Optimized passive seismic interferometry for bedrock detection: A Singapore case study

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Summary

We present a case study of passive seismic interferometry in the city of Singapore to investigate the bedrock depth and to determine the optimal acquisition parameters. The ambient-noise field, dominated by urban traffic noise, is recorded passively for seismic interferometry. We demonstrate that the bedrock depth can be determined from ambient seismic noise within an error of 2 m compared with borehole logs. Both synthetic and field data analysis show that the optimal array size for the passive site investigation can be as short as 30 m with 6 vertical geophones, to resolve a 1-D shear wave velocity profile of 50m in depth. Convergence of the cross-correlograms shows that the minimum acquisition time for ambient-noise acquisition is about 15 mins in a typical working day. Success of this case study demonstrates that accurate near-surface site investigation can be achieved with faster acquisition, fewer receivers and smaller acquisition footprint, all of which improve the efficiency particularly in a highly developed urban environment.

Introduction

Near-surface site investigation is fundamental and critical to various underground developments such as tunnels and caverns. Conventional borehole surveys perform intrusive site investigation with large areal requirements and long investigation duration. Conventional near-surface site investigation is performed by drilling of boreholes or cone penetration test (CPT) (Schmertmann, 1978). In Singapore, several cases reported by Zhao et al. (1995) and Goh et al. (2012) that the boreholes are drilled every 50 m to 200 m along the proposed underground developments, with the depths up to 60 m. Drilling a borehole requires vacant land which can be accessible to place the drilling equipment. Actual drilling of a 50 m deep borehole may take from 3 days to more than a week.

Due to their non-intrusive nature, passive surface-wave methods have gained increasing popularity recently. Aki (1957) proposed a method of spatial autocorrelation (SPAC) to process the signals acquired from ambient-noise. Okada and Suto (2003) introduced the microtremor array measurements (MAM) and applied SPAC to estimate shear wave velocity. Hayashi (2008) further explained the MAM and recommended to place the receivers in a 2D circular, gridded or triangular array, assuming that the direction of the ambient-noise is unknown. Moon et al. (2017) applied the MAM by using SPAC to estimate the bedrock depth and weathering degree in Singapore with the resolution of 5 m. However, these methods require many receivers to be placed in a 2D array, which requires a quite large empty site for array installation.

Conceptually similar with SPAC, another way of using ambient-noise is seismic interferometry. Under the assumption of homogeneous uncorrelated sources, the Green's function between two receivers can be approximated by crosscorrelating the recorded ambient-noise. The approximated Green's function is equivalent to the wavefield recorded at one receiver while an impulsive source acting at the other receiver (Claerbout, 1968; Wapenaar, 2004; Chang et al., 2016). A few past studies on seismic interferometry are based on large and dense arrays. For example, Nakata et al. (2011) reports a 1D shear wave velocity profile produced from an array with over 200 receivers in a linear array of more than 2km long in Japan. Recently, the introduction of distributed acoustic sensing (DAS) uses the optical fiber to acquire the ambient-noise, in lieu of geophone. Dou et al. (2017) and Huot et al. (2017) reported the success derivation of 1D shear wave velocity profiles of 70m from hundred meters of fibers. Chang et al. (2016) construct a tomographic map of group velocity for Long Beach, California.

We focus on seismic interferometry of surface-wave and demonstrate that the bedrock depth can be determined from ambient seismic noise within an error of 2 m compared with borehole logs. We are also motivated reduce footprint and duration of field acquisition, which will make passive surface-wave more attractive and long-term monitoring possible. We conduct both synthetic and field data analysis and show that the optimal array size and acquisition duration for the passive site investigation can be as short as 30 m with 6 vertical geophones with 15 mins recording to resolve a 1-D shear wave velocity profile of 50m in depth.

Field acquisition

The site location is shown in Figure 1(a). The site is in the central of Singapore Island. The location is near a junction of two major roads, which are always busy. The underlying geology of the area is Bukit Timah Granite Formation, one of the four major geological formations in Singapore. It was formed in early to middle Triassic (250-235 million years ago). It consists of predominantly granite. The granite

rock of Bukit Timah Granite Formation is recognized as base rock as it underlies all other formations in Singapore.
An 'L' shape array with 11 4.5Hz vertical geophones has been deployed on site in Apr 2017. The corner receiver coincides with a pre-drilled borehole. Figure 1 (b) shows the details of the array configuration. The array length of each leg is 30m with a 6m interval between adjacent receivers. Passive seismic data are recorded for half an hour started at 10:20 am and ended about 10:50 am. The temporal sampling rate is 2ms.

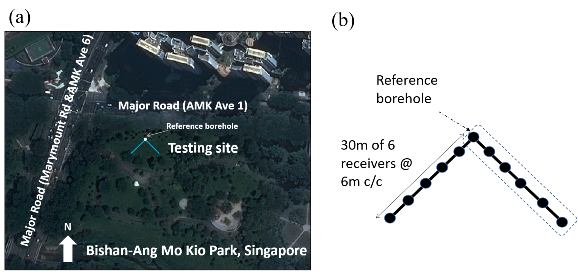

Figure 1: Site location and array configuration: (a) site location, and (b) array configuration.

Results

Direction of Arrival of Ambient-noise
To estimate surface-wave velocity accurately by seismic interferometry, it requires either the ambient-noise is normally distributed around the entire azimuth or the receivers are in line with the principal direction of the ambient-noise. Therefore, it is important to determine the direction of arrival (DOA) of the ambient-noise for acquisition design. As a popular technique, Multiple Signal Classification (MUSIC) is used to estimate the DOA of the surface-waves with multiple frequencies (Kirlin, 1992; Godara, 1997) .

Figure 2 shows the map view of the MUSIC spectrums for different frequencies. The angular of the polar axis is the ambient-noise azimuth while the radial axis indicates the phase velocity of the planewave. The ambient-noise is from north/north-west to south/south-east. The energy is spreading boarder azimuths in low frequency, i.e., 5 Hz and 6 Hz shown in Figure 2(a) and (b). The DOA get narrowed and more concentrated in high frequency, i.e., 7 Hz and 10Hz shown in Figure 2(c) and (d). The phase velocity is decreasing from low frequency to high frequency. The dominant phase velocity at 5 Hz is from about 500 to 900 m/s. It reduces from 400 to 600 m/s at 6 Hz. It subsequently reduces and converge about 200 m/s as frequency increases. With above, the DOA is in generally north/north-west to south/south-east, which is consistent with the road layout at the site location. Resolution of the DOA seems decreasing as frequency goes higher due to the noise source distribution. Velocity dispersion can be seen from serial of beamforming results as illustrated in Figure 2.

Crosscorrelation, Dispersion and Inversion
One leg of the 'L' shape array coincides with the principal DOA as shown in the dashed box in Figure 1(b). These 6 receivers are selected for signal processing. In seismic interferometry, Green's functions can be estimated by turning a reference receiver as the virtual source through crosscorrelation within a short time window. Figure 3(a) shows the original ambient-noises in the first 20s window. Setting receiver No. 6 as the reference, crosscorrelation between the other receivers with the reference one is calculated with moving 20s windows that have 50% overlap. The resulting correlograms are then stacked to enhance the signal-to-noise ratio for the retrieved Green's functions. The estimated Green's functions are shown in Figure 3(b). The dispersive feature can be seen clearly. With the estimated Green's functions, dispersion analysis is carried out by phase shift method. Figure 3(c) shows the phase velocity spectrum. The white dots are the maxima of the semblance at each frequency, which connect to the phase velocity dispersion curve. We observe typical trends such that 1) the phase velocity converges to a low velocity value at higher frequencies, 2) there is a cut-off low frequency associated with high phase velocities, below which the phase velocity spectra are contaminated with instabilities and noisy picks. The low and high frequency/phase velocity combinations determine the reliable minimum and maximum wavelengths, which are about 11~15 m and 180~200 m, respectively. Therefore, the shallowest detectable depth and achievable resolution is about 4~5 m, and the maximum detectable depth may be up to 60~67 m, which is about twice the array length.

Genetic algorithm is used for the dispersion curve inversion. In Figure 4(a), the black solid line is the shear wave velocity profile obtained from the inversion analysis with the best fit of the dispersion curves. The measured and inverted dispersion curves are shown together in Figure 4(b). A good agreement can be observed between 6 and 20 Hz. To determine the bedrock depth for near surface site investigation, we use a cutoff shear velocity of 800 m/s and obtain an accurate estimation within a 2m misfit compared with the borehole log at this site.

Optimal Acquisition Parameters
Other than bedrock depth detection, this case study is also used to investigate the optimal acquisition parameters to achieve stable dispersion inversion result with the smallest array and the shortest duration. The resulting parameters are not only important for efficient site investigations, but also meaningful for spatial and temporal resolution studies for continuous passive monitoring.

A synthetic dataset is created to model planewaves with the same dispersion characteristic in Figure 4(b). Figure 5(a) shows the theoretic waveforms of the planewaves in 6 traces, the identical setting of the actual field acquisition. With the theoretic waveforms, dispersion analysis is carried out. The dispersion spectrum is shown in Figure 5(b), with the picked maxima in Cyan circles. The input dispersion curve is superimposed as white dash line. From the synthetic model, it confirms that a short array (30m for this case) can achieve stable dispersion spectrum with large wavelength (high velocity and low frequency). Parametric study is carried out for other array lengths; the dispersion curves are plotted together with the theoretic one in Figure 5(c). It shows that the 30m-long array achieves the desired accuracy for the dispersion inversion. To quantify the trend, the Mean Absolute Percentage Error (MAPE) between the true dispersion curve and the estimated dispersion curve with different array length is plotted in Figure 6(a). It is evident that arrays that are longer than 30 m fit the theoretical dispersion curve within 3% MAPE.

To determine the optimal acquisition duration, we test the inversion results using real experimental data of various durations. Figure 6(b) is the plot of the resulting MAPE for various acquisition durations. It shows that a passive seismic acquisition as short as 900 (15 mins) would be sufficient to fit the theoretical curve within 3% error. This result is significant to improve the productivity of one-time measurement for site investigation, and meaningful for long-term continuous monitoring. Each 15 to 20 mins, an accurate and stable dispersion curve can be generated and stored. The raw data record of past 15 to 20 mins can be erased or heavily decimated thereafter, which enables a feasible data management solution for the long-term continuous monitoring in an urban environment.

Discussion and Conclusions

Our case study suggests that urban ambient-noise is dominated by traffic noise, which suggests an optimal linear acquisition array orthogonal to the major road in the study area. However, the DOA of ambient-noise may not be consistent throughout the band of frequency of interests, or throughout different acquisition time. In these cases, a two-dimensional array with even azimuthal coverage is needed to obtain accurate phase velocity for each frequency. Otherwise, the phase velocity may be overestimated due to the uneven distribution of the ambient-noise. Secondly, our case study also suggests a shorter than usual array length of 30m. Minimum array length may vary for other near surface geological conditions. However, the availability of such a clear site is still subject to actual site condition, which is jointly constrained by the DOA. This may limit the applicability of the passive seismic methods in fully developed areas due to site constraints. Thirdly, since seismic interferometry makes use of the far-field ambient-noise for Green's function estimation, the near-field irregular excitements and activities, such as pedestrian footsteps and high amplitude pump noise, would degrade the reliability of estimation. Therefore, keeping the receivers undisturbed is an important but highly difficult task in an actual field application.

This paper presents a case study of applying seismic interferometry for near-surface site investigation in urban areas of Singapore. We demonstrate that aligned with the DOA of the ambient-noise, an optimized field acquisition (a short linear array of 30 m, with 6 receivers and a fast acquisition of 15 minutes) would be sufficient to achieve an accurate and stable dispersion curve, thereafter a reasonable shear wave velocity profile. The shear wave velocity profile can be used to indicate the subsurface layers, especially to locate the bedrock depth, which is significant for near-surface site investigation in practice.

Acknowledgments

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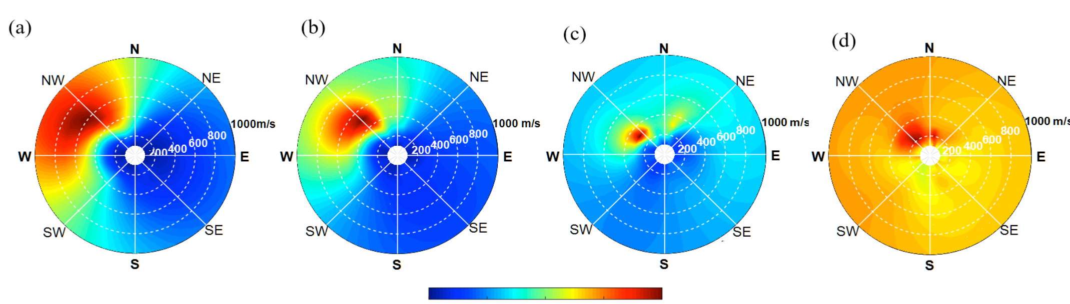

Figure 2: Beamformer output: (a), (b), (c) and (d) at 5, 6, 7 and 10 Hz respectively. The angular and radial axes are ambient source azimuth from the array corner and seismic phase velocity (m/s), respectively.

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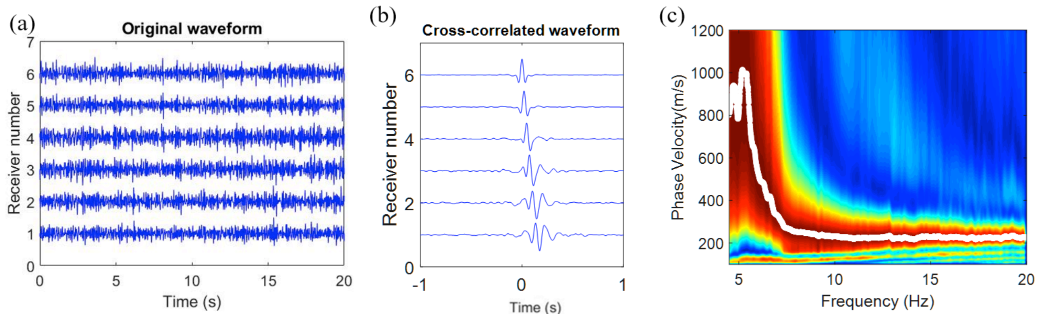

Figure 3: (a) Original measured waveform in 20s windows, (b) estimated Green's functions, and (c) dispersion image, White dots on the images denote the maxima that represent the dispersion curve.

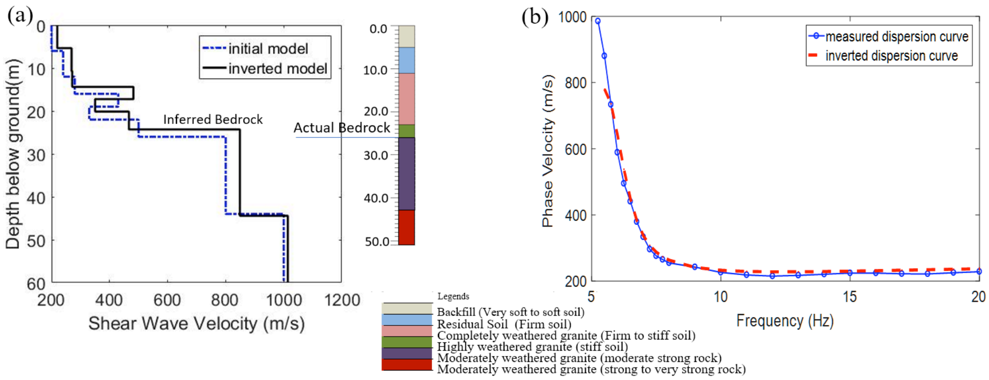

Figure 4: (a) Shear wave velocity profile obtained after inversion of dispersion curve and bore log from the borehole at the center of the array. (d) Measured and inverted dispersion curve.

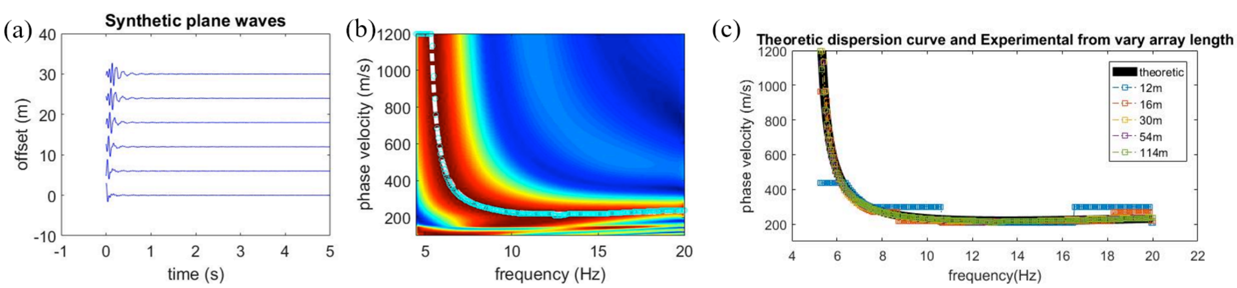

Figure 5: (a) Synthetic waveforms of the plane waves with the dispersion characteristic in Figure 4(b), (b) dispersion image based on Figure 5(a) gather. Cyan circles are the picked maxima, while the theoretic dispersion curve is superimposed as the white dash line, and (c) parametric study result of the dispersion curves from arrays with different length.

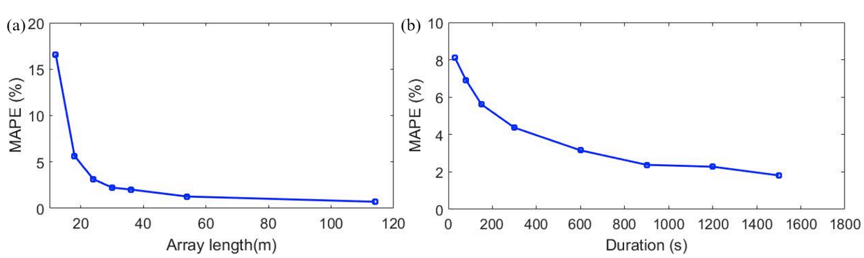

Figure 6: Mean Average Percentage Error (MAPE) between the theoretical dispersion curve and the measured dispersion curve from arrays of various (a) array lengths (using synthetic data) and (b) acquisition durations (using experimental data).