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Roadside Passive MASW for Limestone Bedrock Characterization and Urban Infrastructure Planning in Cam Pha, Quang Ninh Province

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ABSTRACT: Characterizing shallow bedrock beneath urban corridors is important for infrastructure planning in limestone terrain, where irregular rockhead geometry can complicate foundation and excavation design. This study evaluates roadside passive multichannel analysis of surface waves (MASW) as a low-disturbance approach to ground assessment along a 141 m road corridor in Cam Pha, northeastern Vietnam. Traffic-induced surface waves were recorded at four array positions using twenty-four 4.5 Hz geophones spaced 3 m apart. At each position, dispersion images from ten 32 s records were stacked, and selected dispersion curves were inverted to obtain one-dimensional shear-wave velocity (V_s) profiles. An interpolated two-dimensional section was compared with stratigraphy from a nearby borehole. The models extended to approximately 50 m depth and indicated clayey cover with V_s mostly around 270–400 m/s overlying limestone with velocities commonly exceeding 1500 m/s. The interpreted clay–limestone boundary generally occurred at 15–20 m depth, with local deepening near the middle of the section. Depth-averaged velocities over the upper 30 m ranged from 434.24 to 497.63 m/s, corresponding to NEHRP site class C and Eurocode 8 ground type B. The findings support preliminary ground assessment and prioritization of confirmatory investigations for urban infrastructure. However, the interpolated section and single borehole do not uniquely resolve the causes of local bedrock irregularities; additional investigations are needed before site-specific design decisions.

1. INTRODUCTION

Near-surface shear-wave velocity (V_s) is a fundamental parameter for engineering geology, geotechnical design, seismic site classification, and underground-space planning. It controls small-strain stiffness, governs dynamic site response, and provides a physically meaningful link between geophysical observations and engineering parameters used in foundation and earthquake-resistant design (Baglari et al., 2018; BSSC, 2020; CEN, 2004). Surface-wave methods, particularly multichannel analysis of surface waves (MASW), are widely used because they can estimate V_s profiles with limited ground disturbance and comparatively low field cost (Abdelbaset et al., 2025; Baglari et al., 2020; Park and Miller, 2008). Conventional active MASW remains effective for shallow profiling, but its investigation depth is commonly restricted by the low-frequency energy that can be generated by practical active sources such as sledgehammers or small weight drops (Baglari et al., 2018; Park and Miller, 2008). This limitation is critical where the engineering target is a soil-rock interface deeper than the first several tens of metres or where a stiff rockhead must be mapped beneath a soft to medium-stiff cover.

Passive surface-wave approaches partly overcome this limitation by using ambient vibrations generated by wind, machinery, railways, underground traffic, and road vehicles. In urban settings, traffic noise is not only contamination; it can also provide useful low-frequency Rayleigh-wave energy for deeper V_s profiling (Cheng et al., 2018; Ning et al., 2022; Zhang et al., 2022). Roadside passive MASW is a practical branch of this approach because a linear receiver array can be deployed along streets and

highways, while moving vehicles act as repeated and distributed seismic sources (Baglari et al., 2020; Park and Miller, 2008; Zhang et al., 2019). Recent studies have shown that traffic-induced or passive surface waves can support underground-railway investigations, urban near-surface imaging, and infrastructure-oriented site characterization where active-source surveys are limited by access, vibration control, or safety requirements (Zhang et al., 2019; Dai et al., 2019; Zheng et al., 2023).

Despite these advantages, roadside passive MASW still involves important methodological uncertainties. Traffic sources are intermittent, directional, and spatially uneven, so the recorded wavefield may include in-line, off-line, near-field, and multi-source components (Park and Miller, 2008; Zhang et al., 2022; Miatto et al., 2021). These conditions affect the clarity of dispersion images, the reliability of mode identification, and the stability of inversion results. Recent work has therefore emphasized the need to consider acquisition parameters, source geometry, dispersion-curve picking, and local-noise effects when passive surface waves are used in complex urban environments (Baglari et al., 2020; Ning et al., 2022; Hu et al., 2023). A useful case study should consequently do more than demonstrate that passive MASW can generate 1D profiles; it should test whether the profiles are geologically interpretable, whether they agree with independent borehole information, and whether the resulting 2D model adds engineering value.

The geological target in this study is also significant. The survey site in Cam Pha, Quang Ninh Province, lies in northeast Vietnam, where urban and transport infrastructure are expanding across terrains that include clayey cover, coal-bearing sedimentary units, and limestone formations. Limestone terrains are engineering-sensitive because weathering, fracturing, dissolution, and karst-related voids can create abrupt lateral changes in rockhead depth and stiffness. Such irregular rockhead geometry may be missed by a single borehole, whereas a continuous geophysical profile can reveal depressions, fractured zones, or weathered pockets between borehole locations. Similar surface-wave studies have shown that mapping bedrock depth and stiffness contrasts is important for evaluating site response, foundation conditions, and underground construction risk (Ivanov et al., 2006; Moon et al., 2017; Vantassel et al., 2018). For Cam Pha, this issue is especially relevant because the borehole indicates semi-stiff clayey soil overlying strongly fragmented and fractured limestone.

The Vietnamese context gives the study additional practical importance. Vietnam is investing heavily in transport infrastructure, including highways, urban railways, metro systems, underground stations, and regional connectivity corridors. A material-stock assessment for Hanoi showed the scale of planned road and railway expansion and the associated demand for infrastructure construction materials through 2030 (Miatto et al., 2021). This infrastructure push increases the need for rapid, reliable, and non-destructive site characterization methods that can work along roads and urban corridors. However, passive MASW applications in Vietnam remain limited in the international literature, with most published Vietnamese examples focusing on active MASW or combined near-surface methods for foundation design and geotechnical parameter estimation (Nguyen et al., 2025; Nguyen, 2025). There is therefore a clear gap between international advances in traffic-noise surface-wave imaging and the still sparse documentation of roadside passive MASW case studies in Vietnam.

This study addresses that gap by applying roadside passive MASW along a 141 m road section in Cam Pha City and comparing the resulting 1D and 2D V_s models with borehole stratigraphy. The contribution is not only to demonstrate the feasibility of passive MASW in Vietnam, but also to extract engineering information from the obtained VS structure: the depth of the clay-limestone boundary, the lateral variation of the limestone surface, the quality of dispersion picks at four sites, and the V_{s30} -based site classification according to NEHRP and Eurocode 8 (BSSC, 2020; CEN, 2004). By focusing on a roadside configuration in fractured limestone terrain, the study provides a practical example for geophysical screening of transport corridors, underground works, and urban infrastructure sites in Vietnam.

The objectives are therefore to: (i) evaluate whether traffic-noise-based roadside passive MASW can image the subsurface to approximately 50 m depth in the study area; (ii) derive 1D V_s profiles and a 2D V_s section that can be checked against borehole stratigraphy; (iii) identify the depth and lateral geometry of the clay-limestone boundary, including possible local depressions or irregular rockhead features; (iv) compute V_{s30} and related depth-averaged V_s indicators for seismic site classification; and (v) discuss the usefulness and limitations of the method for infrastructure-oriented site investigation in northeast Vietnam.

2. MATERIALS AND METHODS

2.1 Study location and geological setting

The passive MASW survey line (Fig. 1) is 141 m long and follows a roadside corridor in Cam Pha City, approximately 200 km northeast of Hanoi and about 30 km from Ha Long City. Cam Pha is characterized by hilly to mountainous topography and

mixed urban-infrastructure development. The survey area is close to the boundary between the Hon Gai Formation, represented mainly by gravel and siltstone, and the Bac Son Formation, represented by light gray to dark gray limestone. This geological setting is important because clayey cover, fractured limestone, and possible karst-related heterogeneity can produce strong lateral changes in stiffness over short distances.

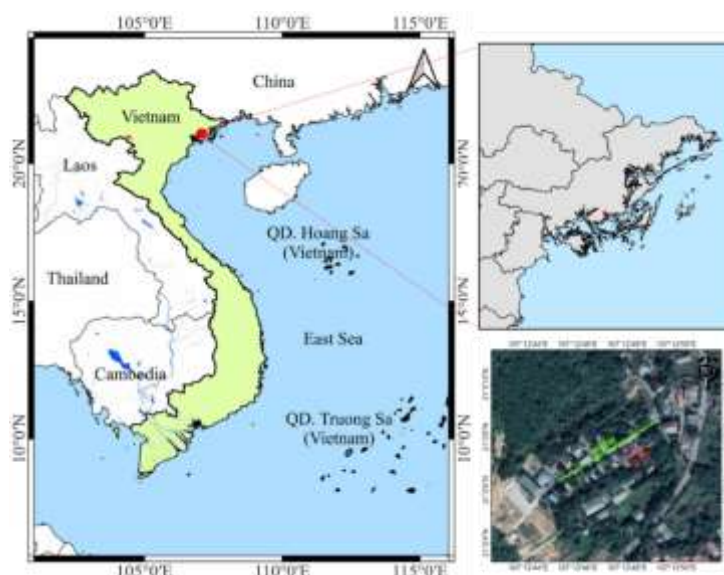


Fig. 1. Map of study area with passive MASW survey line (green line) and geological borehole (red circle).

A geological borehole near the passive MASW line (red circle in Fig. 1) was used to constrain the stratigraphic interpretation. The borehole indicates two main units in the upper 30 m (Fig. 2): (i) semi-stiff clayey soil from the surface to about 15 m depth, including brownish yellow to yellowish gray and brownish gray to yellowish gray sublayers, and (ii) strongly fragmented and fractured limestone below approximately 15 m depth. This borehole provides the main independent reference for evaluating whether the passive MASW velocity models correctly identify the clay-limestone boundary.

Depth (m)	Thickness (m)	Density (g/cm^3)	Lithology	Soil description
9.20	9.20	2.68		Brownish yellow, yellowish gray semi stiff clayey soil
15.00	5.80	2.70		Brownish gray, yellowish gray semi stiff clayey soil
30.00	15.00	2.79		Dark gray, light gray strongly fragmented and fractured limestone

Fig. 2. Borehole stratigraphy used for MASW interpretation

2.2 Roadside passive MASW technique

Passive MASW can be implemented in two main configurations: passive remote MASW and passive roadside MASW. Passive remote surveys commonly use two-dimensional arrays, such as triangular, circular, or square layouts, to record ambient vibrations from natural and cultural sources (Park and Miller, 2005a; Park and Miller, 2005b). In contrast, roadside passive MASW uses a linear receiver spread deployed along a road, where traffic acts as the dominant passive seismic source (Baglari et al., 2018; Park and Miller, 2008). This configuration is suitable for urban corridors because it requires less open space than two-dimensional passive arrays and can exploit low-frequency traffic-generated Rayleigh waves for deeper V_s profiling. The dispersion image in this study follows the phase-shift concept, in which trial phase velocities are scanned by applying phase corrections to the frequency-domain records before stacking the energy response (Park et al., 1998; Park et al., 2004).

$$U(x, \omega) = e^{-i\Phi x} A(x, \omega) \quad (1)$$

where $A(\omega, c)$ is the dispersion-image amplitude at angular frequency ω and trial phase velocity c , $U_n(\omega)$ is the Fourier spectrum recorded at the n th receiver, x_n is the receiver offset, and $n = 1, 2, \dots, N$ denotes the receiver number. Peaks in $A(\omega, c)$ define the frequency-phase velocity trend used for dispersion-curve picking (Baglari et al., 2018; Park and Miller, 2008).

Because the location and number of traffic sources are not controlled, roadside passive MASW must consider different source-geometric assumptions, including inline-plane (IP), offline-plane (OP), and offline-cylindrical (OC) propagation (Park and Miller, 2008). The survey line in Cam Pha was arranged along a relatively straight roadside segment; therefore, the initial interpretation assumed a dominant IP contribution from vehicles moving approximately parallel to the receiver spread. OP and OC arrivals were treated as possible contributors to scattered energy and local noise. This assumption was checked during processing by inspecting dispersion-image continuity, signal-to-noise ratio (SNR), and the consistency between measured and theoretical dispersion curves.

2.3 Field measurement and site conditions

The passive MASW layout is shown in Figs.3 and 4. Twenty-four 4.5 Hz vertical geophones were connected to a GEODE seismograph and deployed along the roadside. The receiver spacing (dx) was 3 m, giving a 69 m spread length, and the receiver array was shifted by $8dx$ (24 m) between adjacent measurement sites. The 3 m spacing was selected as a compromise between resolving the shallow clayey layer and maintaining a sufficiently long spread to sample low-frequency traffic-generated surface waves for deeper investigation (Baglari et al., 2020; Park and Miller, 2008).

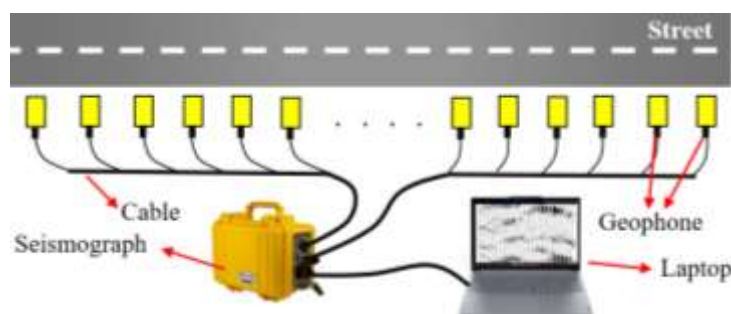


Fig. 3. Equipment system diagram of passive roadside MASW survey

At each of the four passive MASW sites, ten passive records were acquired, producing forty passive records in total. A 32 s recording length and 0.5 ms sampling interval were used. The longer record length is appropriate for roadside passive MASW because traffic sources are intermittent and the target low-frequency energy requires a longer time window than a typical active-source record (Baglari et al., 2020; Park and Miller, 2008; Zhang et al., 2019). Fig. 5 shows representative raw records from the four measurement sites.

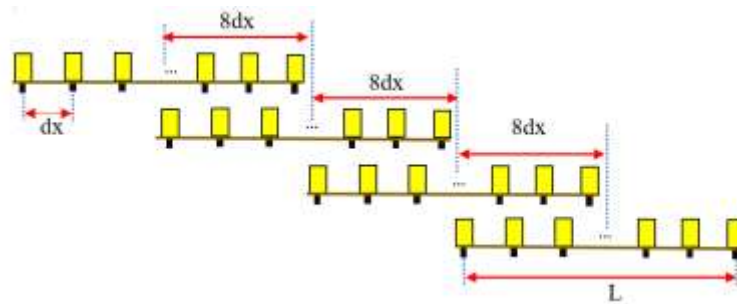


Fig. 4. Receiver array with total length $L = 69$ m is moved along the survey line with interval distance between adjacent center of arrays $8dx = 24$ m. The receiver spacing dx is 3 m.

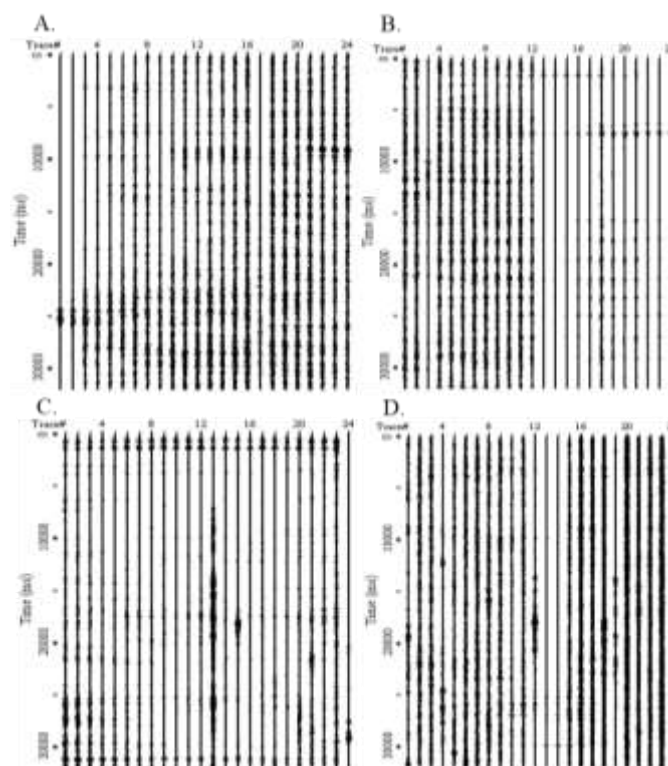


Fig. 5. Raw data record at four sites along passive MASW survey line: (a) MASW 1, (b) MASW 2, (c) MASW 3, (d) MASW 4.

2.4 Data processing and inversion

The passive MASW records were processed using ParkSeis (PS) software (Nguyen et al., 2025; Nguyen, 2025). For each measurement site, the ten 32 s records were transformed to dispersion images and stacked to enhance coherent surface-wave energy. The processing workflow consisted of: (i) checking raw records for trace loss and abnormal spikes; (ii) generating individual dispersion images; (iii) stacking the ten dispersion images at each site; (iv) picking the most continuous fundamental-mode ridge; (v) checking the picked points against SNR; and (vi) inverting the accepted dispersion curve to obtain a 1D V_s profile. Dispersion images were inspected mainly within the frequency band where coherent energy was visible, approximately 2-20 Hz for MASW 1, MASW 2, and MASW 4, and approximately 2-15 Hz for MASW 3 (Fig. 6).

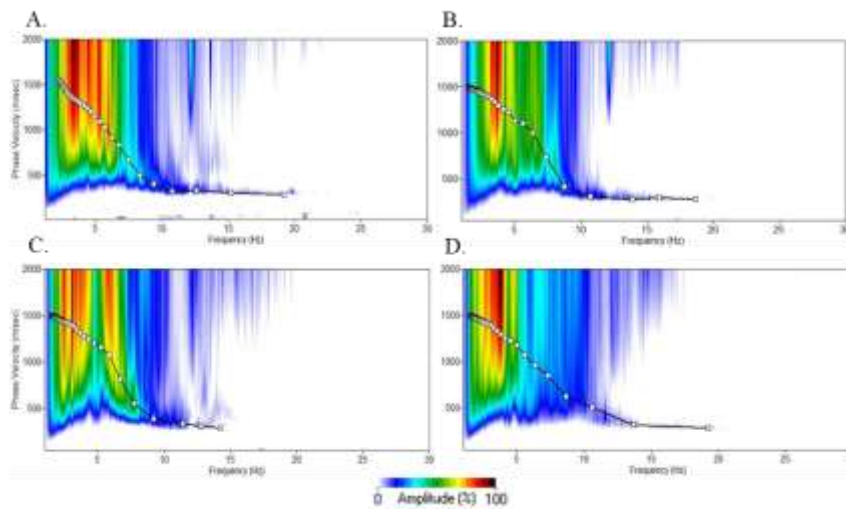


Fig. 6. Dispersion images at four passive MASW survey sites obtained by stacking ten dispersion images at the four sites: (a) MASW 1, (b) MASW 2, (c) MASW 3, and (d) MASW 4.

Dispersion-curve reliability was evaluated using the signal-to-noise ratio (SNR). In roadside passive MASW, the coherent Rayleigh-wave energy generated by traffic is treated as the useful signal, whereas incoherent or off-line arrivals from other cultural sources are treated as noise. At each frequency, SNR was calculated as the ratio between the amplitude at the picked dispersion point and the maximum amplitude along the same frequency slice. Values close to 1.00 indicate that the picked point follows the strongest energy ridge; values substantially lower than 1.00 indicate less stable picks. In this study, most accepted points have SNR values close to 1.00, whereas several MASW 4 points decrease to about 0.60 and were therefore interpreted with greater caution (Fig. 7).

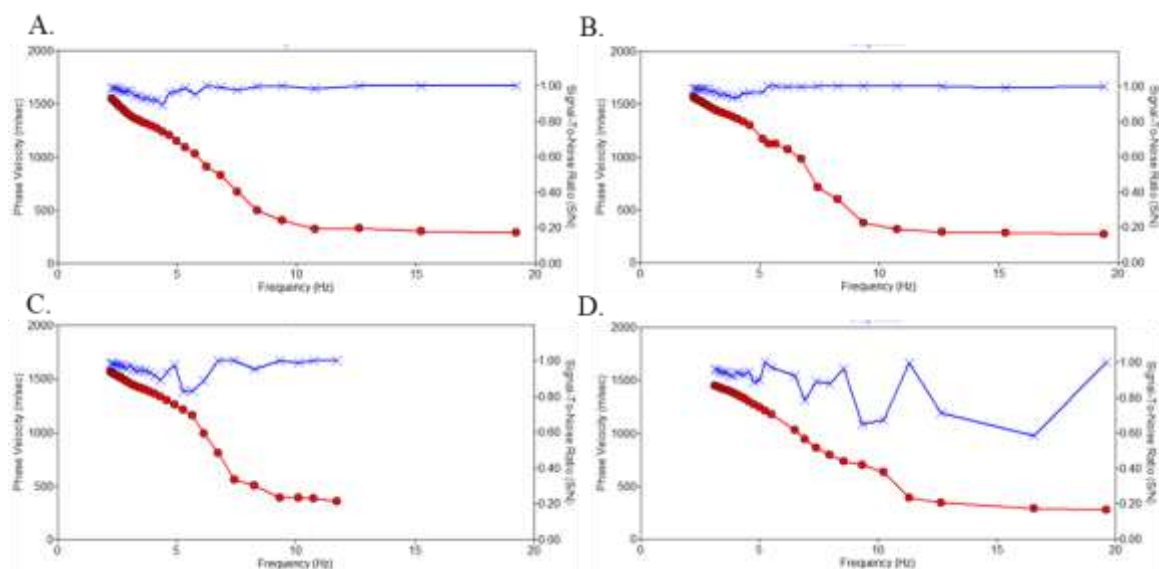


Fig. 7. Measured dispersion curves (red lines with circles) and corresponding SNR values (blue lines with crosses) at the four sites.

The accepted dispersion curves were inverted after three iterations in PS software to obtain 1D V_s profiles at the four MASW sites (Fig. 8). A ten-layer initial model was used, with layer thicknesses and V_s values constrained to follow a geologically plausible increase from the near-surface clayey unit to the underlying limestone. The borehole was not used to force the inversion result, but it provided an independent geological check on the interpreted clay-limestone boundary. The similarity between measured and theoretical dispersion curves was then used as an inversion-quality indicator. The 2D V_s section was

produced by interpolating the four inverted 1D profiles along the survey line; consequently, it should be interpreted as a smoothed representation of lateral velocity variation rather than a fully independent 2D inversion.

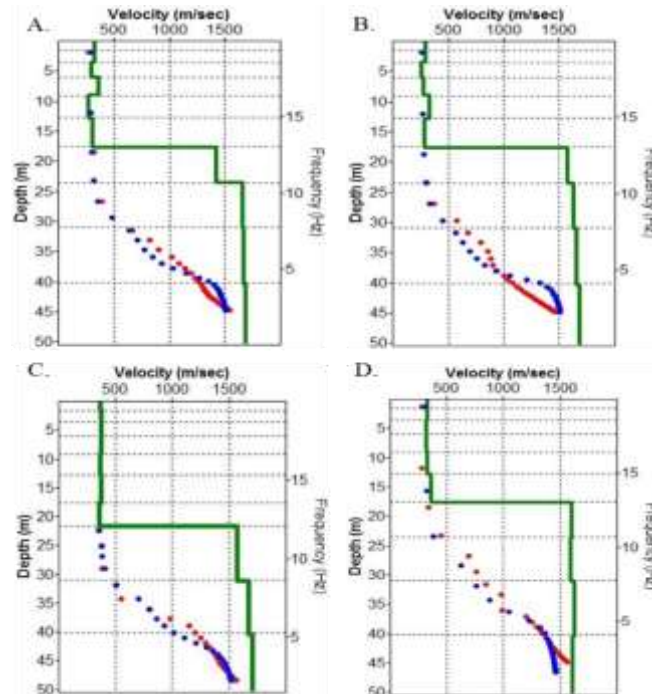


Fig. 8. Inverted 1D VS profiles at the four passive MASW sites

2.5 Seismic site classification computation

The time-averaged shear-wave velocity of the upper 30 m (V_{s30}) was calculated at each MASW site for seismic site classification according to NEHRP and Eurocode 8 criteria (BSSC, 2020; CEN, 2004). The classification thresholds are summarized in Table 1.

$$V_{s30} = \frac{30}{\sum_{i=1}^N \left(\frac{h_i}{V_{si}} \right)} \quad (2)$$

where h_i and V_{si} are the thickness and shear-wave velocity of the i th layer, respectively, and N is the number of layers included within the upper 30 m. When the last layer crosses the 30 m depth, only the thickness portion above 30 m is included in the summation (BSSC, 2020; CEN, 2004).

Table 1. NEHRP and Eurocode 8 site-class thresholds based on V_{s30}

Site class/ground type	NEHRP V_{s30} (m/s)	Eurocode 8 V_{s30} (m/s)
A	>1500	>800
B	760-1500	360-800
C	360-760	180-360
D	180-360	<180
E	<180	Surface alluvium layer with VS of type C or D and thickness between 5 and 20 m, underlain by stiffer material with VS >800 m/s

3. RESULTS AND DISCUSSION

3.1 Results

The roadside passive MASW survey produced coherent dispersion images and interpretable 1D V_s profiles to approximately 50 m depth. This depth is important because it exceeds the practical investigation depth commonly expected from a small active-source MASW survey under comparable urban field constraints (Baglari et al., 2018; Park and Miller, 2008; Hu et al., 2022). The low-frequency energy near about 2 Hz, visible in the dispersion results, is the key factor that enables the deeper imaging. In contrast, the shallow part of the profile is constrained by the higher-frequency content and by the 3 m receiver spacing. The survey design therefore provides a useful compromise between shallow resolution in the clayey cover and deeper penetration into the limestone unit.

The stacked dispersion images show that the fundamental-mode trends are generally clear at the four MASW sites. MASW 1, MASW 2, and MASW 4 display high-energy trends over a frequency range of approximately 2-20 Hz, while MASW 3 shows a stable trend over about 2-15 Hz. The SNR analysis in Figure 7 indicates that most picked dispersion points have SNR values close to 1.00, supporting reliable extraction of the dispersion curves. MASW 4 is the main exception, with several points decreasing to about 0.60. This does not invalidate the profile, but it indicates a more complicated local noise field, probably caused by variable traffic-source geometry, off-line arrivals, or interference from multiple cultural noise sources. This observation is consistent with recent studies showing that local and directional urban noise sources can bias passive surface-wave phase velocity estimation if they are not recognized during processing (Zhang et al., 2022; Miatto et al., 2021).

The inversion quality is acceptable for engineering interpretation. The similarity between measured and theoretical dispersion curves reaches 89.7%, 86.6%, 91.2%, and 92.7% at MASW 1 to MASW 4, respectively. The lowest value at MASW 2 remains within a usable range, while the highest value at MASW 4 indicates that the lower-SNR points did not prevent a stable inversion after curve selection. Across the four 1D profiles, the velocity structure is consistently divided into a low-velocity upper unit and a high-velocity lower unit. The upper unit has V_s values mostly in the range of about 270-370 m/s, matching the semi-stiff clayey soil described in the borehole. The lower unit shows a rapid velocity increase and commonly exceeds 1500 m/s, consistent with strongly fragmented and fractured limestone. The sharp velocity contrast provides a clear geophysical marker of the transition from soil cover to limestone bedrock.

Comparison with the borehole strengthens the interpretation. The borehole identifies clayey soil from the surface to about 15 m depth and fragmented/fractured limestone below this depth. Fig. 9 shows that the 1D V_s profiles reproduce this two-unit structure, although the depth of the velocity transition varies among the MASW sites. This variability is meaningful rather than a processing artefact. If the limestone surface were perfectly horizontal, the high-velocity transition would occur at the same depth across all four 1D models. Instead, the profiles suggest a rockhead depth that fluctuates over short lateral distances. Such behaviour is expected in weathered or fractured limestone terrains, where differential weathering, jointing, and dissolution can produce a non-planar interface.

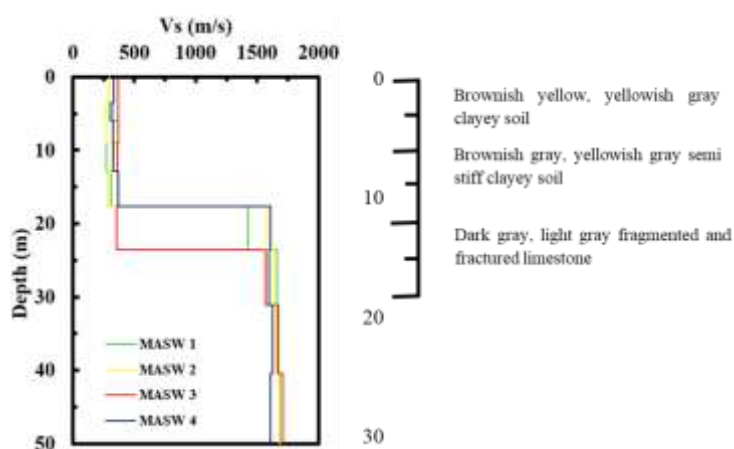


Fig. 9. The 1D VS profiles at four sites along passive MASW are plotted on same diagram compared to petrological composition in borehole

Figure 10 provides the most important result of the study because it converts the four 1D profiles into an interpretable 2D V_s section. The profile confirms the two principal units: a near-surface clayey layer with V_s mostly around 300-400 m/s and an underlying limestone unit with V_s commonly greater than 1500 m/s. The clay-limestone boundary generally occurs at 15-20 m depth, but it is not horizontal. A local downward deflection occurs near the middle of the profile, especially around 40-50 m along the survey line, where the transition zone deepens before rising again toward the end of the line. This geometry indicates lateral variability in the limestone surface and is the main added value of the 2D passive MASW interpretation compared with the single borehole.

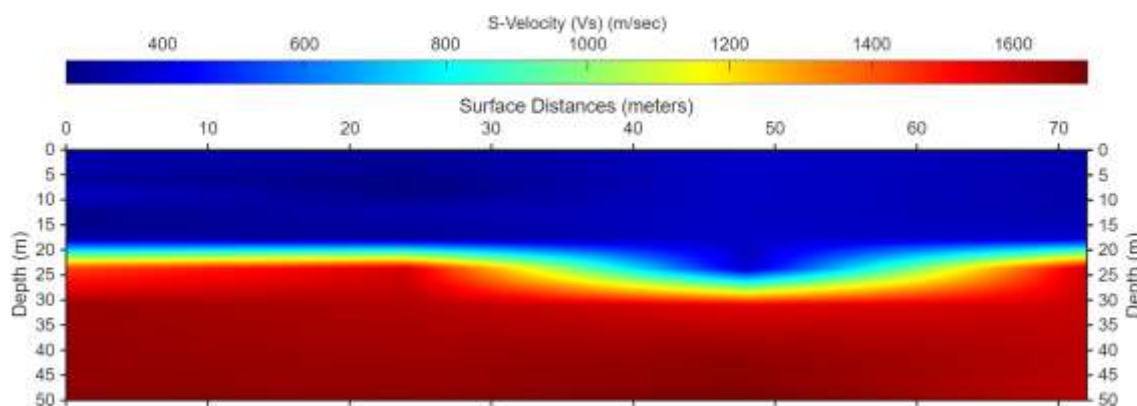


Fig. 10. Interpolated 2D V_s section derived from the four inverted 1D passive MASW profiles. The colour scale represents shear-wave velocity (V_s), with blue colours indicating the low-velocity clayey cover and red colours indicating the high-velocity limestone unit

The depression of the high-velocity boundary has direct engineering significance. In a limestone setting, a local downward deflection may indicate stronger weathering, a fracture zone, or a karst-related dissolution feature. The present data cannot distinguish among these mechanisms uniquely, but the V_s pattern identifies a zone where the stiff limestone surface is deeper and potentially less uniform. This feature should be treated as a target for follow-up verification by additional boreholes, electrical resistivity tomography, or combined active-passive surface-wave analysis. The result is consistent with the broader use of surface-wave methods for mapping bedrock depth and stiffness contrasts in complex sites (Ivanov et al., 2006; Moon et al., 2017; Vantassel et al., 2018; Abdelrahman, 2025).

The depth-averaged V_s values further quantify the stratigraphic interpretation (Fig. 11). V_{s10} ranges from 284.91 to 366.79 m/s and V_{s20} ranges from 321.90 to 370.13 m/s, confirming that the upper 10-20 m are dominated by clayey soil. V_{s30} increases to 434.24-497.63 m/s because the averaging depth includes the upper part of the limestone unit. V_{s40} increases further to 532.52-601.96 m/s, and V_{s50} reaches 617.47-688.19 m/s, reflecting the increasing proportion of high-velocity limestone with depth. The monotonic increase from V_{s10}/V_{s20} to V_{s40}/V_{s50} is important because it demonstrates that the site is not a uniform soil column; instead, it is a layered soil-rock system with a strong stiffness contrast below the clayey cover.

The calculated V_{s30} values at MASW 1, MASW 2, MASW 3, and MASW 4 are 463.47, 439.02, 434.24, and 497.63 m/s, respectively. According to NEHRP, these values correspond to site class C, whereas Eurocode 8 classifies them as ground type B (BSSC, 2020; CEN, 2004). The apparent difference between the two systems results from different threshold definitions rather than inconsistent measurements. From an engineering perspective, the values indicate a relatively stiff site, but the 2D section shows that stiffness is not spatially uniform. Therefore, using only a single V_{s30} value would under-represent the local rockhead depression shown in Figure 10. For infrastructure design, the combined interpretation of V_{s30} , the 2D V_s section, and borehole information is more informative than any one indicator alone.

Overall, the results show that roadside passive MASW successfully captured both vertical layering and lateral heterogeneity at the Cam Pha site. The method identified the clayey cover, mapped the limestone boundary at approximately 15-20 m depth, detected a local depression of the rockhead near the middle of the profile, and provided V_{s30} values suitable for seismic site classification. These findings support the use of roadside passive MASW as a screening tool for road corridors, urban infrastructure, and underground works in limestone terrains, especially where boreholes are sparse and active-source surveys cannot provide sufficient investigation depth.

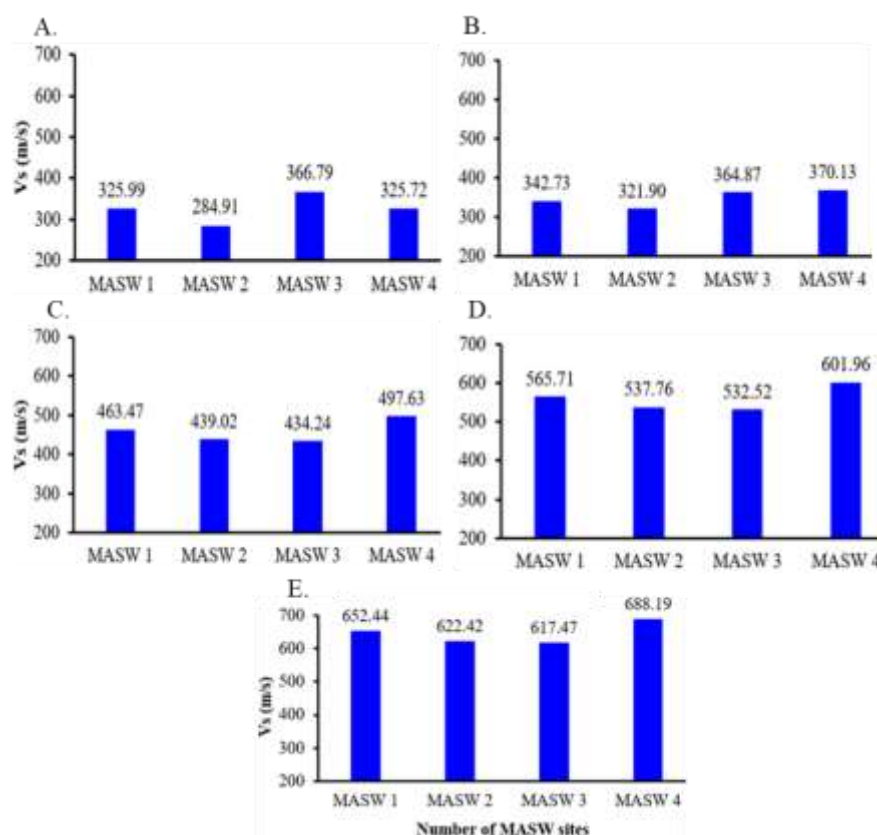


Fig. 11. Average shear wave velocities estimated on the top A) 10, B) 20, C) 30, D) 40, and E) 50 m of soil at four sites

3.2 Discussion

The results place the Cam Pha roadside passive MASW survey within a broader group of urban and infrastructure-oriented surface-wave studies. The near-surface clayey cover has V_s values mostly around 270-400 m/s, which is consistent with medium to stiff cohesive soils reported in active and passive surface-wave site investigations (Abdelbaset et al., 2025; Adly et al., 2017). The underlying limestone unit commonly exceeds 1500 m/s, producing a sharp stiffness contrast that is comparable to bedrock or very stiff rock units mapped by surface-wave methods in bedrock-depth studies (Ivanov et al., 2006; Vantassel et al., 2018). The agreement between these velocity ranges and the borehole stratigraphy indicates that the passive MASW profiles are not only numerically stable but also geologically interpretable. Similar urban and combined active-passive investigations also show that passive surface waves are most valuable when interpreted together with local geological constraints (Zheng et al., 2023; Maggio et al., 2022; Manakou et al., 2023).

The most important geological information is the non-planar clay-limestone boundary in the 2D V_s section. The local downward deflection near 40-50 m along the profile suggests that the limestone surface is deeper and less uniform in the middle of the line. In limestone terrain, such a feature may reflect differential weathering, a fractured zone, or karst-related dissolution. From an engineering perspective, this is not a minor geometric detail: an irregular rockhead can affect pile socket depth, excavation support, differential settlement, and the alignment of underground utilities or tunnel approaches. The present MASW profile cannot uniquely determine the mechanism of the depression, but it identifies a high-priority target for confirmatory boreholes, electrical resistivity tomography, fault-oriented passive imaging, or combined active-passive surface-wave testing (Guan et al., 2021; Ning et al., 2021).

The V_{s30} values of 434-497 m/s also support the engineering interpretation. These values fall in NEHRP site class C but Eurocode 8 ground Type B because the two classification systems use different threshold ranges (BSSC, 2020; CEN, 2004). Similar differences between site-class systems are common when V_{s30} lies near class boundaries. However, V_{s30} alone should not be overinterpreted at this site. The average value indicates a relatively stiff profile, whereas the 2D V_s section shows a

laterally variable soil-rock interface. Therefore, the combined interpretation of V_{s30} , the 2D profile, and borehole information is more useful for design than assigning a single class to the whole site.

Several limitations remain. Traffic noise is an opportunistic source; its direction, intensity, and frequency content vary through time, as also recognized in traffic-noise and passive-source studies (Zhang et al., 2022; Dou et al., 2017; Shao et al., 2022). This variability explains why MASW 4 has lower SNR at several picked frequencies. Surface-wave inversion is also non-unique and its vertical resolution decreases with depth, so the 2D section should be interpreted as a smoothed interpolation from four 1D models rather than a full 2D inversion (Hu et al., 2023; Socco et al., 2010; Liu et al., 2023). Future surveys should increase the number of spread positions, combine passive and active records, and consider common-virtual-source or cableless receiver workflows where traffic conditions allow (Dai et al., 2015; Guedes et al., 2024). These improvements would help separate local-source effects from real geological heterogeneity and would be especially useful for underground railway, road-corridor, and karst-risk investigations (Zhang et al., 2019; Dai et al., 2019; Zheng et al., 2023).

4. CONCLUSION

First, roadside passive MASW can provide a useful screening approach for the Cam Pha site when constrained by borehole or complementary geophysical data. The traffic-noise records imaged the subsurface to about 50 m depth, which is deeper than the practical range commonly expected from small active-source MASW surveys in similar urban field conditions.

Second, the 1D and interpolated 2D V_s models identify a clayey cover with V_s mostly around 270-400 m/s overlying fragmented and fractured limestone with V_s commonly greater than 1500 m/s. The clay-limestone boundary occurs at about 15-20 m depth and locally deepens near the middle of the survey line, indicating lateral rockhead variability.

Third, the calculated V_{s30} values of 434-497 m/s classify the site as NEHRP class C and Eurocode 8 ground type B. This classification indicates a relatively stiff site, but the local rockhead depression shows that site response and foundation conditions cannot be represented adequately by V_{s30} alone.

Finally, future applications should combine roadside passive MASW with additional boreholes, active-source MASW, electrical resistivity tomography, or other independent constraints. Such integration is necessary where limestone weathering, fracturing, or karst-related irregularities may control foundation performance and underground-infrastructure risk.

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AUTHOR CONTRIBUTIONS

Nguyen Nhat Kim Ngan: Conceptualization, Investigation.

Nguyen Nhat Kim Ngan: Methodology, Laboratory Analysis.

Nguyen Nhat Kim Ngan: Data Curation, Formal Analysis.

Nguyen Nhat Kim Ngan: Supervision, Writing—Review & Editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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