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

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SEG19 SAN ANTONIO, TX 15-20 SEP 2019 INTERNATIONAL EXPOSITION 89TH ANNUAL MEETING

INTRODUCTION

Challenges :

- Near-surface bedrock may vary from a few meters to a few tens of meters underground.
- Civil engineers' common practice for bedrock profiling is drilling boreholes.
- Because of strict regulations in an urban environment, non-invasive geophysical surveys are demanded to complement boreholes drilling.
- Civil engineering projects require very high resolution of a few meters both vertically and horizontally.

Background:

- Interferometry theory turns continuous ambient noise to empirical Green's functions by cross-correlating any two receivers' recordings.
- To the extreme, crosscorrelation becomes autocorrelation.
- Claerbout [1985] 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".
- Some recent studies showed the feasibility to retrieve P-wave reflection and image deep earth structure by autocorrelating microseismic noise [Ito and Shiomi, 2012; Saygin *et al*., 2017 and Taylor *et al*., 2016].

TUNING PROCESS

Autocorrelation of ambient noise

- Based on the idea of Claerbout [1985], autocorrelation of ambient noise $U(x_i,t)$ can approximate a zero-offset seismic trace.
- It follows the convolution model and can be expressed as:

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

where $w(x_i,t)$: source signature, $r(x_i,t)$: receiver signature, and $e(x_i,t)$: reflectivity.

Assumptions

- Source signature is identical within a certain area: $w(x_i,t) \rightarrow w(t)$.
- Identical and negligible receivers' effect: $r(x_i,t) \rightarrow r(t)$.

Required prior knowledge

- Bedrock depth from a reference borehole is required to estimate a two-layer reflection coefficient $\hat{e}(x_{\text{ref}},\omega)$.

Coupled signature of source and receiver

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

Approximated reflectivity

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

Time to depth conversion

- Require another reference borehole to estimate average velocity of soil layer.

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

where d_1 and d_2 are bedrock depths based on the two reference boreholes.

- Bedrock depths at other traces can be estimated:

$$d_i = d_1 + 0.5\bar{V}\,(t_i - t_1) \quad (5)$$

FIELD CASE STUDY

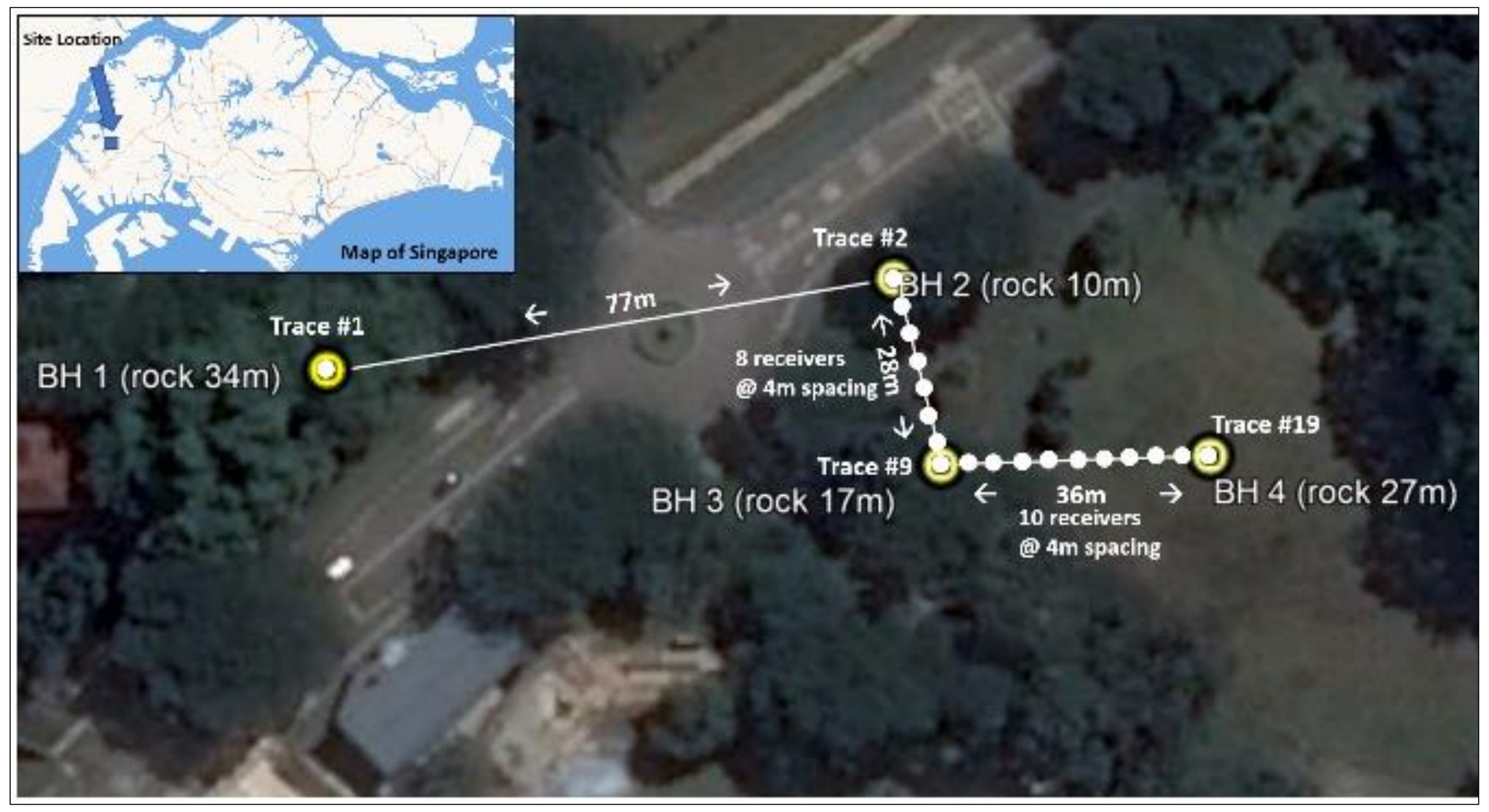

***Figure 1**. Site location and receivers' layout plan.*

- Receiver: 4.5 Hz vertical geophones.
- Record length: approx. 40 mins.
- #1 was acquired separately from others.
- #2-#19 were acquired simultaneously.
- Both acquisitions were in weekday mornings.
- 4 boreholes available on site.
- Bedrock depths vary from 10 to 34m.
- Site location: a turf ground in campus near a road cross junction.
- Traffic is overserved as a major component of the ambient noise.

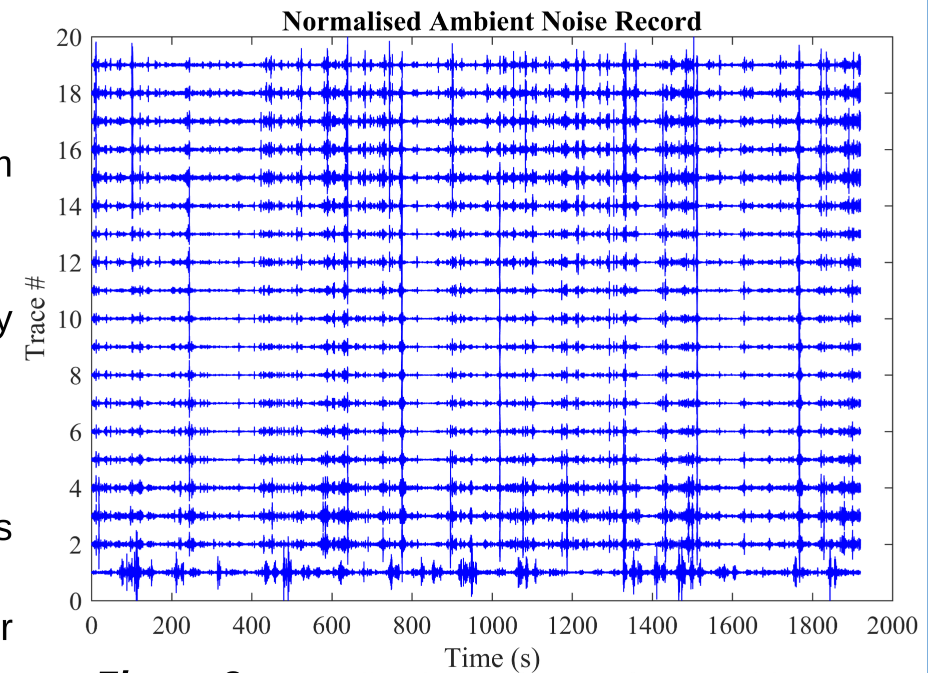

***Figure 2**. Normalized waveforms of raw ambient noise.*

RESULTS

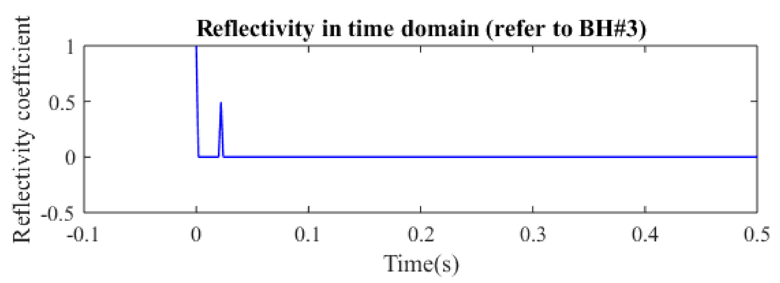

***Figure 3**. Input reflectivity referring to BH#3.*

- A reflectivity assumed referring to BH#3 (Trace #9).
- Coupled signature of passive source and receiver estimated from Trace#9.
- Fine-tuning process can be observed in spectrum from raw ambient noise, via autocorrelogram, to coupled signature.

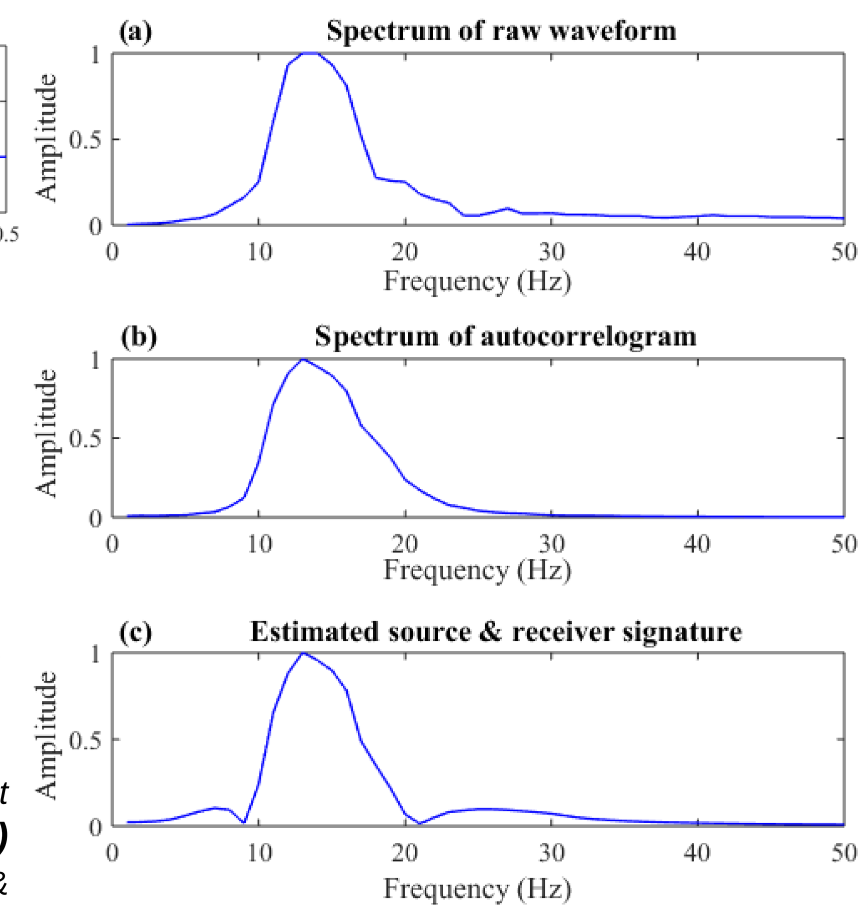

***Figure 4**. Normalized frequency spectrum at BH#3, from: **(a)** raw waveform, **(b)** autocorrelogram and **(c)** estimated source & receiver signature.*

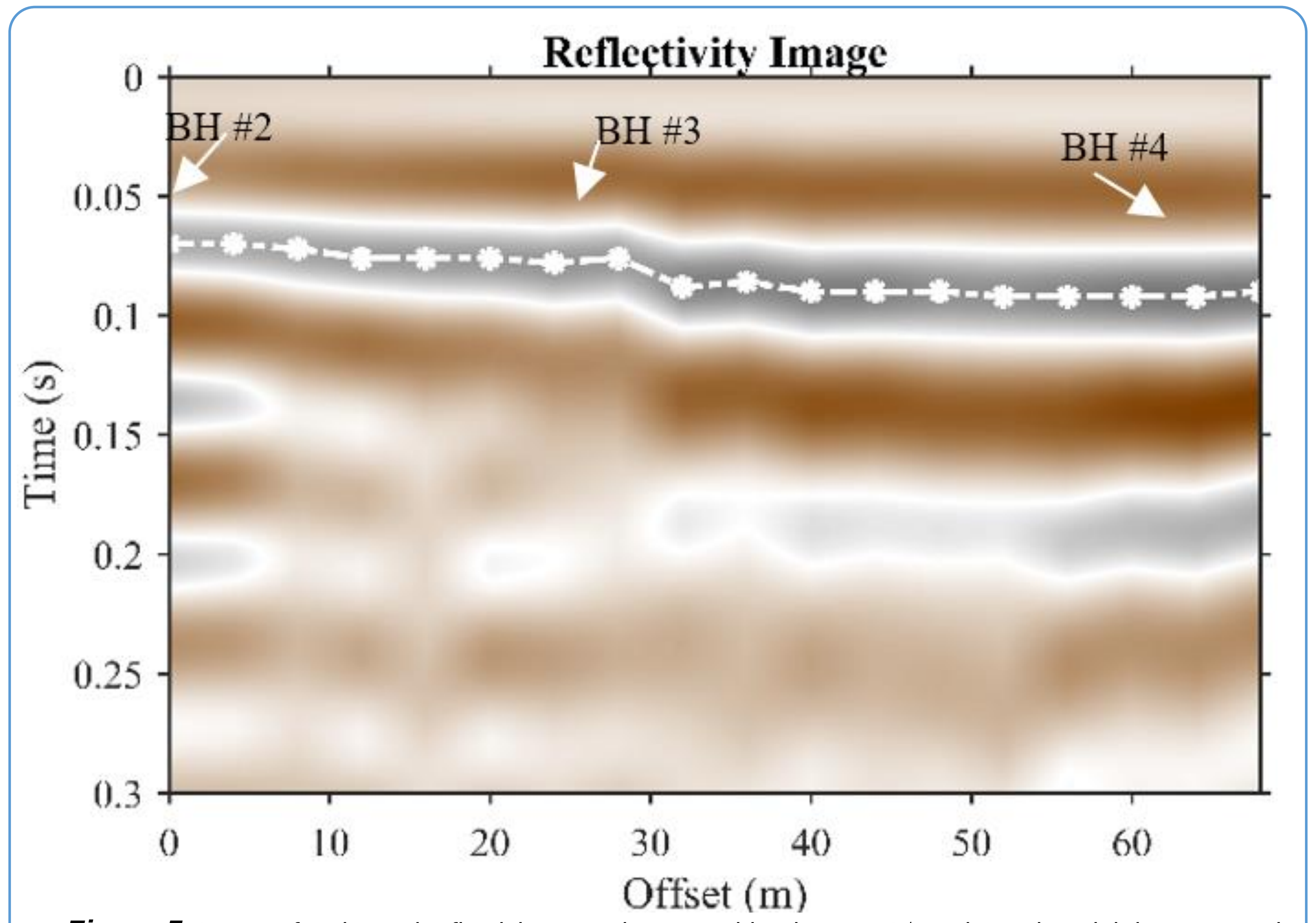

***Figure 5**. Image of estimated reflectivity at each trace, white dots are 1st peaks and straightly connected.*

- Fine tuned reflectivity image shows soil/rock interface.
- Based on BH#2 and BH#3, average velocity is approx. 1.7 km/s.
- With estimated velocity, bedrock depth profile shows agreement with boreholes, and a minor fault around BH#3.
- Another 9 field tests carried out in Singapore. Estimated average soil velocity within similar range.

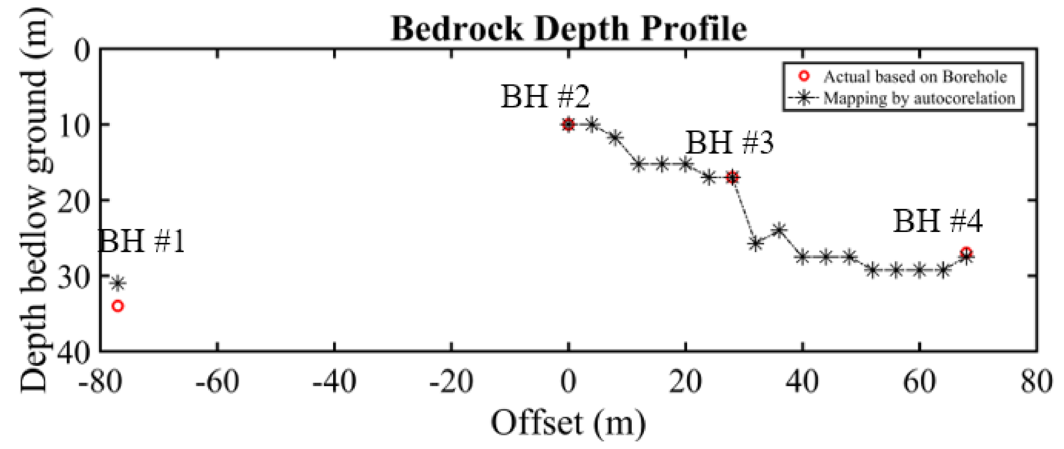

***Figure 6**. Estimated bedrock depth (black stars) with actual bedrock depth (red circles), and interpreted bedrock profile (dash line) from Trace #2 (BH#2) to Trace #19 (BH#4).*

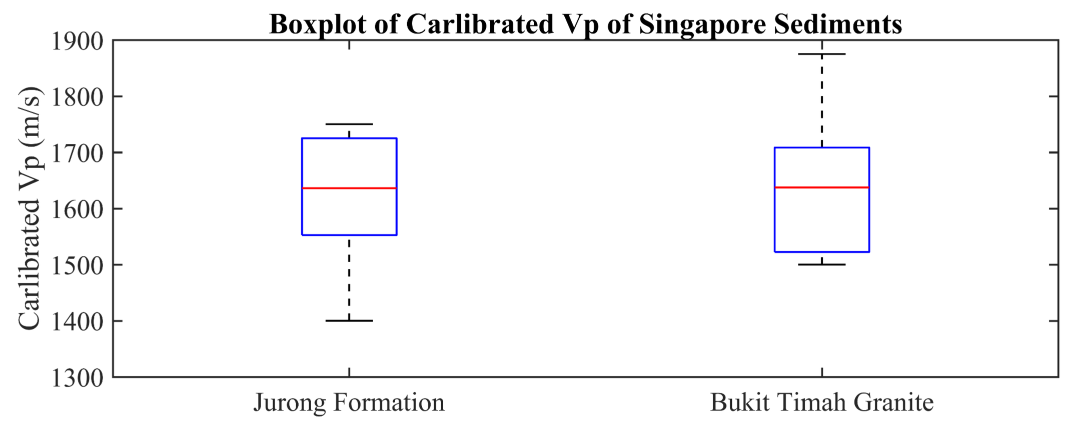

***Figure 7**. Boxplot show basic statistics of the average P-wave velocity of soil layers for the two major geology in Singapore*

SUMMARY

- It is a tuning process for autocorrelation of urban ambient noise.
- Case studies in Singapore demonstrate achievable vertical resolution, with aid of reference boreholes.
- Average velocity of soil layer can be estimated with any two traces at reference boreholes.
- Further investigation to establish better understanding of ambient noise autocorrelation.

ACKNOWLEDGEMENT

We would acknowledge the EDB Petroleum Engineering Professorship and Singapore Ministry of Education Tier-1 Grant R-302-000-165-133.

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