Noise Tomography Based Urban Ground Collapse Monitoring Using Distributed Acoustic Sensing

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LIANG LYU, YOU-WU WANG, JIAN-FU LIN, JUN-FANG WANG and YI-QING NI

ABSTRACT

With extensive development of urban underground space, ground collapses occasionally occur, resulting in property damage, injuries, or fatalities. Therefore, establishing an effective ground monitoring and collapse prevention system is necessary for reducing collapsing risk. Distributed Acoustic Sensing (DAS) technology has great potential for ground collapse monitoring around rail system for capacity of long-distance high-density monitoring and immunity to electromagnetic interference (EMI). In this study, experimental investigations were conducted using a high-performance DAS interrogator integrated with a 4 km-long distributed optical fiber to record background ambient noise inside a subway tunnel. Noise2Noise (N2N) unsupervised denoising model was employed to preprocess the DAS data across different time spans, thereby enhancing the signal-to-noise ratio (SNR). Additionally, noise tomography method in terms of passive multichannel analysis of surface waves (MASW) algorithm was utilized to extract the surface waves and calculate the dispersion curves containing soil layer information Stacking methods, including Phase-Weighted Stacks (PWS) and Generalized Average of Signals (GAS), were applied to further improve the SNR of the dispersion curves. Ultimately, a 2D S-wave velocity model to 45m depth was constructed, revealing low-velocity soil defects such as hollow and settlement. The result demonstrates that integrating DAS with tomographic imaging using urban ambient noise can provide a reliable basis for preventing ground collapse hazards.

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INTRODUCTION

The foundational principle behind seismic tomography is based on the propagation characteristics of seismic waves as they travel through the Earth [2]. Seismic events, whether originating from natural earthquakes or artificial sources, generate wavefields that are altered during their propagate through the subsurface media. These alterations encode critical information about the physical properties of the subsurface, including parameters like P-wave and S-wave velocities and attenuation characteristics [3]. Through the application of sophisticated mathematical and physical models, inversion techniques can extract these physical parameters from seismic data. This process transforms raw field observations into detailed two-dimensional or threedimensional images of underground structures [4]. Such images not only delineate the geometry of subsurface layers but also reveal heterogeneities and anisotropies associated with different geological formations.

Traditionally, high-frequency surface wave methods have relied on active sources (e.g., hammers or vibroseis trucks) to generate seismic waves. Techniques like MASW are subsequently employ to extract phase velocity dispersion curves for inversion [5]. Although these active-source techniques yield high-resolution imaging of the shallow subsurface due to their higher frequency content (ranging from several Hz to tens of Hz), they are often associated with high operational costs and intensive labor efforts. Furthermore, the inherently high-frequency nature of these methods limits their depth of penetration, potentially leading to insufficient imaging of deeper subsurface features that are critical for certain engineering and urban planning applications [6]. Over the past two decades, ambient noise tomography has emerged as a promising alternative, demonstrating successful applications in imaging both crust-mantle and shallow surface structures [8]. This method offers notable advantages over traditional active source approaches, including lower costs, enhanced safety, and improved penetration depth, given that ambient seismic noise typically occurs at lower frequencies [8]. In this study, we investigated the effects of different stacking durations and stacking methods on NCFs derived from ambient noise data collected along a new constructed subway in China. N2N models are first applied to enhance the SNR and inter-channel correlation of DAS signals. Based on the stacked NCFs, we extracted phase velocity dispersion curves through passive source MASW and inverted them to obtain a 2D S-wave profile of the test site. Our results indicate that this method can reliably and effectively estimate the Swave structure of the site, showing great potential for application in urban ground collapse monitoring.

TEST DESCRIPTION

The test site is situated along a subway line in Shenzhen city in China. In this experiment for environmental noise data in terms of ambient micro-vibration collection, DAS was used to record the ambient noise over a three-day period. Data was collected at intervals of 2, 5, and 10 meters with sampling frequencies of 200 Hz and 1000 Hz. Each individual configuration was maintained for 2.5 hours. Additionally, two intersections located approximately 300 and 550 meters from the survey start point, respectively, were identified as consistent sources of environmental noise.

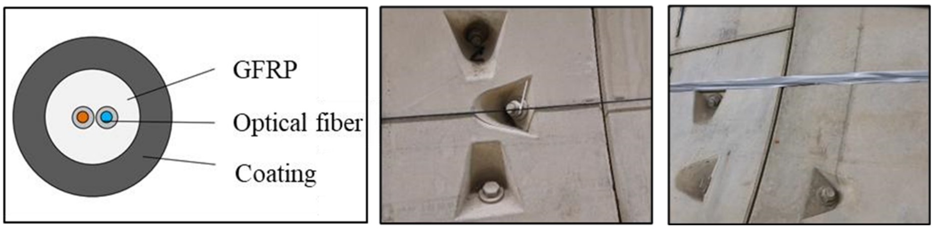

Figure 1. Sensing fiber and fixed method in subway tunnel.

Vibrations caused by construction and human activities, which can be detected by the instruments, were also recorded. Due to the absence of on-site supervision at nighttime, data was only collected during the daytime periods. The detection utilized a custom-designed, high-sensitivity micro-vibration sensing fiber cable. This cable is comprised of sensing optical fiber, glass fiber reinforced plastic (GFRP), and an outer protective sheath, and belongs to a professional-grade interferometric vibration sensing system. The high-sensitivity cable is characterized by its flexibility and exceptional mechanical strength, enabling it to effectively detect subtle external vibrations. It can be directly shallow buried in diverse environments, including grasslands, gravel surfaces, sandy areas, and loose soil. The optical fiber is fixed to both sides of the tunnel wall using cable ties and adhesive tape as shown in Figure 1.

DATA PROCESSING

For DAS, the key advantage of N2N resides in the ability to splice optical fibers within the cable sleeve, enabling the capture of two nearly identical replicas of any external seismic source, each accompanied by its own independent noise [9]. Moreover, continuous recordings provide extensive training sets comprising these independent noisy signal pairs without the need of manual labeling, thus enabling a fully automated approach for any DAS deployment.

Figure 2 illustrates that the raw DAS data are significantly affected by high levels of random noise. Specifically, a vibration occurring around 10000 seconds across the 200-to-400-meter range and at approximately 30000 seconds across the 400-to-700-meter range is nearly completely masked by background noise. However, after applying DAS-N2N denoising, the signal-to-noise ratio is significantly improved, making these vibration signals distinctly detectable.

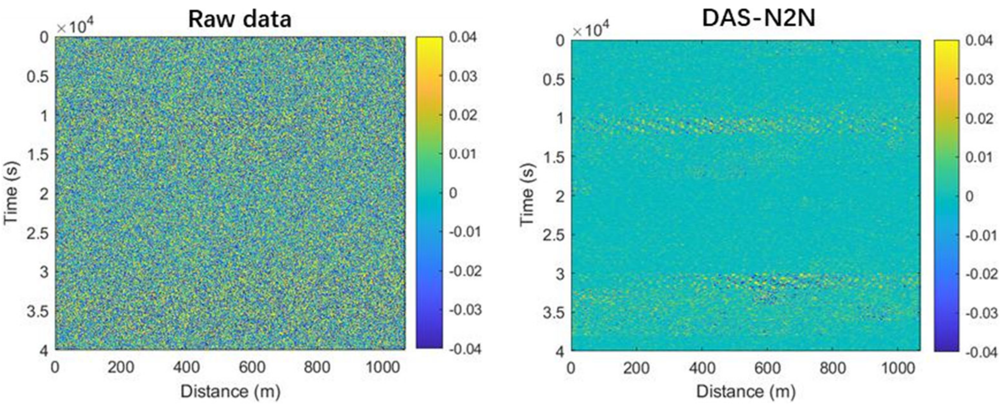

Figure 2. Comparison of DAS data without and with DAS-N2N denoising.

The procedure for extracting cross-correlation functions (CCFs) adheres a well-recognized workflow that has been widely utilized in previous DAS correlation research [10]. In this work, continuous 60-second records were initially normalized in both the time and frequency domains prior to calculating the CCFs. Subsequently, the CCFs were stacked to improve the signal-to-noise ratio of the surface wave signals, thereby generating reliable datasets for dispersion analysis. Furthermore, based on the ambient noise spectral characteristics, only those records band-pass filtered between 2 and 40 Hz were chosen as the normalization reference in the time domain, followed by the application of spectral whitening across this frequency interval.

NCFs are obtained by stacking the CCFs from pre-processed waveform segments recorded between station pairs. The effects of both the stacking duration and the choice of stacking method on the quality of the NCFs were examined in this study. Three stacking techniques including linear stacking, PWS, and GAS method were compared. In linear stacking, all CCFs are directly summed together [11]. The PWS method, however, accentuates the stacking process by leveraging the phase information—signals with similar instantaneous phases receive greater weight, which helps boost coherent signals while diminishing incoherent noise. Meanwhile, the GAS method operates in the frequency domain by averaging complex spectra using the Generalized Average of Complex Numbers (GACN), thereby simultaneously utilizing both amplitude and phase information to enhance coherent signals and suppress noise.

The first column of Figure 3 illustrates the effects of stacking duration and method on NCFs, obtained by cross-correlating virtual source (channel 1) with all other stations using different stacking methods. In addition to linear stacking, surface wave signals can be observed in almost all the stacking results. For short term stacking (1 hour), linear stacking produces NCFs with a low signal-to-noise ratio, thereby complicating the identification of surface wave signals, which are likely due to the relatively poor quality of the vibration signals recorded by DAS. Both the GAS and PWS stacking methods significantly improve the NCF signal-to-noise ratio, with the PWS method providing the most pronounced enhancement. Furthermore, continuous recordings of 5 minutes, 30 minutes, and 150 minutes were separately used for NCFs stacking. As depicted in the second column in Figure 3, a comparison of the resulting cross-correlation functions reveals that the 5-minute stacking already exhibits a certain level of correlation, while the 150minute result is exceptionally clear. The dispersion of Rayleigh surface waves was determined using the MASW technique in combination with the phase shift method. In the frequency domain, the phase difference across channels was computed based on both the phase velocity and the distance between channels. Following the adjustment of the signals from each channel, they were summed to obtain stacking energy corresponding to a specific frequency and phase velocity. For each frequency, the phase velocity associated with the peak stacking energy on the frequency-phase velocity map was selected, which then constructed the dispersion curve. This curve characterizes the S-wave velocity structure beneath the midpoint of the linear channel array.

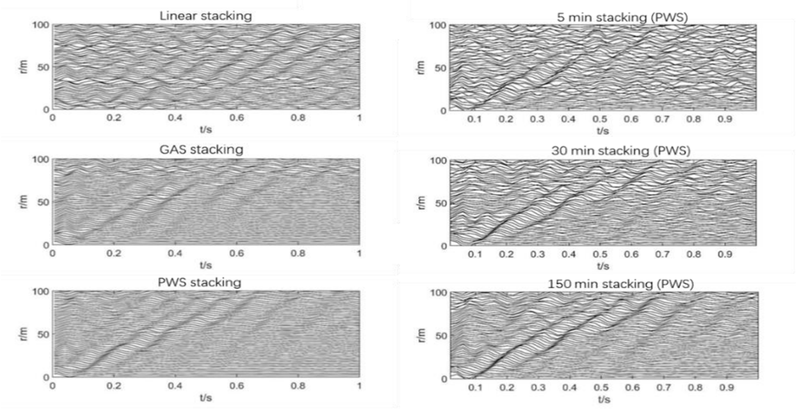

Figure 3. Comparison of the effects of stacking duration and method on NCFs.

Figure 4 presents the surface wave dispersion spectra obtained using various stacking durations. Stacking with durations longer than 30 minutes yield highquality dispersion curves within the 6–15 Hz range, with the 150-minute stacking exhibiting the best quality. In contrast, the 5-minute stack resolves signals only up to approximately 12.5 Hz, and the 1-minute stack is of insufficient quality for reliable dispersion curve extraction. The inversion of dispersion curves is a typical ill-posed problem characterized by strong nonlinearity and lack of uniqueness. The aim is to determine a locally optimal S-wave velocity model that most closely matches the observed dispersion data. To achieve this, a Monte Carlo method was applied to explore the solution space and identify the optimal model. The objective function was formulated as the root mean square error (RMSE) between the observed and synthetic data. The synthetic dispersion data can be forward-modeled using fast delta matrix algorithms available in open-source software packages such as Computer Programs in Seismology or disba [12].

In addition to S-wave velocity, parameters such as layer thickness, density, and P-wave velocity also affect the dispersion data. Given the relatively high uncertainty associated with low-frequency data, as shown in Figure 4, dispersion data with frequencies above 6 Hz was used for inversion when available. Based on the extracted dispersion curves, the phase velocity at 6 Hz was estimated to be approximately 500 m/s, corresponding to a wavelength of about 85 m. Previous studies indicate that the detection depth for surface waves in shallow structures is typically between 0.5 and 0.67 times the wavelength, which limits the reliable inversion depth to around 45 m [13]. The layer thickness was set at 4 m, which is twice the channel spacing. Moreover, the P-wave velocity and density were estimated using empirical formulas, and they were adjusted simultaneously with updates to the S-wave velocity model during the inversion process.

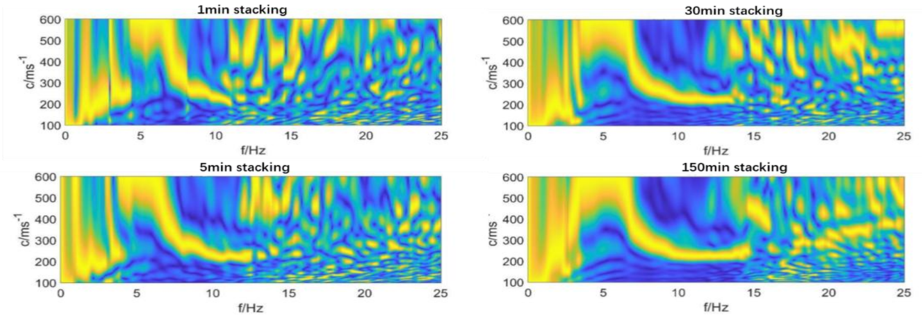

Figure 4. Comparison of the effects of stacking duration on dispersion spectrum.

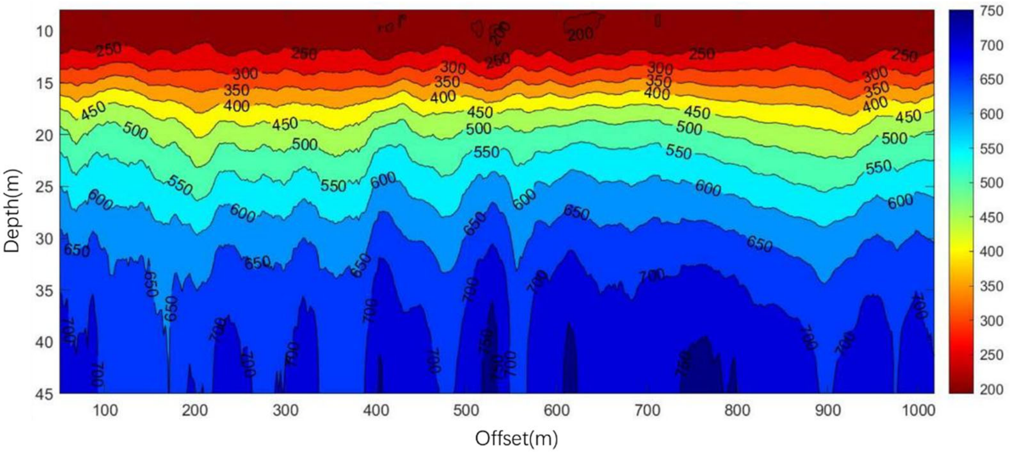

Figure 5. 2D S-wave velocity profile obtained based on one-dimensional inversion results.

Consequently, a two-dimensional velocity profile was constructed by combining all the one-dimensional velocity models, thereby providing a more comprehensive analysis of the subsurface structure. The complete 2D velocity profile is assembled from all 1D models, as illustrated in Figure 5. Prior to construction, rigorous pre-construction geological surveys were conducted to ensure that the site conditions are favorable and stable. These assessments confirmed that the geological environment is robust, with no potential risks such as water-filled cavities or karst zones, which could otherwise lead to surface subsidence. The results of this test further validate the expected stability; the final model shows significant lateral homogeneity. Consequently, the test section of the subway route was demonstrated to have a geologically stable foundation, thereby significantly mitigating the potential risks associated with construction-induced geological hazards.

CONCLUSION

A seismic ambient noise observation experiment was conducted using DAS in Shenzhen, Guangdong Province, China. Pre-processing the DAS data with the N2N model can effectively improve inter-channel correlation and remove interference signals. By analyzing the continuously recorded ambient noise data, high-quality NCFs can be obtained. For this short-term stacking (2.5 hours), various weighted stacking methods (e.g., GAS, PWS) effectively improves the SNR of the NCFs, with the PWS method yielding the best results. Subsequently, a multi-channel surface wave analysis was then employed to extract Rayleigh wave dispersion data in the 6–15 Hz frequency range. Through a comprehensive inversion of the one-dimensional S-wave models, a two-dimensional S-wave velocity profile reaching a depth of 45 meters was developed. This study demonstrates the feasibility of shallow S-wave tomographic imaging using ambient noise data, providing reliable prior information for engineering construction, urban underground space utilization, and infrastructure disaster prevention monitoring.

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