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Advanced passive seismic survey for bedrock depth estimation in urban environments: cross-correlation seismic interferometry using traffic noise

Seonho Hwang, Changho Shin, Taeseo Ku
Department of Civil and Environmental Engineering, Konkuk University, Seoul, Republic of Korea, tsku@konkuk.ac.kr

ABSTRACT: Urban site investigations often confront space limitations, safety constraints, and intense cultural noise that undermine the effectiveness of active-source surface wave surveys. This study presents an enhanced cross-correlation seismic interferometry workflow that transforms traffic noise into a distributed virtual source for shallow subsurface characterization. Ambient wavefields (7–20Hz) recorded along a compact 6-geophone, 30m linear array are first analyses with Multiple Signal Classification (MUSIC) beamforming. Dominant directions of arrival (DOA) are identified and an azimuthal filter (45°–270°) is applied, substantially improving Green's function coherence and dispersion curve resolution. A field experiment at Sori Park, Seoul, demonstrates the method's efficacy. Passive records (30min) and a conventional 24- geophones MASW survey (46m array) were both inverted with an identical genetic algorithm scheme starting from the same stratigraphic model. Above 10 m, the two V_S profiles agree and match an SPT derived reference; below this depth, the cross-correlation inversion resolves the weathered-rock (~12m) and soft-rock (~13 m) interfaces within ±0.4 m of borehole control significantly closer than the MASW result. Mean absolute percentage error (MAPE) analysis of twenty random subsets shows that a 25min recording (30s windows) keeps the dispersion-curve error below 3%, providing a practical guideline for survey duration. The proposed workflow eliminates the need for active sources, reduces array length by ~35%, and delivers better estimate of critical horizons in noise dominated urban settings. These findings validate cross-correlation interferometry, augmented by MUSIC based directional filtering, as a cost effective and robust alternative to conventional MASW for shallow subsurface imaging, bedrock detection, and geotechnical design in densely developed areas.

KEYWORDS: Bedrock depth; Cross-correlation; MUSIC Beamforming; Passive seismic survey; Surface wave; Traffic noise.

1 INTRODUCTION

In response to the limitations of invasive penetration tests in urban environments, non-invasive surface wave-based geophysical methods have gained increasing attention over the past two decades. Among them, the Multichannel Analysis of Surface Waves (MASW) has become one of the most widely adopted techniques for estimating near surface shear wave velocity (V_S) profiles. MASW employs either active or passive sources to produce surface waves, which are recorded by a series of geophones and analyzed in the frequency-wavenumber domain to construct dispersion curves. However, MASW exhibits notable limitations in urban settings. It typically requires a large spatial footprint to ensure sufficient investigation depth and is highly sensitive to ambient noise contamination (Ryden et al. 2006), which can distort dispersion characteristics. Unwanted signals from pedestrians, traffic, or nearby construction can lead to ambiguous or unreliable surface wave data, degrading the accuracy of the inverted V_S profiles. To address these limitations, cross-correlation seismic interferometry has emerged as a passive and more spatially compact alternative (Zhang et al. 2019). This method utilizes ambient seismic noise to extract the empirical Green's function between two receiver locations via cross-correlation, enabling wavefield reconstruction without the need for active sources. Nevertheless, traditional cross-correlation methods face challenges in complex urban noise environments, especially where dominant traffic noise propagates anisotropically and concentrates energy along multiple primary directions of arrival (DOA). This directional bias can result in unstable Green's function estimation and lower the quality of dispersion curves. To overcome this issue, the present study applies the Multiple Signal Classification (MUSIC) beamforming algorithm to identify the dominant DOA and selectively extract signals aligned with that direction. The resulting azimuthal filtering enhances the stability and clarity of the waveforms used for dispersion analysis. Based on this framework, we propose an enhanced cross-correlation seismic interferometry method optimized for urban geophysical site investigations, which minimizes ambient noise interference, reduces spatial requirements, eliminates the need for active sources, and ultimately provides a viable and cost-effective solution for shallow subsurface characterization in densely developed urban areas.

2 BACKGROUND

2.1 *Cross-correlation seismic interferometry*

Cross-correlation seismic interferometry is a passive-source-based geophysical method that is fundamentally distinct from conventional multichannel analysis of surface waves (MASW), which typically employs either active or passive sources. While MASW generally utilizes artificial energy sources (e.g., hammer impacts) or ambient noise to analyze the surface waves recorded by a series of geophones, cross-correlation interferometry relies solely on ambient noise to indirectly extract subsurface information, eliminating the need for active sources. The core principle of this method is the reconstruction of the empirical Green's function between two receiver locations through cross-correlation of passive wavefields. Specifically, as described by Wapenaar (2004), the cross-correlation of waveforms recorded at geophones A and B yields a result equivalent to the waveform that would be recorded at B if a virtual source were placed at location A. In other words, the response function between the two points can be retrieved from only ambient seismic noise, without the need for any active signal generation. To accurately recover the Green's function, it approximates the waveforms of surface wave, provided ambient noise is either evenly distributed around the area, or there is a principal DOA of ambient noise which coincides with the geophone array (Zhang et al. 2019). Therefore, identifying dominant noise sources and selecting stable directions of arrival (DOA) are critical preprocessing steps to ensure data reliability and coherence. This technique is particularly advantageous in urban environments where active source deployment is impractical or restricted. It allows for the generation of shear wave velocity (V_S) profiles using fewer geophones and smaller spatial coverage, making it cost effective and operationally efficient. Accordingly, cross-correlation seismic interferometry has gained increasing attention in recent years for its applicability in urban subsurface imaging, microtremor studies, and bedrock interface detection with improved resolution. The cross-correlation function used in this technique is mathematically expressed as:

$$CC_{AB}(r,s) = u_A(r_A,s)u_B^*(r_B,s) \tag{1}$$

where $u_A(r_A,s)$ represents the waveform recorded at geophone A from a source at location s, and $u_B^*(r_B,s)$ denotes the complex conjugate transpose of the waveform recorded at geophone B from a source at location s.

2.2 *MUSIC Beamforming*

The retrieval of the Green's function using cross-correlation theoretically assumes a random and isotropic noise field. However, in real world urban environments, particularly near intersections dominated by traffic noise, the ambient wavefield is often highly anisotropic due to the directional nature of the sources (Ayala-garcia et al. 2021). In such cases, the conventional assumptions of cross-correlation are violated, potentially leading to biased or directionally skewed Green's function estimates. Therefore, it is essential to identify the dominant DOA of the incoming energy prior to cross-correlation, to enhance the reliability of the Green's function reconstruction. The Multiple Signal Classification (MUSIC) algorithm is a high-resolution spectral estimation technique widely adopted in array signal processing for identifying the DOA and phase velocity of incoming wavefields. It exploits the spatial coherence of waveforms recorded across an array of sensors, each experiencing phase and amplitude variations depending on the signal's direction. The core principle of MUSIC lies in performing eigen-decomposition of the spatial covariance matrix constructed from the array data. This decomposition partitions the data into a signal subspace spanned by eigenvectors associated with the dominant signals and a noise subspace formed by eigenvectors corresponding to the smallest eigenvalues. The MUSIC pseudospectrum is then constructed by evaluating the inverse of the projection of steering vectors onto the noise subspace. Peaks in this spectrum indicate potential DOA candidates. By effectively suppressing incoherent noise and resolving closely spaced sources, MUSIC enables precise characterization of the anisotropic ambient wavefield (Zhang et al. 2019).

3 FIELD TESTING AND DATA ACQUISITION

A field experiment was conducted at Sori Park, located in Songpa-gu, Seoul, to compare cross-correlation seismic interferometry with the conventional active MASW. Figure 1 shows the detailed map of testing site. Both passive and active surface wave surveys were implemented. For the active survey, seismic data was acquired using a linear array of 24 geophones spaced at 2 m intervals, resulting in a total array length of 46 m. The seismic source was placed with a 5 m offset from the nearest receiver. The data were recorded at a sampling frequency of 8000 Hz (equivalent to a 0.125ms sampling interval). To enhance the signal-to-noise ratio (SNR), ten repeated source excitations were performed and subsequently stacked. The resulting stacked active waveforms are shown in Figure 2(a). For the passive survey, measurements were conducted at the same location to enable direct comparison through cross-correlation analysis. Ambient noise data were recorded from 11:10 AM to 11:40 AM, yielding a continuous 30 min dataset. A 30 m-long linear (1D) geophone array was deployed, consisting of six geophones spaced at 6 m intervals. The sampling frequency was set to 500 Hz, and the data were segmented into 30 sec time windows, producing 60 total segments. The stacked passive waveforms are presented in Figure 2(b), and the corresponding cross-correlated traces are shown in Figure 2(c). The passive array was strategically deployed near the intersection of Saemal-ro and Beobwon-ro, targeting traffic induced ambient noise as the primary source. The array was oriented along the dominant noise propagation to improve directional coherence and enhance the reliability of the Green's function retrieval. To assess the shear wave velocity (V_S) profiles obtained from each method, an empirical correlation model based on the Standard Penetration Test (SPT) proposed by Heo et al. (2022) was applied. The model is expressed as:

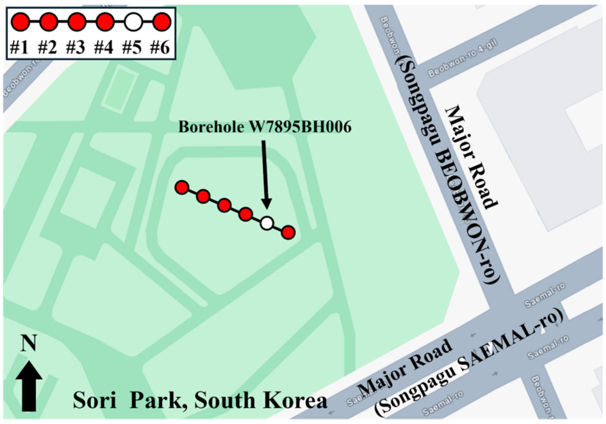

Figure 1. Detailed map of the test site, showing the receiver array layout (passive source survey) and the location of reference borehole.

$$V_s = 129.5N^{0.218}D^{0.098} \tag{2}$$

where N is the SPT blow count (blows/ft), D is depth (meter), and V_S is in m/s.

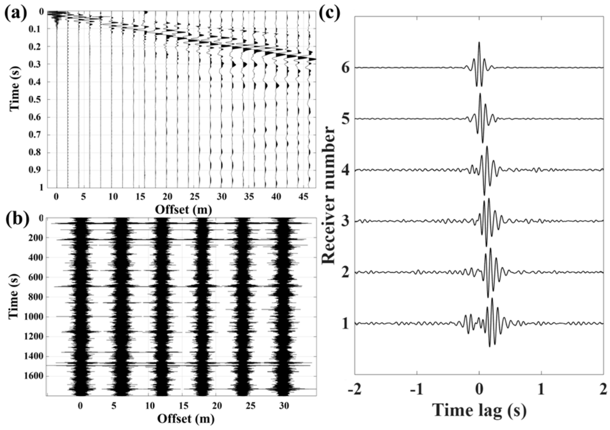

Figure 2. Waveforms of field acquisition data from: (a) Conventional MASW (active source), (b) Original passive source waveform, (c) Cross-correlated waveform.

4 DIRECTIONAL FILTERING, DISPERSION ANALSIS AND INVERSION

4.1 *Directional filtering using MUSIC beamforming*

To identify the dominant DOA of ambient noise, the MUSIC beamforming algorithm was applied to analyze the spatial energy distribution of the recorded signals. The resulting amplitude spectrum is presented in Figure 3. The spectrum spans a frequency range of approximately 4.5–25 Hz, with energy concentrated between 4.5 and 23 Hz, and particularly high amplitudes observed in the 7–18 Hz band. This is interpreted as traffic-induced noises originating from a nearby intersection. To exclude non directional noise generated by environmental factors such as pedestrian movement or activity

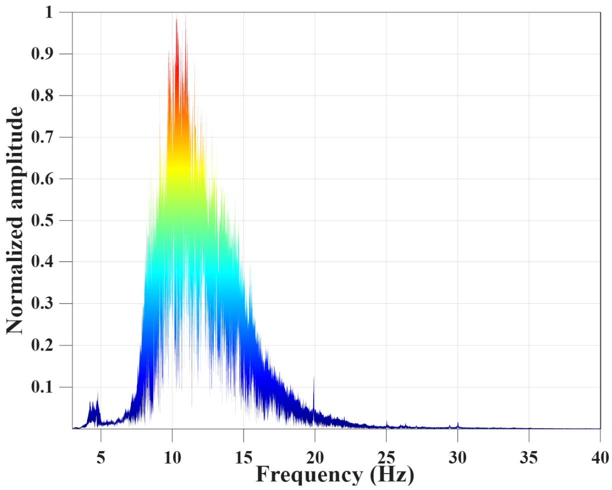

Figure 3. Amplitude spectrum for each trace from the passive source waveform.

on a basketball court, the MUSIC analysis was limited to a refined frequency window of 7–20 Hz. The beamforming results at four representative frequencies 9 Hz, 10 Hz, 16 Hz, and 17 Hz are shown in Figures 4(a), 4(b), 4(c), and 4(d), respectively. In each figure, high amplitude peaks indicate the dominant wave propagation direction and corresponding phase velocity. At 9 Hz and 10 Hz, the wavefronts predominantly arrive from the east to southeast (EW–SE) direction with a phase velocity of approximately 300 m/s, which aligns well with the geophone array orientation and the expected direction of the noise from the intersection. In contrast, at 16 Hz, a separate dominant energy is observed from approximately 140° (between W and NW) with a phase velocity around 200 m/s. Similarly, at 17 Hz, dominant peaks appear near 140° and 180°, corresponding to the northwest (NW) and west (W) directions, also with phase velocities of approximately 200 m/s. These signals are interpreted to originate from another intersection on the opposite side of the target location. Such directional inconsistencies can degrade the resolution of the cross-correlation results. To mitigate this issue, signals arriving within an azimuthal range of 45° to 270° were selectively extracted, and directional filtering was applied prior to dispersion curve construction.

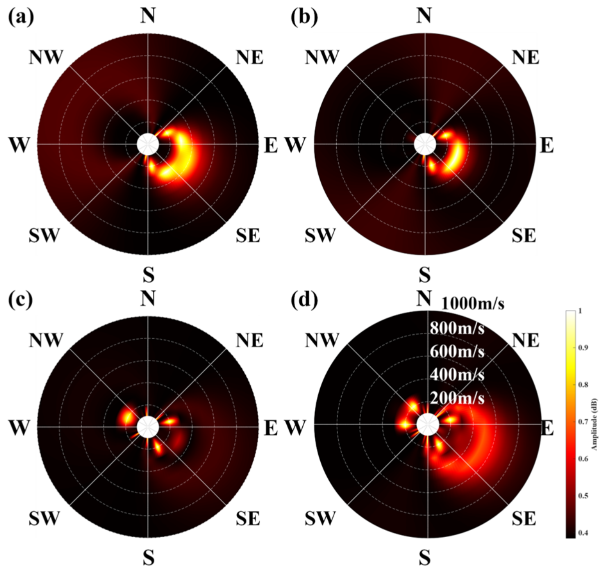

Figure 4. Results of MUSIC Beamforming at the testing site: (a) 9Hz, (b) 10Hz, (c) 16Hz, (d) 17Hz.

4.2 *Dispersion curves*

Figure 5(a) shows the dispersion curve derived from the original, unfiltered cross-correlation data. The curve exhibits poor correlation around 8 Hz and degraded resolution in the 10–20 Hz range due to the inclusion of incoherent signals. In contrast, Figure 5(b), obtained from the directionally filtered signals, shows improved correlation near 8 Hz as well as enhanced continuity and resolution across the entire frequency band. These results demonstrate that MUSIC based directional filtering significantly improves the clarity and reliability of the dispersion image.

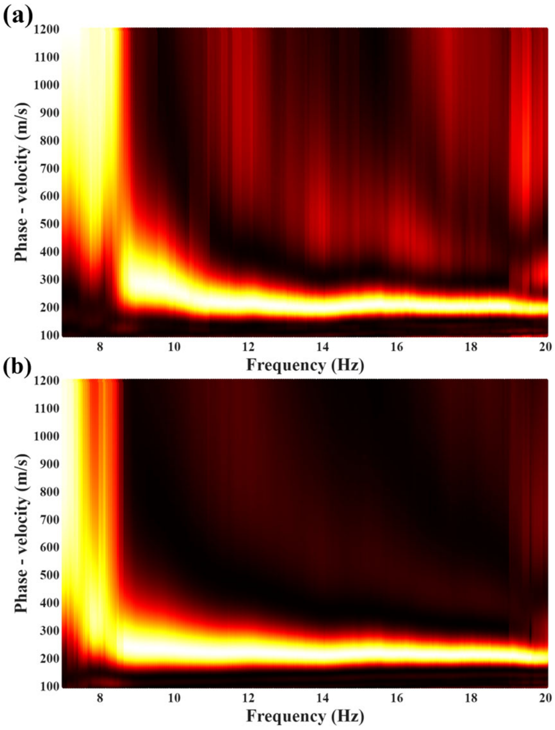

Figure 5. (a) Dispersion curve from original cross-correlation signal, (b) Dispersion curve after directional filtering.

4.3 *Inverted V_S profile*

Figure 6 compares shear wave velocity (V_S) profiles obtained with two surface wave techniques, cross-correlation (red solid line) and conventional MASW (black dashed line) alongside the SPT-derived velocities (blue circles). Both inversions were carried out with a Genetic Algorithm (GA) that started from the same initial subsurface model, comprising fill, two sedimentary soil layers, weathered soil, weathered rock and soft rock. Using identical GA settings and minimizing the misfit to their respective dispersion curves, the two methods yielded similar trends above 10 m, where the MASW profile also aligns reasonably with the SPT data. Below this depth, however, the cross-correlation result delineates the weathered rock interface (~12 m) and the soft rock transition (~13 m) within ±0.4 m of the borehole depths, demonstrating overall better agreement than the MASW inversion. The improved accuracy of the cross-correlation profile is attributed to: Higher signal-to-noise ratio and directional coherence achieved by treating traffic noise as a distributed virtual source. MUSIC-based DOA filtering (45°–270°) enhances dispersion curve continuity in the 7–18 Hz band and guides the GA towards a more stable solution. Even with the same initial model and optimization algorithm, the cross-correlation technique therefore provides better estimate of critical horizons especially the weathered rock and soft rock boundaries while requiring only a compact 6-geophone, 30 m array.

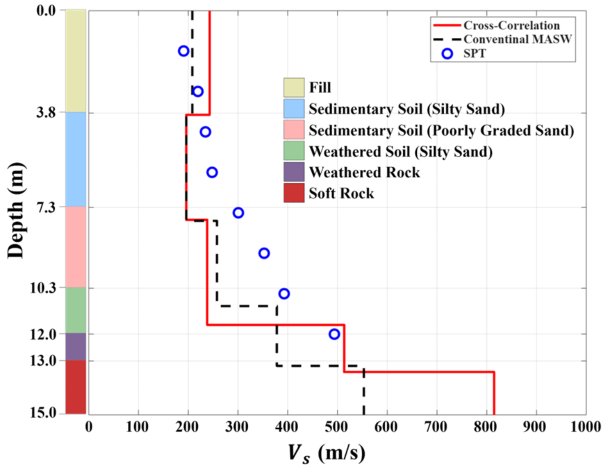

Figure 6. Inverted S-wave velocity profile of Sori Park, Seoul.

5 OPTIMIZING ACQUISITION DURATION

To identify an appropriate acquisition duration that balances data quality and survey efficiency, the mean absolute percentage error (MAPE) was used as an objective cost function for the record-length optimization. First, the full 30 min passive record was taken to derive the reference dispersion curve, D_0. Twenty subsets were then generated by randomly extracting contiguous time windows of a prescribed length, and each subset produced its own dispersion curve, D_r. The MAPE equation is expressed as follows:

$$\mathrm{MAPE} = \frac{100}{N}\sum_{1}^{n}\frac{|D_0 - D_r|}{D_0} \tag{3}$$

Figure 7 summarizes the results for a nominal 30-second time window. Each boxplot displays the inter quartile range (25th–75th percentiles), whiskers span the full non outlier range, red crosses mark statistical outliers, red circles denote arithmetic means, and short red bars show medians. A spline interpolated through the medians of incrementally longer records visualizes how MAPE decays with increasing acquisition time. Setting a target error threshold of 3% and disregarding windows dominated by outliers, the MAPE curve flattens beyond 1500 s (≈ 25 min), indicating that additional recording yields diminishing returns.

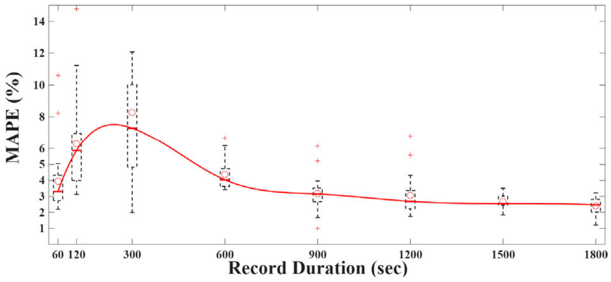

Figure 7. Box plot of MAPE with record length for a time window of 30 s.

Applying the same workflow to other window lengths gives practical guidelines: for 10-second windows, at least 30 min of data are required to stay below the 3% threshold, whereas 20-second windows achieve stable results in 25 min. These findings confirm that a 25-minute survey—well within typical site access constraints—provides statistically robust dispersion information, while avoiding unnecessary field time and data storage in this geological context.

6 CONCLUSIONS

This study proposed an effective passive-source-based geophysical site investigation method for detecting bedrock depth in complex urban environments. In contrast to general approaches that often incorporate unnecessary azimuthal noise thereby degrading the approximation of the empirical Green's function, this study demonstrated that directional filtering based on the identified DOA can significantly enhance waveform coherence and improve the reliability of the retrieved signals. By extracting trace data within a specified azimuthal range, waveforms associated with the dominant noise source were selectively stabilized, leading to the generation of an improved dispersion curve with enhanced resolution and continuity. Subsequently, shear wave velocity profiles were successfully derived through inversion, enabling reliable stratigraphic interpretation. When considering the spatial footprint required for testing and the passive nature of the ambient wavefield, the cross-correlation seismic interferometry method proved to be more effective in detecting bedrock interfaces than the conventional active-source MASW technique. Notably, this approach achieved higher accuracy in delineating the depth to weathered and soft rock layers, confirming its suitability for urban settings where access and active-source deployment are often constrained. Furthermore, the integration of directional filtering and cross-correlation processing contributes not only to improved signal-to-noise characteristics but also to practical applicability in noise dominant environments such as parks, intersections, or densely built-up areas. Overall, the findings of this study validate the cross-correlation based interferometric approach as a reliable and robust alternative for shallow subsurface characterization and bedrock detection, particularly in challenging urban settings with infrastructure constraints.

7 ACKNOWLEDGEMENTS

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