A new method based on seismic interferometry for reducing surface-wave noise in seismic data

Chaiwoot Boonyasiriwat and Jaroon Sinsawasmongkol

ABSTRACT

A new method based on seismic interferometry is presented for reducing surface-wave noise in land seismic data. This method is much simpler than the conventional interferometric method previously proposed. The efficiency and effectiveness of our method is shown by the application to land data acquired in a north-east area of Thailand.

INTRODUCTION

Surface waves are evanescent wave that propagates along a free surface of a medium. In the case of seismic wave, two types of surface waves, Rayleigh and Love waves, occur due to the interference of body P-waves and S-waves. Rayleigh wave is generated by the interference of P-wave and SV-wave while Love wave is generated by the interference of P-wave and SH-wave. Rayleigh wave or usually called groundroll is the surface wave that is recorded by geophones recording vertical ground motion. In seismic exploration, the vertical-ground-motion data or seismograms (vertical particle displacement, velocity, or acceleration) are usually used in seismic reflection data processing to obtain an image of the Earth's subsurface structures. In this situation, primary reflections are normally the signal while the other events including direct waves, refractions, multiple reflections, and surface waves are considered as noise.

Land seismic data are usually corrupted with strong surface-wave noise which, therefore, is the main noise that must be removed to enhance the signal-to-noise ratio of seismic reflection data and to prevent any artifacts due to the noise in the seismic section obtained after data processing. Many methods to reduce the surface-wave noise have been proposed in the past decades. Among these methods seismic interferometry (Halliday et al., 2007, 2010; Xue et al., 2009; Xue, 2010) is one of the efficient methods that can be applied even when there is an aliasing issue of surface-wave events in the data. The key idea of the seismic interferometry method for reducing surface-wave noise is to first create a prediction of the noise by cross-correlating data traces, and then to adaptively subtract the predicted noise from the data. The signal-to-noise ratio of the prediction is improved by stacking predicted traces from many common shot gathers from various source positions. This simple idea can become quite complicated to implement into a compute program that can be universally applied to any seismic data set.

In this work, we propose a new method based on seismic interferometry that is much simpler than the previously proposed method. The key improvement of our method is that the prediction of surface-wave noise in a common shot gather (CSG) can be obtained by processing the same CSG using cross-correlation and convolution of data traces. Therefore, the proposed filtering method can easily be applied to any data set. The efficiency and effectiveness of the method is shown in the application to a land data set acquired in a north-east area of Thailand.

In the next section, we briefly describe the conventional seismic interferometry method for predicting surface-wave noise. Then, the new method is presented in the consecutive section. Numerical results are then shown with a discussion followed by a conclusion.

CONVENTIONAL SEISMIC INTERFEROMETRY METHOD FOR PREDICTING SURFACE-WAVE NOISE

Consider a surface wave propagating from a source at s_1 to receivers at g_1 and g_2 as shown in Figure 1. The time-domain surface-wave event recorded at g_1 and g_2 are denoted as $d(g_1|s_1)$ and $d(g_2|s_1)$, respectively, where their frequency-domain counterparts are denoted as $D(g_1|s_1)$ and $D(g_2|s_1)$. Using the high-frequency approximation and ignoring amplitude factor, the surface-wave data in

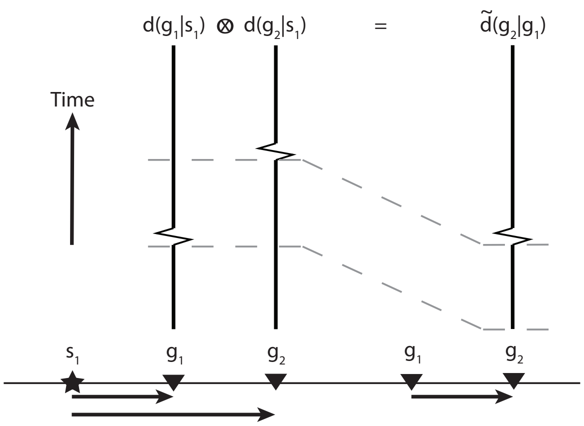

Figure 1: The key diagram that demonstrated how seismic interferometry (cross-correlating two data traces) can be used to predict surface wave propagating from position g_1 to g_2. (For more details, please see the text.)

the frequency domain can be represented by

$$D(g_1|s_1) = e^{i\omega\tau_{s_1 g_1}}, \tag{1}$$

and

$$D(g_2|s_1) = e^{i\omega\tau_{s_1 g_2}}, \tag{2}$$

where $\tau_{s_1 g_1}$ and $\tau_{s_1 g_2}$ are the traveltimes of surface wave propagating from s_1 to g_1 and g_2, respectively.

Recalling the cross-correlation theorem

$$f \otimes g = \mathcal{F}^{-1}(\mathcal{F}(f)^* \mathcal{F}(g)) \tag{3}$$

where f and g are two functions, $\mathcal{F}$ and $\mathcal{F}^{-1}$ denote the direct and invert Fourier transform operators, respectively, and $*$ denotes the complex conjugate. Applying the cross-correlation theorem to the surface wave data $d(g_1|s_1)$ and $d(g_2|s_1)$ yields

$$\begin{aligned} d(g_1|s_1) \otimes d(g_2|s_1) &= \mathcal{F}^{-1}\left(\mathcal{F}(d(g_1|s_1))^* \mathcal{F}(d(g_2|s_1))\right) \\ &= \mathcal{F}^{-1}\left(D(g_1|s_1)^* D(g_2|s_1)\right) \\ &= \mathcal{F}^{-1}\left((e^{i\omega\tau_{s_1 g_1}})^* e^{i\omega\tau_{s_1 g_2}}\right) \\ &= \mathcal{F}^{-1}\left(e^{i\omega(\tau_{s_1 g_2} - \tau_{s_1 g_1})}\right) \end{aligned} \tag{4}$$

According to equation 4, cross-correlating the two data traces cancels the phase of the common raypath of surface wave and yields a virtual data trace of surface wave propagating from g_1 to g_2 denoted by $\tilde{d}(g_2|g_1)$ as shown in Figure 1.

Since the data traces $d(g_1|s_1)$ and $d(g_2|s_1$ also contain other seismic events such as reflections, the predicted surface-wave trace obtained always contains some noise. The conventional interferometric prediction method improves the signal-to-noise ratio (S/N) of the prediction by stacking virtual traces obtained from many common shot gathers containing geophones at the same position g_1 and g_2. Suppose there are n of these CSGs with shot positions $s_1, s_2, ..., s_n$ as shown in Figure 2. The S/N of the

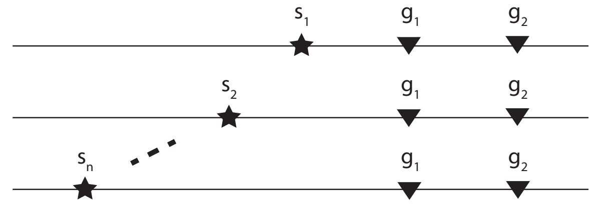

Figure 2: The diagram showing n shot positions, $s_1, s_2, ..., s_n$, with common geophones at g_1 and g_2.

surface-wave prediction can be increased by a factor of $\sqrt{n}$ by averaging these virtual traces:

$$\tilde{d}(g_2|g_1) = \frac{1}{n}\sum_{i=1}^{n} d(g_1|s_i) \otimes d(g_2|s_i). \tag{5}$$

Once the surface-wave prediction is obtained, an adaptive subtraction is applied to reduce surface-wave noise from the original data. The reason that we cannot simply subtract the prediction directly from the data is that the phase and amplitude of the surface-wave prediction are usually incorrect compared to those of the actual surface-wave noise. For more rigorous description of the method, the reader is recommended to see the work of Xue et al. (2009).

The principle of this method is quite simple but some issues arise when we want to implement the method into an efficient computer program that can be applied to predict surface waves in all CSGs of any data set. These issues are as follows.

- To predict surface waves propagating from position g_i to g_j in a CSG, the computer program needs to search for CSGs that contain geophones at g_i and g_j, and perform cross-correlation and trace averaging to obtain one predicted trace. Consequently, to obtain a predicted virtual gather, the computer program needs to perform a large amount of data searching which could cause the program to be inefficient.

- The computer program may take a long time to process the data if the entire data set cannot be loaded into the computer memory since the program needs to load CSG data several times. This is due to the fact that computer time for loading data from storage devices such hard disk is several orders of magnitude slower than performing calculation.

These problems can be overcome if the process of predicting surface waves in a CSG only requires data within that CSG. This is the key improvement of the new method proposed in the next section.

A NEW SEISMIC INTERFEROMETRY METHOD FOR PREDICTING SURFACE-WAVE NOISE

In this section, we describe the new method based on seismic interferometry for predicting surface-wave noise in seismic land data. To solve the issues of the conventional method, we use both cross-correlation and convolution of data traces as shown in Figure 3. In this method, we first choose a small-offset reference trace $d(g_1|s)$ (g_1 is close to the source position s). The second trace must be recorded by geophone at g_2 whose offset is larger than g_1. Then, the two traces are cross-correlated to obtain a virtual trace $\tilde{d}(g_2|g_1)$. This is the first step of the method which is the same as the conventional method. The second step is to apply convolution of the virtual trace and the reference trace to obtain a surface-wave prediction $\tilde{d}(g_2|s)$. This can be summarized as

$$\tilde{d}(g_2|g_1) = d(g_1|s) * [d(g_1|s) \otimes d(g_2|s)]. \tag{6}$$

The idea of using both cross-correlation and convolution is borrowed from the refraction interferometry work of (Mallinson et al., 2011; Bharadwaj et al., 2012).

To increase the S/N of the prediction, the two-step process (equation 6) is iteratively applied to the virtual trace as shown in the pseudocode:

```
p(g2,s) = d(g2,s)
for i from 1 to n
  p(g2,s) = d(g1,s) * [ d(g1,s) x p(g2,s) ]
end
```

Here $\times$ denotes the cross-correlation operator and `p(g2,s)` is the final prediction after n iterations. The geophone position g_2 is then varied to obtain the prediction for the rest of geophones which are on the same side with respect to the source position as the reference geophone g_1. The same procedure is then repeated for geophones on the other side to obtain a complete prediction for the CSG of interest. It is worth noting that we do not obtain surface-wave predictions at the two reference traces and possibly at a few geophone positions with smaller offset than the reference geophones.

Once the prediction is obtained for a CSG, the adaptive subtraction is then applied to reduce surface-wave noise from the CSG. This process is the same as the conventional method.

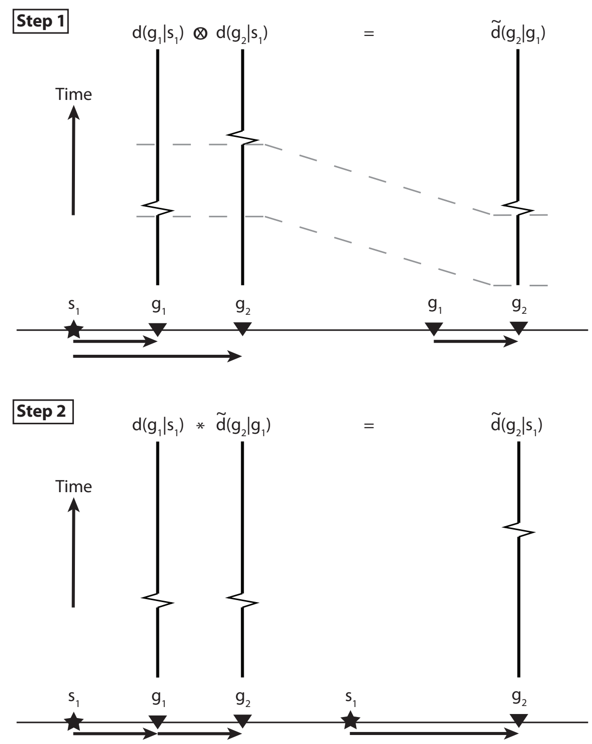

Figure 3: The key diagram that demonstrated how the new seismic interferometry method can predict surface wave propagating from position s to g_2 using both cross-correlation ($\otimes$) and convolution ($*$).

FIELD DATA RESULTS

To evaluate the effectiveness of the proposed seismic interferometry method, we applied the proposed method and FK filtering to the land data from PTTEP. The filtering result is shown in Figure 4. Figures 4a and 4b show the filtering result from FK filtering for common shot gather number 10 (CSG10). The result shows that seismic interferometry is more effective in reducing surface-wave noise in the data than FK filtering. In this case, FK filtering is not so effective due to the aliasing of surface-wave events. As expected, seismic interferometry filtering is immune to the aliasing problem. However, there is still residual surface-wave noise left in the filtering result. We remove the residual noise using FK filtering (Figure 4c). Although we did not show the filtering result from the conventional seismic interferometry filtering, we expect it to be as effective as the new method. However, we need to compare the two methods in the future. In addition, we need to apply the proposed method to more data sets to accurately evaluate its performance.

DISCUSSION

In this section, we present some discussion about the advantages and disadvantages or issues of the proposed method. The merits of the proposed method are (1) that it is very simple to implement compared to the conventional method and (2) that the noise prediction for a CSG can be efficiently performed since only the data from that CSG are needed unlike the conventional method that required many CSGs to be loaded into the computer memory. Despite of these advantages, the proposed method still has some issues that need be solved. The first issue is that the position of the reference near-offset geophone strongly affects the quality of the prediction. This is sensible since each trace has a different signal-to-noise ratio. To successfully apply the proposed method, a good reference trace is needed. This requires the processing person to judge and to choose the referene trace. The second issue is that noise in near-offset traces from source to the reference geophone are not predicted and thus not reduced. However, this is only a few near-offset traces.

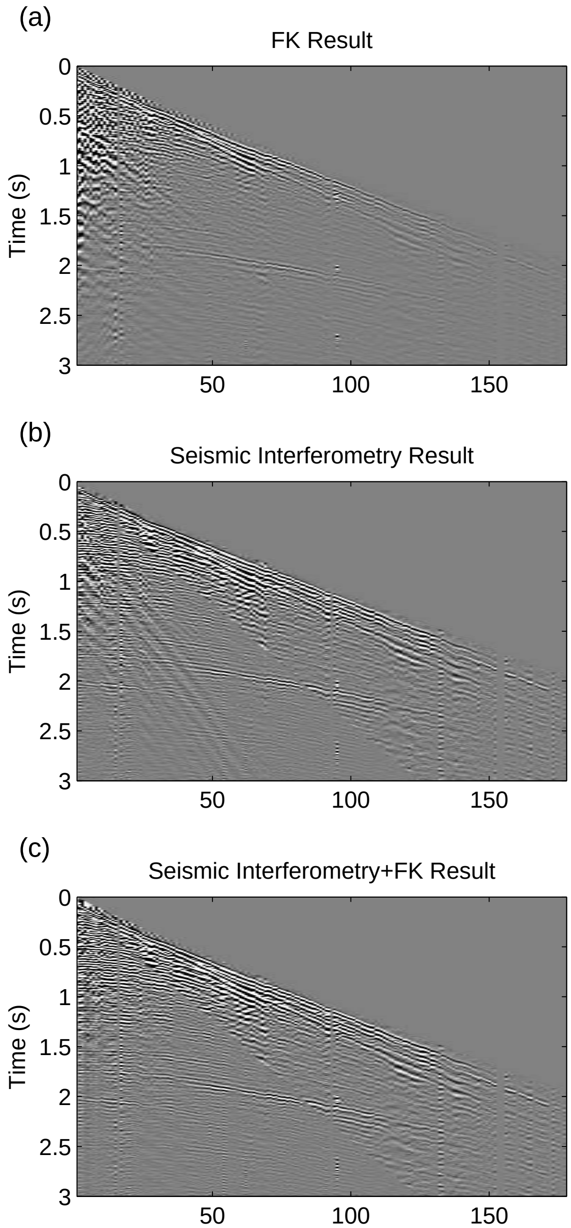

Figure 4: Comparison of filtering results obtained using three methods: (a) FK filtering, (b) new seismic interferometry filtering, and (c) hybrid between the new seismic interferometry and FK filtering.

CONCLUSION

A new method has been developed based on the principle of seismic interferometry for reducing strong surface-wave noise in land seismic data. The proposed method was applied to a 2D real surface-seismic-profile (SSP) data from PTTEP acquired in a north-east area of Thailand. A comparison with FK filtering shows that the proposed method is more effective but it still could not completely remove the surface-wave noise. FK filtering was then applied to the filtering result of the new seismic interferometry method to remove the residual noise. This hybrid was shown to be quite effective in reducing the noise from the data used in this paper. Nonetheless, more data sets should be used to test the performance of the proposed hybrid method.

ACKNOWLEDGMENTS

We would like to thank PTTEP for the financial support and the land seismic data used in this project.

REFERENCES

Bharadwaj, P., G. T. Schuster, I. Mallinson, and W. Dai, 2012, Theory of supervirtual refraction interferometry: Geophysical Journal International, **188**, no. 1, 263–273.

Halliday, D., A. Curtis, J. A. Robertsson, and D. V. Manen, 2007, Interferometric surface-wave isolation and removal: Geophysics, **72**, A69–A73.

Halliday, D., A. Curtis, P. Vermeer, C. Strobbia, A. Glushchenko, D. V. Manen, and J. A. Robertsson, 2010, Interferometric ground-roll removal: Attenuation of scattered surface waves in single-sensor data: Geophysics, **75**, SA15–SA25.

Mallinson, I., P. Bharadwaj, G. T. Schuster, and H. Jakubowicz, 2011, Enhanced refractor imaging by supervirtual interferometry: Leading Edge, **30**, no. 5, 546–550.

Xue, Y., 2010, Least squares datuming and surface waves prediction with interferometry: PhD thesis, University of Utah.

Xue, Y., S. Dong, and G. T. Schuster, 2009, Interferometric prediction and subtraction of surface waves with a nonlinear local filter: Geophysics, **74**, no. 1, SI1–SI8.