Near-surface bedrock profiling using urban ambient noise: An autocorrelation approach

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Summary

We present a field case study to introduce an autocorrelation approach for near-surface bedrock mapping using urban ambient noise. The autocorrelogram of each long recording approximates the impulse response of a zero-offset seismic experiment. Through the case study, we demonstrate that the proposed method can fine tune the autocorrelograms to achieve super-resolution both laterally and vertically. Compared with engineering boreholes, the estimation error of bedrock depth from ambient noise is within 3 m. Calibrated with two or more boreholes, we can estimate a realistic average P-wave velocity of the soil layer based on the travel time picks on the autocorrelograms. Compared with conventional crosscorrelation-based ambient noise approach, the proposed method does not require simultaneous acquisition, involves less computational efforts, and extracts bedrock information from reflected P-waves.

Introduction

Different communities may have different definitions of bedrock, e.g., engineering bedrock and seismic bedrock. Here, we focus on engineering bedrock. It is more commonly used in earthquake and civil engineering. Unlike seismic bedrock, the engineering bedrock refers to the shallow rock mass which may have less than 1000m/s of shear wave velocity. Seismic bedrock refers the interface of upper crust which may have 3000m/s or above of shear wave velocity. Engineering bedrock can be seen as an outcrop and at as deep as 50 m below ground (DSTA 2009; Zhao et al. 1995). Engineering bedrock mapping is conventionally performed by drilling boreholes to directly recover the soil and rock core samples. Site investigation using boreholes would be time consuming, costly, invasive and always subject to site conditions. Hence, near-surface geophysical surveys, such as seismic reflection/ refraction, multichannel analysis of surface waves, micro-tremor array measurement, attract an increasing attention in practice thanks to their low cost, high efficiency in spatial coverage, and minimally invasive nature.

Among the many geophysical surveys, passive seismic methods are the least intrusive. They make use of existing urban ambient noise to extract a near-surface shear wave velocity profile, which leads to efficient mapping of the engineering bedrock (Subramaniam et al. 2019; Zhang et al. 2019). Most of these passive seismic methods are fundamentally based on the interferometry theory, where cross-correlating long continuous ambient noise at two receivers results in approximated Green's function between these two receivers. When recorded on land, the approximated Green's function is dominated by surface waves, leaving the low amplitude body waves undetectable from the cross-correlograms.

When the distance between two receivers approaches zero, the crosscorrelation becomes autocorrelation. The auto-correlograms approximate the recordings of zero-offset experiments. Claerbout and Black (2005) pointed out that by autocorrelating the data of hours and days duration we convert the chaos of continuing microseismic noise to something that might be the impulse response of the earth. So from the autocorrelation we might be able to draw conclusions in usual ways, alternately, we might learn how to make earth models from autocorrelations When the vertical geophone recordings are used for autocorrelation, the resulting signal can be directly interpreted as reflected P-waves (Ito and Shiomi 2012; Saygin et al. 2017; Taylor et al. 2016). Not only has the autocorrelation technique the potential to image deeper sections of the subsurface, but it also alleviates the requirement of simultaneous recordings across all stations by the crosscorrelation methods.

In this abstract, we present a case study of utilizing urban ambient noise for engineering bedrock detection based on the autocorrelation approach. With the help of a couple of reference boreholes, we propose to map out the depth profile of the bedrock based on the time differences measured on the processed autocorrelograms and an estimated P-wave velocity. The resulting engineering bedrock estimation lies within +/-3m for multiple sites where pre-drilled boreholes can be used to validate the proposed approach. The average P-wave velocity can be reasonably estimated as well.

Method

During passive seismic monitoring, receivers are installed on the ground and record the ambient noise simultaneously or separately at different stages. For each receiver, the recorded ambient noise $U(x_i, t)$ is a time (t) series. Its autocorrelation is approximately equivalent to a zero-offset seismic trace, which can be expressed by the classic convolution model. This is shown in Equation (1):

$$U(x_i, t) * U(x_i, t) \approx w(x_i, t) \otimes r(x_i, t) \otimes e(x_i, t) \qquad (1)$$

where $U(x_i, t)$, $w(x_i, t)$, $r(x_i, t)$ and $e(x_i, t)$ are the original ambient noise record, source signature, receiver signature, and reflectivity at x_i receiver, respectively. The symbol '$*$' is for crosscorrelation and '$\otimes$' for convolution. Note that the reflectivity time series $e(x_i, t)$ also include reflectivity from multiple reflections.

The 1st step of the proposed method is using Equation (1) to individually obtain the autocorrelograms for each trace. Before moving on to subsequent steps, we need to simplify the problem by making two realistic assumptions. First is for the term of source signature $w(x_i, t)$. It is reasonable to assume the source signature is identical within a certain area, so long as the ambient noise is recorded in a similar period of the day. The second assumption is identical and negligible receivers' effect. This would be realistic, if the installation of each receiver is done by experienced personnel. With these two assumptions, the two terms $w(x_i, t)$ and $r(x_i, t)$ in Equation (1) can be rewritten as $w(t)$ and $r(t)$.

A simple two-layer reflection coefficients $\hat{e}(x_1, \omega)$ can be estimated based on the average velocity and the boundary of soil and bedrock. Thereafter, the coupled signature of source and receiver can be estimated based on the autocorrelograms of the recordings at one of the borehole locations.

$$\hat{w}(\omega)\,\hat{r}(\omega) \approx \frac{U(x_1,\omega) * U(x_1,\omega)}{\hat{e}(x_1,\omega)} \quad (2)$$

where $\hat{w}(\omega)\,\hat{r}(\omega)$ is the approximated coupled signature of source and receiver in frequency (ω) domain. $U(x_1, \omega)$ is the recorded ambient noise trace at either of the two reference borehole locations in frequency domain. $\hat{e}(x_1, \omega)$ is the reflectivity in frequency.

Assuming the coupled signature of source and receiver from Equation (2) is identical for all receivers, we derive the reflectivity at other receiver locations by the following deconvolution:

$$e(x_i, \mathrm{t}) = \mathrm{F}^{-1}\hat{e}(x_i, \omega) = \mathrm{F}^{-1}\frac{U(x_i,\omega) * U(x_i,\omega)}{\hat{w}(\omega)\,\hat{r}(\omega)} \quad (3)$$

where $\mathrm{e}(x_i, \mathrm{t})$ is the reflectivity in waveforms at x_i receiver, and $\hat{e}(x_i, \omega)$ is its frequency form. 'F^{-1}' denotes the inverse Fourier transform operator. $U(x_i, \omega)$ is the recorded ambient noise trace in frequency domain from x_i receiver.

With the reflectivity waveforms obtained by Equation (3), the peaks of the waveforms are deemed to represent the engineering bedrock in time domain. At least two reference boreholes are needed to estimate an overburden P-wave velocity and to map out the bedrock depth from the time domain reflectivity. With the difference of actual engineering bedrock depth from the two reference boreholes $(d_1 - d_2)$, and the two-way travel time difference $(t_1 - t_2)$ as indicated as the first peak in reflectivity waveforms, a representative average P-wave velocity $\bar{V}$ can be calibrated:

$$\bar{V} = \frac{2\,(d_1 - d_2)}{t_1 - t_2} \quad (4)$$

Assuming that the overburden layer above the bedrock is homogeneous, we use the same calibrated average P-wave velocity (Equation (4)) for other receiver locations at the same site, despite the thickness of sediments. The engineering bedrock depth at other receiver location d_i can be estimated by Equation (5) as:

$$d_i = d_1 + 0.5\bar{V}\,(t_i - \mathrm{t}_1) \quad (5)$$

Field acquisition

We present an example in Singapore. Figure 1 shows the site location, layout of the receiver array, location and the measured bedrock depth of reference boreholes. The site is in the western region of Singapore, as indicated by the blue arrow in the left corner map of Figure 1. The field testing was at a road junction where there are 4 reference boreholes. There were 19 receivers of 4.5 Hz geophones installed as shown in white dots. Trace #1 and a group of Trace #2-#19 were acquired on different dates but similar time in each day, which supposing similar ambient noise sources from urban environment, such as traffic, nearby daily activities, etc. The distance between Trace #1 and #2 is about 77 m, and the spacing of the group of traces from #2 - #19 is about 4 m. Trace #1, #2, #9 and #19 coincide with the 4 reference boreholes. Noise acquisition lasted for about 32 minutes on each day.

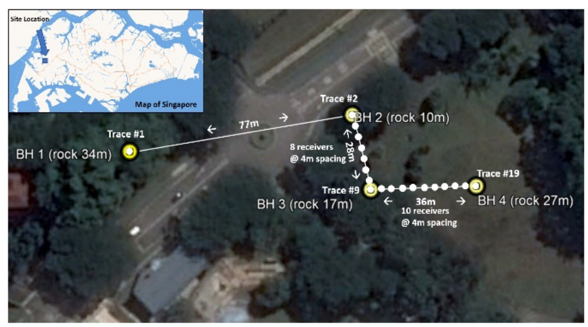

Figure 1. Site location and receivers' layout plan.

Results

As shown in Figure 1, there are 4 reference boreholes available on site. we could choose any two out of the 4 reference boreholes. We present the case of choosing BH #2 and #3 as reference. The raw record of ambient noise is firstly normalized trace by trace, as shown in Figure 2. It is apparent that Trace #1 and the rest traces were recorded at different time, which makes the conventional array-based passive seismic processing infeasible. No coherent information can be retrieved by cross-correlating the inconsistent waveforms.

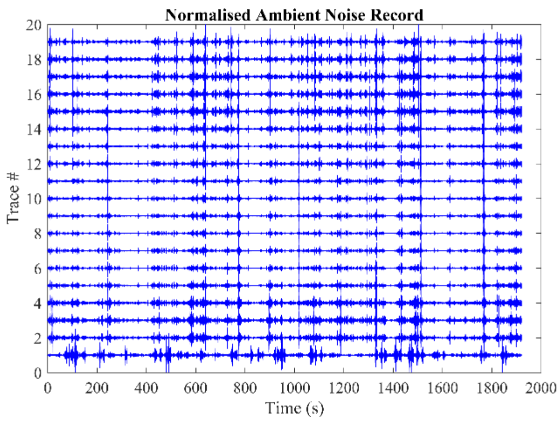

Figure 2. Normalized waveforms of raw ambient noise.

BH#3 is selected to estimate the reflectivity model in time domain as its location coincides with Trace #9. We assume a simple 2 layer (soil and rock) model for this case. To work out the reflectivity coefficient, we assume the P-wave velocity of 1500 m/s and 3000 m/s; density of 1900 kg/m^3 and 2400 kg/m^3 for soil and rock layer, respectively. Based on the borehole, the bedrock top is 17m below ground level there. With these, a sparse two-layer reflectivity model is shown in Figure 3.

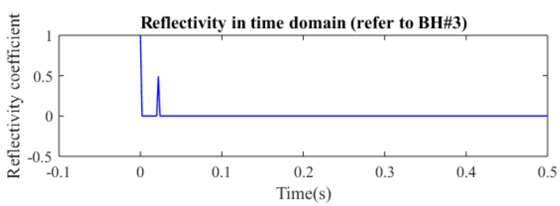

Figure 3. Input reflectivity referring to BH#3.

At BH#3 location (Trace #9), we plot the spectrum of raw waveform, autocorrelogram and the estimated source & receiver signature respectively in Figure 4. Though the peak frequency is all around 15 Hz, fine tuning changes still can be seen. It presents the tuning process regarding how the frequency spectrum is reshaped by the proposed method from the raw waveform to the estimated source & receiver signature, which is assumed to be identical and to derive the reflectivity waveforms for other traces.

With the estimated signature of source & receiver as shown in Figure 4(c), the reflectivity waveforms are derived for all traces. The image of reflectivity waveforms is shown in Figure 5 from BH#2 (Trace #2) to BH#4 (Trace#19), where the receivers are as close as 4 m apart from each other. The first peaks are strong and continuously laterally, as highlighted by the white dots and a dash line in Figure 5. Based on the 2-layer assumption, we believe the first strong event represents the soil-bedrock interface. It is inferred that the engineering bedrock is dipping from BH#2 towards BH#4. It also indicates that there might be a minor fault or folded layer at BH#3 location, as there is a relatively larger drop of the reflectivity in time domain.

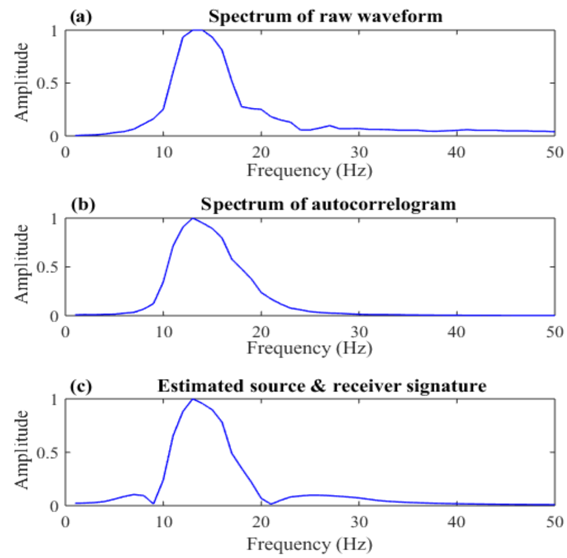

Figure 4. Normalized frequency spectrum at BH#3, from: (a) raw waveform, (b) autocorrelogram and (c) estimated source & receiver signature.

Besides the apparent first peaks, other interesting events are also shown in the reflectivity image in Figure 5. For example, we can see another event before 0.15 sec at BH#2 and extending laterally towards BH#4 around 0.2 sec, with amplitude dimming between BH#2 and BH#3. The shape of this event is similar as the first peak. Hence it may be one of the multiples. Furthermore, near BH#2 location, there is another event around 0.2 sec, which extends to BH#3 with a different shape from the first peak. This event is more likely to contain certain information of a deeper and stiffer layer. Unfortunately, we do not have any deep-borehole information to investigate it at this moment. Nevertheless, we see the potential to reconstruct deeper earth model by the proposed method.

With the known bedrock depth at BH#2 and BH#3, and the time difference from the first peaks of the reflectivity waveforms, an average P-wave velocity of the soil layer is estimated as 1700 m/s. The engineering bedrock depths are estimated at each trace location and plotted as the stars shown in Figure 6. The four measured bedrock depths from boreholes are shown as red circles. The estimated bedrock profile is shown as the dash line, by directly connecting the stars from BH#2 to BH#4, as the trace interval is as close as 4 m. However, since the BH#1 is 77m away to BH #2, the bedrock profile in-between is not interpreted. The bedrock varies from about 10 m to 30 m at this site. The estimate error is within ±3 m at BH#1 and BH#4, which sits in the acceptable range for engineering applications. As indicated earlier in the time domain, there is a minor fault about 10 m elevation difference of the bedrock around BH#3 location. This is expected in this region of the Jurong Formation of Singapore geology, a sedimentary formation that is featured with interbedded folds.

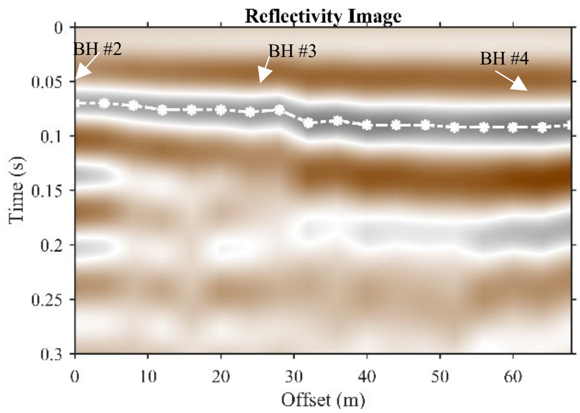

Figure 5. Image of estimated reflectivity at each trace, white dots are 1st peaks and connected by white dash line.

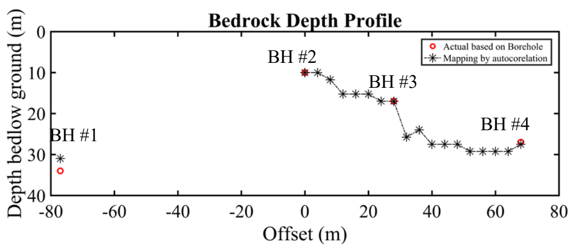

Figure 6. Estimated bedrock depth (black stars) with actual bedrock depth (red circles), and interpreted bedrock profile (dash line) from Trace #2 (BH#2) to Trace #19 (BH#4).

Besides the above field testing, we conducted another 4 field testings in the western sedimentary region of Jurong Formation and 5 testings in igneous rock of Bukit Timah Granite Formation, in the northern and central part of Singapore. Each two available reference boreholes can estimate the average P-wave velocity of soil layers once. Based on the available reference boreholes, we have obtained estimates of P-wave velocity on 10 different sites. Generally, based on the mini database from the 10 sites, the average P-wave velocity of soil layers varies spatially. A boxplot is presented in Figure 7 for both Jurong and Bukit Timah Granit Formations. Though the maximum and minimum values vary a lot, the P-wave velocity are mainly distributed within a same order of magnitude, based on the 25th and 75th percentile shown in the two blue boxes. The median values are also similarly as about 1600 to 1700m/s as shown in the red lines. It is reasonable since the soil layers above the engineering bedrock is mainly composite of backfill material and residual soils, despite of different geology.

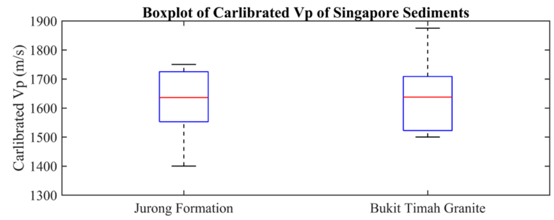

Figure 7. Boxplot show basic statistics of the average P-wave velocity of soil layers for the two major geology in Singapore.

Discussion and Conclusions

Noted from the results presented above, the achievable vertical resolution is up to 10 m. However, the wavelength is about 110 m, based on the peak frequency of 15 Hz and the estimated P-wave velocity of 1700 m/s. The achieved super-resolution is beyond the common rule that the vertical achievable resolution of a quarter of wavelength. The proposed method, as demonstrated through this field testing, fine tunes the frequency spectrum progressively. It also takes the advantage of two reference boreholes to derive a realistic average P-wave velocity of soil layer. With the tuning process, we achieve the vertical super resolution by identifying the peaks of the waveforms.

Unlike other passive seismic surveys which mostly rely on crosscorrelation and surface wave inversion, the proposed method does not require simultaneous acquisition. It also requires less computational efforts. The horizontal resolution is not limited by the half of wavelength rule. Its flexibility allows the engineers to design site investigation with a small acquisition footprint and to utilize all available data efficiently.

The proposed autocorrelation-based approach can be jointly conducted with the crosscorrelation-based approach. In this event, both P-wave and S-wave velocity can be derived, thereafter the Poisson's ratio. These would be even more useful for practicing engineers to solve their real engineering problems.

In summary, the proposed method fine tunes the autocorrelograms of ambient noise to achieve a super vertical resolution. It has several advantages than a crosscorrelation based approach but can't derive S-wave information. With the crosscorrelation test together, more useful information can be derived for engineering applications.

Acknowledgments

We acknowledge Singapore MOE Tier-1 Grant R-302-000-165-133 and Singapore Land Transport Authority (LTA, Award Number R-302-000-164-490; PI- Dr. Taeseo Ku) for their financial support.