Deep bedrock detection based on ambient noise recorded by a short geophone array: A Singapore case study

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Summary

The city-state of Singapore sits on the granite bedrock called Bukit Timah formation. Due to the NW-SE oriented Nee Soon fault, the Bukit Timah granite is buried deeply (100–300 m) below the Old Alluvium sediments on the east part of Singapore. We present a case study of detecting the deep bedrock using urban ambient noise recorded by a short array. The passive seismic recordings contain significant amount of low frequency signals, which are mostly originated from the coastline, as well as high frequency signals from urban traffic and anthropogenic noise. Empirical Green’s functions obtained from the ambient noise show a clear separation in direction between the low frequency surface wave and high frequency body wave at the test site. The inverted shear wave profile from the surface wave dispersion not only matches the borehole log for the bedrock depth, but also reveals a hard sediment sandwiched between the soft sedimentary layer. By investigating the convergence of the dispersion curves, we find out the best compromise of cost, efficiency and accuracy at this site can be achieved in 20 min using an array of 105 m to detect the granite bedrock around 100 m deep. Our study demonstrates that accurate bedrock investigation can be achieved with faster acquisition, fewer receivers, and passive seismic sources, all of which improve the feasibility of a geophysical survey particularly in a highly developed urban environment.

Introduction

Information of bedrock depth is very important to fields such as hydrology, ecology, soil mechanics, and geology engineering (Anbazhagan et al. 2009). Thus, estimation of bedrock depth attracts continuous interests from geoscientists. Reflection and refraction seismic method can provide us the structural information based on P-wave velocity (Schmelzbach et al. 2005, Sheng et al. 2006). However, due to the “blindness” of refractions to slow formations and the limited resolution of the P-wave data, seismic reflection and refraction methods cannot resolve near-surface structure to the desired requirements of geological and civil engineers. Moreover, in the densely populated urban area, strong active sources with long geophone arrays for reflection and refraction measurements are not always feasible.

Alternatively, surface wave measurements are commonly utilized to resolve shear wave velocity and the near-surface structures. Both the active source and passive source surface wave analysis can provide us the shear wave velocity structure with higher resolution compared with P-wave data. Among the active surface wave methods, multichannel analysis of surface waves (MASW) is widely used for estimation of shear wave velocity profiles of soil sites (Park et al. 1999, Xia et al. 1999). By converting the time-space domain (t-x) data to frequency-velocity domain (f-v) for the dispersion analysis (Shen et al.2015), 1D and 2D shear wave velocity profiles can be obtained from inversion. However, when the target layer is buried deep (over 100 m), the low frequency energy generated by an active source is not sufficient to provide information with good signal-to-noise ratio.

Recent passive seismic survey studies in urban environments demonstrate that low frequency surface waves can be effectively retrieved from the ambient urban noise (Park et al. 2006, Cheng et al. 2015, Zhang et al. 2018). For the passive surface wave method, ambient noise from traffic and environment are used as the source. Using seismic interferometry, approximated Green’s functions that are often dominated by Rayleigh and Love waves on land can be obtained (Snieder et al., 2006, Wapenaar et al. 2010). Due to non-intrusive nature and relatively large detection depth, passive seismic imaging has attracted increasing applications in urban environments. Nonetheless, existing studies on passive seismic often require a large 2D array that records for months before information can be extracted at greater depth.

In this case study, we demonstrate that the bedrock depth of 120 m can be effectively detected based on ambient noise recorded for 20 min using a linear array of similar length of 105m. Comparing the estimated Green’s function from the ambient noise with the active seismic record at the same site, we noticed that both surface wave and body wave are effectively reconstructed after seismic interferometry.

Data Processing

Our passive seismic data processing flow can be divided into four principle parts following Bensen (2007).

Data preparation: This step includes removing instrument response, bandpass filter, notch filter, one-bit normalization and spectral whitening to remove instrument response and to broaden the frequency spectrum.
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Short window cross-correlation and stacking: In this step, we retrieve Green’s functions by cross-correlating recorded ambient noise within chosen time windows in frequency domain:

\[
G(x_2, x_1, \omega) = \sum_{i=1}^{N} U(x_2, x_i, \omega)U^*(x_1, x_i, \omega)
\]

Where \(U(x_2, x_1)\) stands the wavefield excited at \(x_1\) and received by the receiver \(R2\) at the location \(x_2\), \(U^*(x_1, x)\) is transpose of the complex conjugate of the wavefield excited at \(x_1\) and received by the receiver \(R1\) at the location \(x\). The cross-correlation of observations at two receivers gives the response between the two receivers where \(R2\) can be regarded as a virtual source. The cross-correlograms of all short time windows (\(N\)) are stacked together to improve the signal-to-noise ratio of the estimated Green’s function.

Dispersion curve estimation: We use frequency-domain slant-stack to transform the time-space domain Green’s function to a phase-velocity spectrum. Dispersion curve can be obtained by tracing the maximum value through this phase velocity map.

Dispersion curve inversion: For getting the shear wave velocity and estimate the information of depth to bedrock, an inversion procedure based on particle swarm optimization (PSO) is applied in our work. PSO is a population based evolutionary optimization and had been applied for getting optimal compromise solutions in engineering (Shao et al. 2017) and geophysical data inversion (Shaw et al. 2007, Song et al. 2012).

Field data

The Singapore island is composed of three main geological formations: sedimentary rocks (the Jurong Formation) in the south and south-west, igneous rocks (the Bukit Timah Granite) in the north-central part, and the Quaternary sediments (the Old Alluvium) in the east. There are also granite intrusions at Chandi and Pulau Ubin (Figure 1a). Our study area belongs to the Quaternary sediments. In this area, log data shows that the depth to bedrock vary from 80-200 m and it gets deeper from north to south (Pitts et al. 1984).

We conducted experiments in the northeast coast of Singapore (Figure 1(b)). The region is a densely populated area and has a well-developed transportation system including highways, local roads, railroads, Changi airport and Paya Lebar Base. The survey line is parallel to a local canal and perpendicular to the coastline and a highway. The array is 100 m away from the northern shoreline and 400 m away from the highway in the south. A variable salinity plant locates in the southeast of the line; direct distance from the line is about 400 m. There exists a pre-drilled borehole in the east side of the survey line about 330 m away, which provides us the geological information of this area and benchmarks our shear wave inversion result. A linear array of 24 vertical-component geophones was deployed at 7.5 m interval. The measurements are conducted from 19:05-22:11, so the surroundings are relatively quiet, providing good signal especially for low-frequency ambient noise. To compare with the empirical Green’s function, active seismic experiments with a sledgehammer were also conducted.

Figure 1: (a) geological map of Singapore. Red star stands for the survey area, (b) map of the survey site: red line indicates the survey array, R01 indicates the 1st geophone and R24 indicates 24th geophone. Red dot indicates the position of borehole.

Figure 2: (a) Active seismic recording of 4 seconds, and (b) Passive seismic recording of 3 hours.

Both the active and passive data are collected with the same array. The active data were recorded for 4 seconds after a sledgehammer trigger. The passive data were recorded for 3 hours. The active data (Figure 2(a)) show a clear separation between the slow, low-frequency surface wave and the fast, high-frequency body wave. The passive data, on the other hand, are not interpretable in its raw recordings.

Figure 3 compares the average spectrum of the active seismic data in (a) with that of the passive data in (b). It is evident that although the sledgehammer creates a wide
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spectrum that centered round 40 Hz, the active seismic data are rather weak at the low frequency band below 10 Hz. In contrast, the passive seismic data are dominated by the low frequency signals, which enable high-fidelity surface wave inversion with deep penetration depth.

The phase velocity spectrum is calculated by slant stack in the frequency domain. Figure 4 shows the phase velocity spectra of the active seismic data. In the high frequency band (40-120 Hz), non-dispersive body wave around 2000 m/s can be clearly identified. In the intermediate frequency band (15-40 Hz), multimodal dispersion can be observed. A zoom-in view in the low frequency band (<8 Hz) is shown in Figure 4(b) highlights the dispersion of the fundamental mode. The dispersion curve is shown as dash line by picking the maxima on the phase velocity spectrum. Nonetheless, due to the weak signal-to-noise ratio, the resolution below 2.5 Hz is unsatisfactory.

Figure 3: Average frequency spectrum of (a) active seismic data and (b) passive seismic data.

Figure 4: Phase velocity spectrum of the active data (a) shown for wide frequency range and (b) zoomed in to the low frequency range.

We use the 24th geophone (offset at 0 m) as the virtual source and perform cross-correlation on the ambient noise to retrieve the empirical Green’s function in Figure 6. Two distinct wave trains can be observed. At positive lags, a slow, low-frequency wave train propagates from the 24th geophone to the others in the south. At negative lags, a fast, high frequency wave train propagates from the 1st geophone to the others in the north. This clear distinction in directionality indicates that most of the low-frequency ambient noise is from the coastline, where as the high frequencies from the in-land urban area. Moveout of the slow wave and fast wave roughly agrees with the active seismic data (Figure 2(a)). Although it is common to see accurate reconstructions of surface waves from ambient seismic data, such clear and accurate reconstruction of the fast, body-wave-like waves is rarely reported in the literature.

Figure 5: Empirical Green’s functions retrieved by cross-correlating the ambient noise recordings.

Figure 6: Phase-velocity spectrum of the estimated Green’s function (a) at the high frequency range, and (b) at the low frequency range.

Figure 6 shows the phase velocity spectrum of passive data. In the high frequency band (8-37Hz), a dispersive curve with a high velocity of 2000-4500m/s can be identified. The velocity corresponds well with the wave velocity in negative time lag of Figure 5. The dispersive curve has
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similar characteristic with surface waves but in a much high velocity and frequency. The wave is known as guided wave and consist of postcritical reflections and refractions where the deeper layer has a faster velocity than the one above it (Li et al. 2018). Due to the existence of guided waves, it can be concluded that there exists a high-speed interlayer underground. A zoom-in view in the low frequency band (<8 Hz) is shown in Figure 6(b) highlights the dispersion of the fundamental mode. Compared with Figure 4(b), the dispersion curve observed from passive data is much more reasonable in low frequency range (<2.5Hz).

A randomly selected 20min data with an array length of 105 m (15 traces) is used for dispersion curve calculation. Shear velocity inversion is performed by fitting the modeled dispersion curve with the picked one. We focus our attention on inversion results of fundamental-mode dispersion curves for layer thicknesses and surface wave velocities by fixing P-wave velocities and densities. After 100 iterations, observed and modeled dispersion curves are almost perfectly overlapped (Figure 7(a)). Compared with the borehole log 330 m east to the array, the inverted shear velocity structure agrees well with the local sedimentary geology, which indicates a strong sedimentary layer sandwiched in between a weak sedimentary layer. This unusual geological condition may be the reason for the clear distinction between the high frequency body wave and the low frequency surface wave shown in Figure 3(a) and Figure 5. Especially at the depth of 20m, there is a 16m high-speed sandwich layer in our inversion result. It is maybe the reason for existence of guided waves in Figure 6(a).

The inversion result indicates that the bedrock depth in this area is 125 m from the best fitting model, which is reasonable and satisfactory estimations of the benchmarking bedrock depth of 118 m from the borehole log (Figure 7(b)).

**Conclusions**

In this study, we demonstrate that deep bedrock (> 100 m) investigation can be achieved using passive seismic survey in an urban environment like Singapore. Compared with active seismic methods, passive seismic survey acquires more abundant low frequency signals, most likely from the ocean waves, which generate high-resolution phase velocity spectra for low frequency surface wave inversion. The high frequency ambient noise contributes to the distinct body wave reconstruction at this site, which is rarely reported in ambient noise imaging. Based on a quantitative test, we suggest an optimal array length of 105 m and an optimal duration of 20 min to achieve the balance between efficiency and accuracy required by practicing engineers. The surface wave inversion result confirms again that a short array of length L can effectively detect subsurface structure buried within the depth of O(L).

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