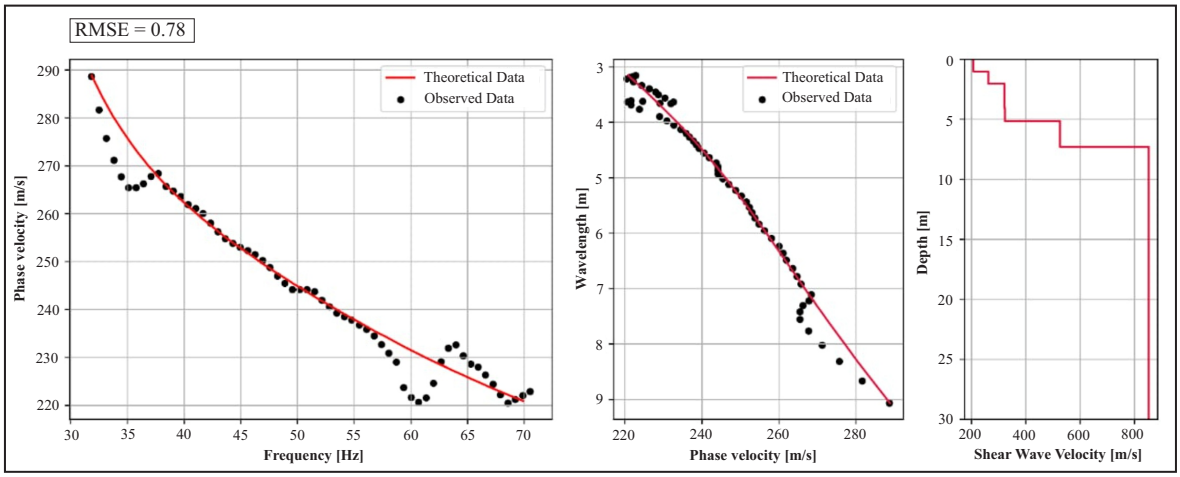

Figure 4. MASW inversion, depicting the relationship between observed and theoretical dispersion data, as well as the derived shear wave velocity (Vs) profile.

surface-wave inversions by investigating a broad spectrum of potential velocity profiles (Ivanov *et al*., 2011; Xia *et al*., 2000). The resultant Vs profile showed a compacting sedimentary sequence marked by a slow rise in shear wave velocity with depth. The shallow strata showed lower velocities, consistent with unconsolidated materials, whereas the deeper portions showed a significant increase in Vs, indicating denser lithology. These results complement earlier MASW studies in sedimentary settings (Xia *et al*., 2000). Table 2 compiles projected shear wave velocity data across many depth intervals to provide a quantitative evaluation of subsurface stiffness.

Table 2 illustrates the Vs depth variation, highlighting the transition from unconsolidated surface layers to more competent geological formations with increasing depth.

Interpreting variations in shear wave velocity (Vs) profiles produced by the MASW technique requires the inversion analysis shown in Figure 5. Emphasizing difficulties with velocity differences and inconsistent stratification, this figure shows dispersion curves and Vs profiles for two scenarios: (a) and (b). Fundamental for NEHRP seismic site categorization and geotechnical engineering applications, these findings provide important new perspectives on subsurface stiffness and stratigraphy (Ivanov *et al*., 2011; Roma and Foresta, 2011; Xia *et al*., 2000).

The variation in Rayleigh wave velocity with wavelength is depicted using colour gradients, representing the dispersion misfit percentage. While larger misfit values (blue) reflect variations probably resulting from complicated subsurface layering or higher-mode Rayleigh wave interference, and lower misfit values (red and orange) indicate a significant connection between theoretical and observed data. Higher modes hinder dispersion curve interpretation in geological en-

Table 2. Shear Wave Velocity (Vs) Profile

Depth (m)	Shear Wave Velocity (m/s)	Interpretation
0 – 4	200 – 250	Loose surface sediments
4 – 8	250 – 350	Moderately compacted sands and silts
8 – 15	350 – 500	Stiff clayey sediments or weathered bedrock
15 – 30	500 – 700	Consolidated bedrock or dense gravel
> 30	> 700	Competent bedrock

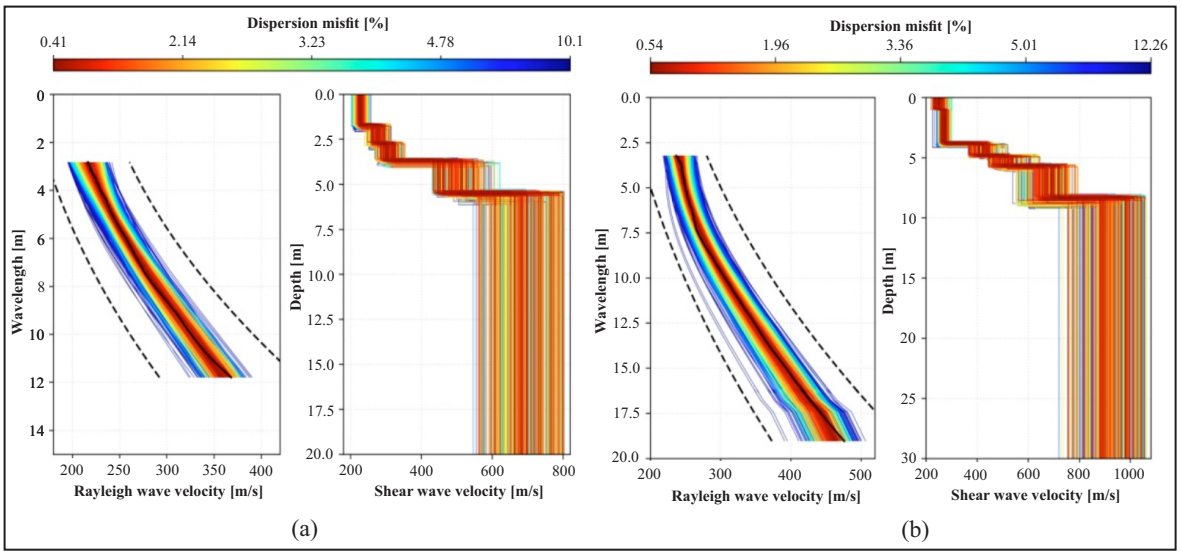

Figure 5. The MASW inversion model for firing directions: (a) forward and (b) backward. The observed dispersion curve is depicted by the black line, while the colour bar represents the error range in the theoretical model.

vironments with significant velocity contrasts or uneven stratification, where these issues are most evident (Ivanov *et al*., 2011; Roma and Foresta, 2011). But the figure dashed boundaries precisely characterize well-defined dispersion patterns, indicating that the fundamental mode of Rayleigh waves was essentially extracted a required initial step for accurate Vs profiling (Casto *et al*., 2008; Roma and Tononi, 2011).

Depth penetration and surface structure in the Vs profiles vary greatly. Suggesting a compacted sedimentary sequence, in profile (a) Vs increases regularly from ~200 m/s at the surface to ~800 m/s at depth. Profile (b) reveals a more consolidated or compact subsurface by comparison with a higher Vs gradient and over 1,000 m/s at deeper depths. The smooth Vs transition in profile (b) suggests uniform geological layering, whereas the abrupt jumps in profile (a) may reflect sharp lithological contrasts or depositional variations.

These findings align with the study objective of comparing MASW- and SPT-derived Vs profiles for NEHRP seismic site classification. The observed changes in Vs highlight the effect of velocity contrasts and uneven stratification on Vs30 calculations, which profoundly affect site classification accuracy (Ghanbari *et al*., 2018; Xia *et al*., 2000). By bettering subsurface characterisation via the integration of many geophysical techniques and refining inversion techniques, seismic hazard assessments will be more accurate, and infrastructure design will be enhanced (Ivanov *et al*., 2011; Mulargia and Castellaro, 2009).

Geological Interpretation

By matching the shear wave velocity (Vs) profile with regional borehole data, one may verify a change from compacted sediments to bedrock at deeper levels. The gradual rise in Vs indicates a normal depositional environment in which overburden pressure causes surface sediments to compress over time. This trend aligns with natural sediment consolidation processes, reinforcing the reliability of the inversion results.

Borehole data from a nearby site identified clay and silty deposits within the upper 5 m, followed by sandstone and weathered rock between 8 and 15 m. This lithological sequence corresponds well with the Vs values obtained from MASW inversion, further confirming the method accuracy in subsurface characterization. The strong correlation between MASW-derived Vs profiles and borehole data enhances confidence in surface wave techniques for geotechnical and seismic investigations (Foti *et al*., 2014; Stephenson *et al*., 2005; Xia *et al*., 2000).

Vs30 Analysis Based on NEHRP Standards

Standard Penetration Testing (SPT) N-values inverted shear wave velocity (Vs) profile provides an insight into the underlying geology and seismic site classification (Figure 6). The Vs profile shows a constant velocity increase with depth from surface unconsolidated clayey deposits to deeper layers of competent claystone and sandstone. Whereas near-surface materials have Vs values below 600 m/s, indicative of soft soils, deeper layers surpass 600 m/s, and indicate stronger geological formations. This speed pattern matches SPT N-values, which also climb with depth, implying higher soil resistance and compaction a basic sign of lithological consistency and mechanical strength (Xia *et al*., 2000).

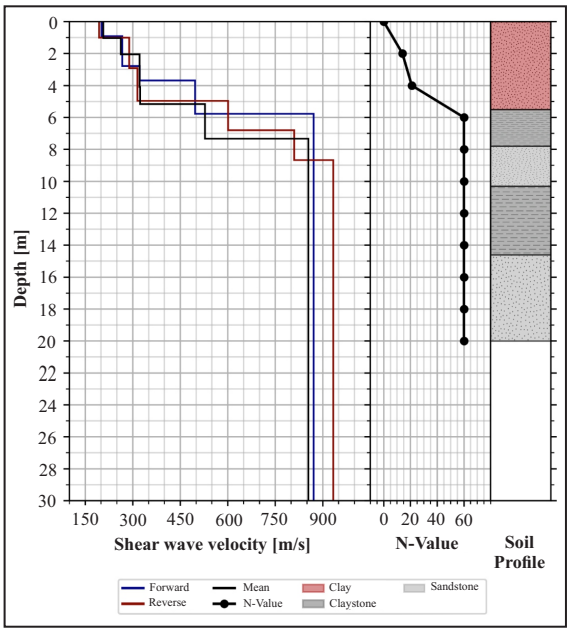

Figure 6. Comparison of Vs profile with borehole data.

A key parameter in seismic site classification is Vs30, which represents the average shear wave velocity in the upper 30 m (Ismet Kanli *et al*., 2006; Meneisy *et al*., 2023; Xie *et al*., 2023). It is computed using the standard (5):

$$V_{S30} = \frac{\sum_{i=1}^{n} H_i}{\sum_{i=1}^{n}\left(H_i/V_{S,i}\right)}, \qquad \sum_{i=1}^{n} H_i = 30\,\text{m}. \quad ..(5)$$

where H_i is thickness of layer i (m); $V_{S,i}$ is shear wave velocity of layer i (m/s); n is the number of layers in the upper 30 m. .

Figure 6 Vs profile offers a complete picture of fluctuations in subsurface velocity, displaying forward (blue), reverse (red), and mean (black). Included also is the N-value profile (black line with markers) from SPT testing, therefore illustrating the relationship between soil resistance and Vs trends. The accompanying soil profile indicates a transition from sediments heavy in clay in the top layers to claystone and sandstone at deeper depths. From 150–300 m/s at the surface to over 900 m/s at depths more than 10 m, the Vs profile exhibits a constant velocity increase with depth. The lower Vs values may be explained by the first 6 m corresponding to clay-rich strata; deeper layers made of claystone and sandstone show much greater velocities. The trend in N-value suggests even more growing soil resistance and compaction depth. The calculated Vs30 value of 541.7 m/s corresponds to NEHRP Site Class C, very stiff soil or soft rock with Vs30 values between 360 and 760 m/s, with the same velocity range obtained by (Karabulut, 2018) with a different site. Since the underlying materials are competent, this classification suggests that the site is quite stable for evaluation of seismic hazard and building development.

From an engineering and seismic standpoint, especially within certain frequency ranges, stiff soils (Site Class C) may nonetheless show modest ground motion amplification. As a result, infrastructure and buildings in this region have to follow seismic design rules, and include dampening systems and reinforced foundations to lessen any amplification effects (Mulargia and Castellaro, 2009). More geotechnical studies including deep borehole logging and geophysical imaging are advised to help improve site characterization. These techniques would verify the existence of competent rock strata under 20 m, therefore affecting the foundation stability and seismic wave propagation. The results highlight the need of combining geophysical and geotechnical techniques for a complete knowledge of subsurface conditions, hence improving infrastructure resilience and seismic hazard reducing ability (Stephenson *et al*., 2005).

Conclusions

This paper presents the efficacy of the MASW approach in seismic site classification and creation of shear wave velocity (Vs) profiles. From loose surface sediments to harder claystone and sandstone, the results show a constant increase in Vs as depth increases. The anticipated Vs30 value of 541.7 m/s categorizes the site as NEHRP Site Class C, indicating very stiff soil or soft rock, which reflects robust ground characteristics. In contexts where traditional intrusive methods may prove to be costly or unfeasible, our findings demonstrate the reliability of MASW for seismic site characterization.

Although their strengths, the differences between the MASW- and SPT-derived Vs profiles draw attention to the difficulties presented by velocity contrasts, uneven stratification, and higher-mode Rayleigh waves. These elements could alter the Vs30 calculations, therefore influencing the site categorization accuracy under the NEHRP criteria. Using Monte Carlo inversion methods has shown to be successful in lowering uncertainty and strengthening the resilience of Vs profiling. Strong links between the MASW findings and borehole data further confirmed the MASW suitability for geotechnical and seismic hazard evaluations. Still, further improvement in subsurface characterization in challenging geological environments depends on constant improvement of inversion methods and integrated multimethod approaches.

Site Class C soils may still somewhat increase ground motion from an engineering and seismic hazard standpoint, so seismic-resistant design issues for infrastructure become very important. Damping systems and strengthened foundations help reduce the possible amplification effects. Deep borehole logging and other geotechnical studies, like further geophysical imaging, are advised to improve site characterization even more. These actions will assist in verifying the existence of competent rock strata underneath 20 m, therefore affecting the foundation stability and seismic wave propagation. In the end, the combination of geophysical and geotechnical techniques guarantees a thorough knowledge of subsurface conditions, and helps in the better design of infrastructure and the reduction of earthquake risk.

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