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Pre-processing for Seismic While Drilling Data with Unfavorable Pilot Condition Acquired in the Vicinity of Geothermal Well in Pohang, Korea

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ABSTRACT

Seismic While Drilling (SWD) surveys that use drill-bit vibration energy as a source were conducted to acquire velocity information in the vicinity of geothermal well in Pohang, Korea in 2012 and 2013. The cross-correlation between a pilot signal and geophone signals is a primary processing step for SWD data. Hence sensitivity of the pilot sensor becomes a crucial factor for SWD processing. Generally, pilot sensors are located on the top of the drill-pipe or in the bottom hole assembly to measure reference drill-bit vibration signals. However, in case of our surveys, two pilot sensors were deployed both on the Blowout Preventer (BOP) and top drive due to the safety issue and time-pressing drilling schedule. As a consequence, Signal to Noise Ratio (SNR) of pilot signals and their simple cross-correlation results were not satisfactory input data for further SWD processing.

Accordingly, we focused on exploiting several pre-processing techniques to improve SNR of pilot signals and cross-correlation results. Comparison analysis for pilot signals according to drilling conditions shows that the frequency range from 40 to 140 Hz are reinforced for top-drive pilot signals during drilling operation. This enhancement of the specific frequency band is also observed similarly in the amplitude spectrum of the data observed at a borehole accelerometer located near the drill well. According to these observations, top-drive pilot signals whose 40 to 140 Hz frequency bands are relatively strong were selected for further SWD processing.

Because of extremely noisy environments (e.g. electronic noise, mud noise, engine noise, and rig noise), harmonic noise subtraction and adaptive noise subtraction were inevitably needed to refine pilot signals and geophone signals before cross-correlation. Pilot de-convolution and selective stack were also applied to cross-correlograms. As a result of these pre-processing works, the SNR of the cross-correlogram was improved for further SWD processing.

1. INTRODUCTION

SWD survey was attempted for the Enhanced Geothermal System (EGS) pilot plant project in Korea. The purpose of this SWD survey was to obtain velocity information near the geothermal well in Pohang. This velocity information is an essential background input data to a micro-seismic analysis for an upcoming hydro-stimulation test as a key step of EGS pilot plant project (Song et al., 2015).

In SWD survey, controlled sources like dynamites or vibroseis are not used inside the borehole or on the surface. Instead, SWD survey utilizes drill-bit vibration energy as a seismic source in a borehole. For this characteristic similar to passive seismic, SWD survey has some advantages that could be ideal for EGS drilling project. If proper processing applied, SWD survey can provide velocity information near the target well without interrupting drilling operation. Moreover, SWD data could be useful information for predicting a possible risk for future drilling operation by imaging subsurface layers ahead of the drill-bit (Malusa et al., 2002).

For operating SWD survey, a pilot sensor that measures the drill-bit vibration signals is required along with geophone arrays used in the typical geometry of Reverse Vertical Seismic Profiling (RVSP) survey. This measured drill-bit vibration signal is cross-correlated with the geophone signal to make a typical RVSP gather (Poletto and Miranda, 2004).

During our SWD survey (acquisition geometry is shown in Figure 1), the position of the pilot sensor became an important issue. In previous studies, pilot sensors are normally located on the top of the drill-string or in the bottom hole assembly to directly measure reference drill-bit vibration energy to guarantee the sufficient SNR of the cross-correlogram (Rector and Marion, 1991; Poletto and Miranda, 2004).

However, for our first SWD survey in 2012, a pilot sensor was deployed on the BOP due to safety issue and time-pressing drilling schedule. This pilot-sensor location eventually caused a poor SNR problem in the cross-correlogram for considering further RVSP processing. Afterwards, the second SWD survey was in 2013 with a pilot sensor located both on the top-drive and BOP. The SNR of the top-drive pilot signal and its cross-correlogram was improved compared to the previous BOP pilot case, yet SNR of the cross-correlogram was still neither sufficient nor consisitent for further RVSP processing throughout the whole data.

Thus, in this study, to overcome the lack of SNR, we firstly tried to separate relatively better pilot signals from the entire data by analyzing the main frequency band of the drill-bit vibration signal. After pilot selection, due to strong noisy environment (e.g. electronic noise, mud noise, engine noise, and rig noise), harmonic noise subtraction and adaptive noise subtraction were tested in synthetic data and applied for conditioning the top-drive pilot signal. After cross-correlation, pilot de-convolution and selective stacking were also applied for improving SNR of the cross-correlogram.

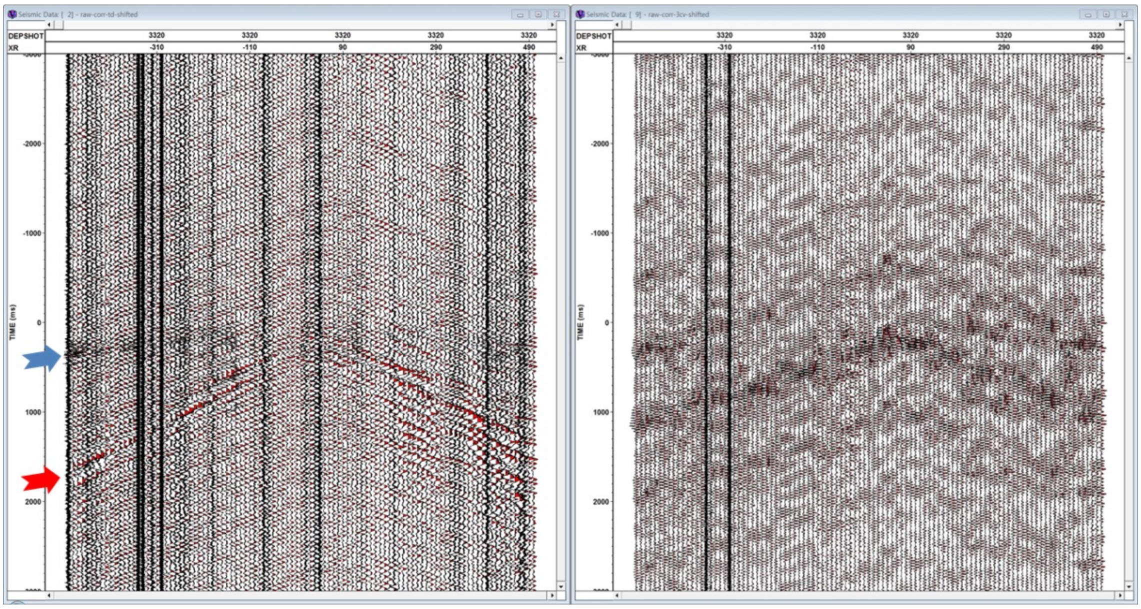
Figure 1: Geometry of the SWD survey in the vicinity of the geothermal well in Pohang, Korea, 4 radial seismic survey lines were deployed around the geothermal well (survey line 1 is extended 200 m and the other survey lines extended to 500 m using a 14-Hz geophone with 10 m interval and three-axial geophones were also deployed in every 50 m, a three-component borehole accelerometer is installed at EXP01 which is 150 m deep near the geothermal well for micro-seismicity monitoring.)

2. TOP-DRIVE PILOT SELECTION

Figure 2a and 2b show simple cross-correlation results of geophones from survey line 2 to 3 shown in Figure 1 with the top-drive pilot and the BOP pilot respectively. As can be seen in Figure 2a, a linear event is observed with relatively high frequency and velocity (blue arrow). We believe that this event is a direct wave from drill-bit vibration. In addition, a ground-roll-like dispersive linear event is also found with relatively low frequency and velocity (red arrow). On the contrary, in the Figure 2b, repetitive blurred pattern are observed, but direct wave energy is not clearly identified as in the case of using the top-drive pilot.

However, it is evident that simple cross-correlation does not ensure the SNR of the cross-correlogram for the both pilot signal cases. The direct wave is very weak even in the case of using the top-drive pilot. Furthermore, cross-correlation does not provide the consistent result which implies that the energy of the drill-bit vibration is varies depending on drilling conditions.

To resolve this problem, we decided to compare frequency spectrums when drilling is on operation and not on operation (tripping out/in) to find the main frequency band of the top-drive pilot sensors. Figure 3 illustrates amplitude spectrums of the top-drive pilot sensor and EXP01 sensor installed near the geothermal well for micro-seismicity monitoring when drilling is on operation and tripping out/in. During drilling operation, 40-140 Hz and around 200 Hz frequency components are clearly resurrected compared to when tripping out/in. Amplitude spectrum of EXP01 sensor shows the correspondence with that of top-drive pilot sensor in the low frequency part. According to these observations, we refined our main target band to cover a range from 40 to 140 Hz and extracted top-drive pilots for further processing (Figure 4).



(a) (b)

Figure 2: Cross-correlograms of geophone traces from line 2 to 3 with (a) the top-drive pilot and (b) BOP pilot when the drill-bit depth is 3,320 m (60 Hz notch filter is applied for a display purpose.)

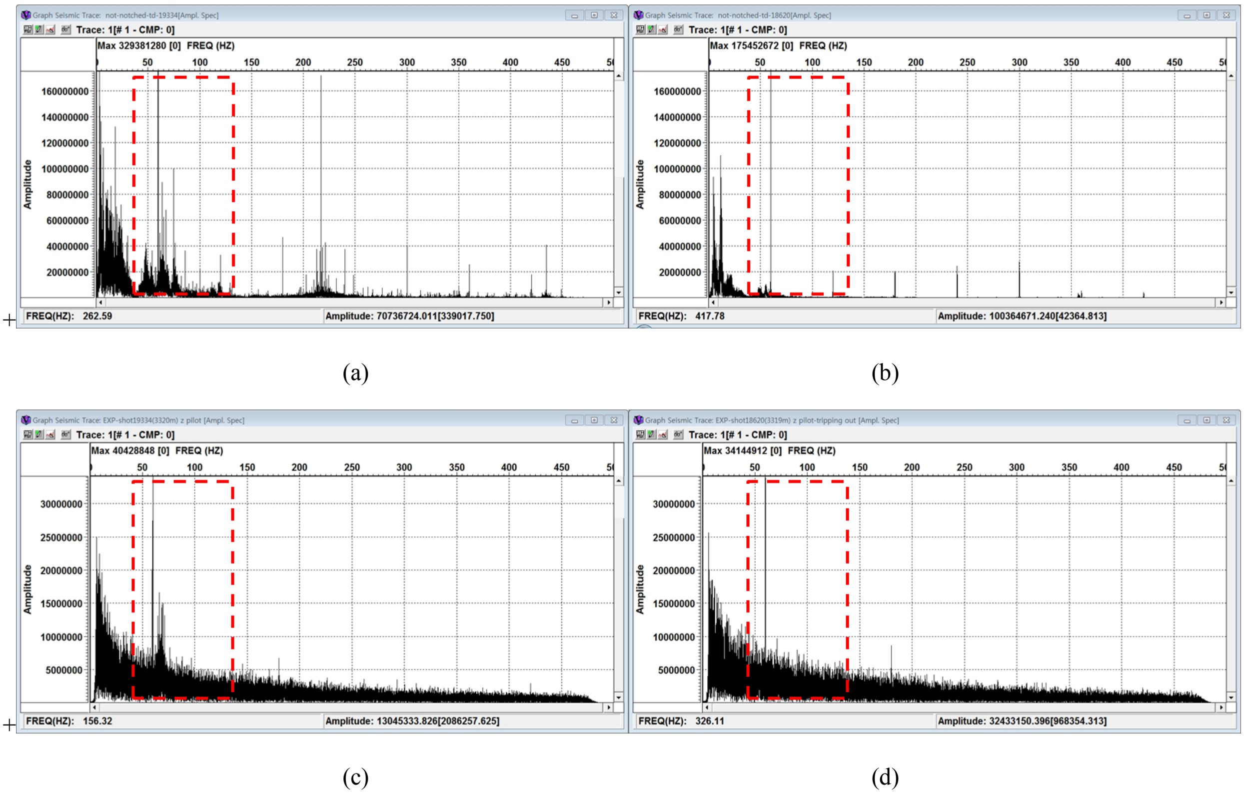


Figure 3: Amplitude spectrums of (a), (b) the top-drive pilot sensor and (c), (d) EXP01 sensor when drillling is on operation (left panels, drilling depth is 3,320 m.) and tripping out/in (right panels, drilling depth is 3,319 m.)

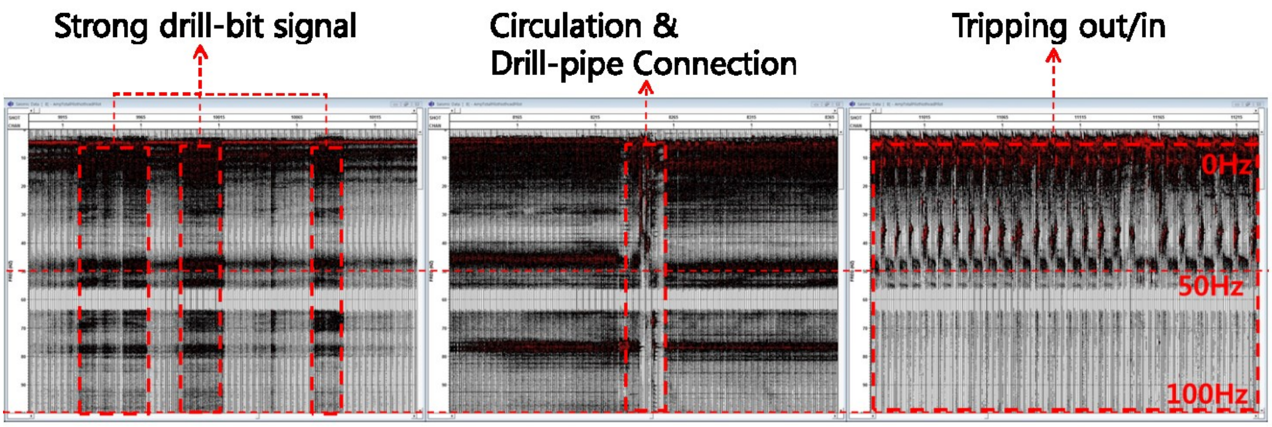


Figure 4: Classification and Selection of the top-drive pilots with amplitude spectrums (Note that many amplitude spectrums are aligned vertically, 60Hz notch filter is applied for a display purpose.)

3. HARMONIC NOISE SUBTRACTION FOR TOP-DRIVE PILOT SIGNAL

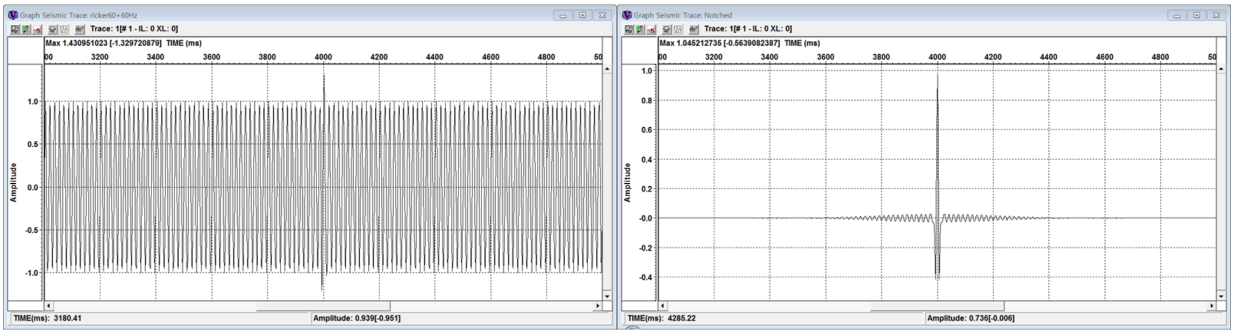
In the previous amplitude spectrum of the top-drive pilot sensor (Figure 3a and 3b), we can easily find 60 Hz and its harmonics are excessively strong. This excessive noise is generally originated from the power line noise. This strong power line noise distorting and masking the drill-bit vibration signal should be reduced or removed for better SNR.

Simple notch filtering in the frequency domain can remove the 60 Hz component easily, but notch filtering can also distort the signal if the signal has also 60 Hz frequency component. Specifically for SWD, due to narrow frequency band nature of the drill-bit vibration energy (Poletto and Miranda, 2004), the loss of frequency component would not be desirable.

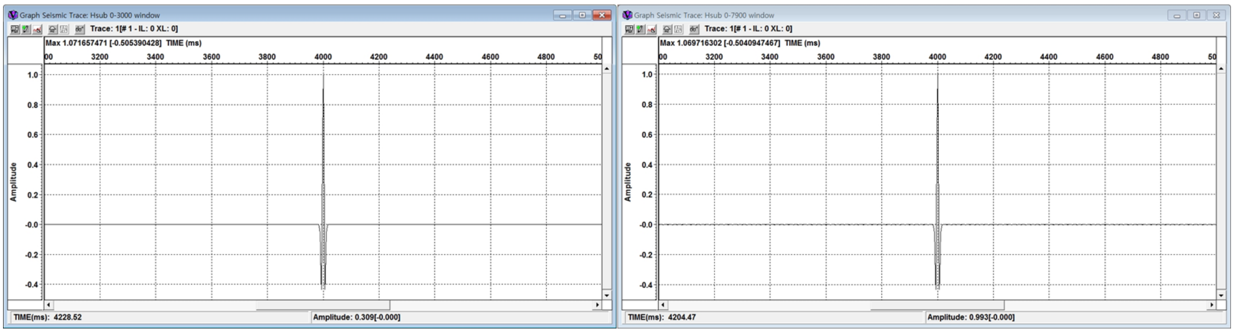
Butler and Russell (1993) proposed a harmonic noise suppression algorithm that uses sine and cosine basis functions to invert harmonic noise components minimizing distortion of an original signal. This algorithm exploits a time window that includes only harmonic noise components, which is not applicable to SWD data because drill-bit vibration exists and mixed with noise component throughout the entire time.

To apply harmonic noise subtraction algorithm to SWD data, we assume if a noise component is sufficiently dominant, the error of inverted harmonic noise component is negligible though we use a time window containing a signal and noise mixture. Figure 5 represents synthetic data test results using mixture of Ricker wavelet with 60 Hz main frequency and the noise component (60 Hz sinusoidal function). This simple synthetic test indicates that harmonic noise subtraction can estimate a 60 Hz noise component correctly although a time window is not refined in noise components under the condition that noise components are dominant.

In this manner, harmonic noise subtraction was applied to the top-drive pilot signal for removal of 60 Hz and its harmonics (e.g. 120, 180, 240 … 420 Hz). Figure 6 shows that 60 Hz frequency component is well attenuated but the other frequency components are conserved. On the contrary, significant difference is not clearly shown in cross-correlograms between Figure 2a and Figure 6b. It is because 60 Hz notch filter is already applied to Figure 2a for a display purpose.

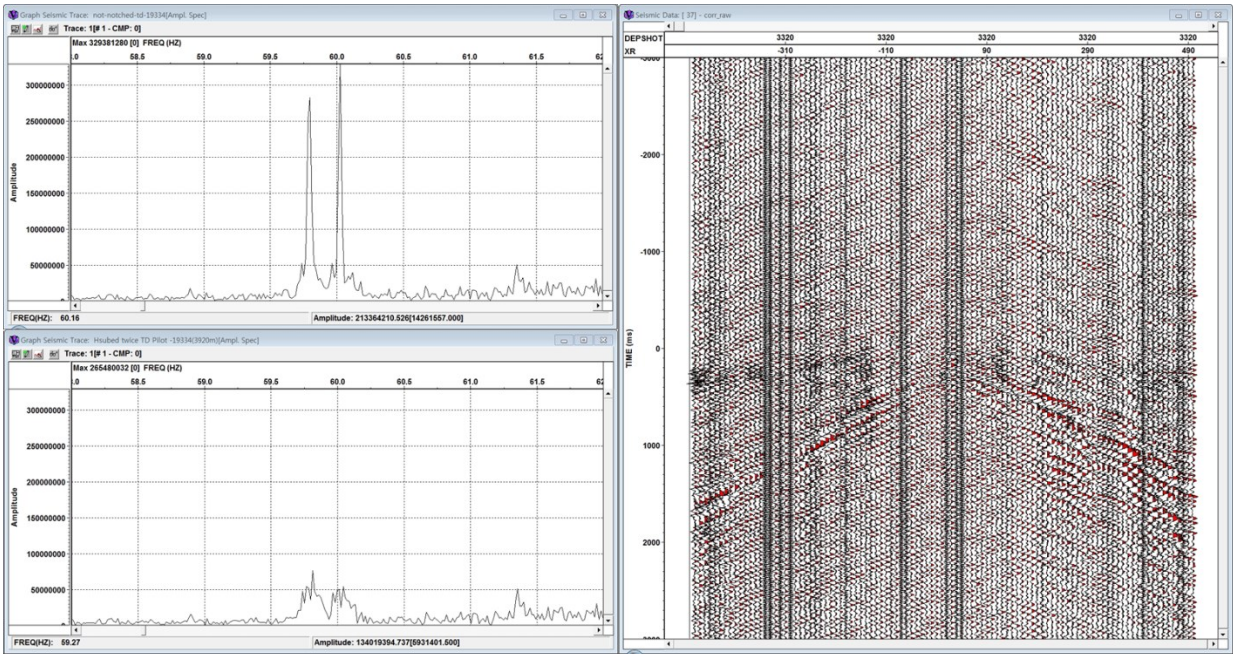


(a) (b)



(c) (d)

Figure 5: Synthetic test for harmonic noise subtraction with mixture of Ricker wavelet with 60 Hz main frequency and 60 Hz noise component, (a) input signal, mixture signal where 60 Hz noise is dominant, (b) 60 Hz notch filtered result, (c) harmonic noise subtraction result with time window 0-3,000 ms (containing only 60 Hz noise), (d) harmonic noise subtraction result with the entire time window.



(a) (b)

Figure 6: Application of harmonic noise subtraction to the top-drive pilot when the drilling depth is 3,320 m as shown in Figure 2 (a), (a) the original amplitude spectrum (upper panel) and the processed amplitude spectrum (lower panel) of the top-drive pilot and (b) the cross-correlogram with the processed top-drive pilot.

4. ADAPTIVE NOISE SUBTRACTION FOR TOP-DRIVE PILOT SIGNAL

After removing power line noise, other noise components still prevail in the drilling operation field. For the top-drive pilot sensor, the vibrations from the engine, mud flow in the drill-pipe, and rig generated noise could affect the top-drive pilot signal. To alleviate this noisy environment, adaptive noise subtraction using two sensors can be applicable (Widrow et al., 1975; Poletto and Miranda, 2004).

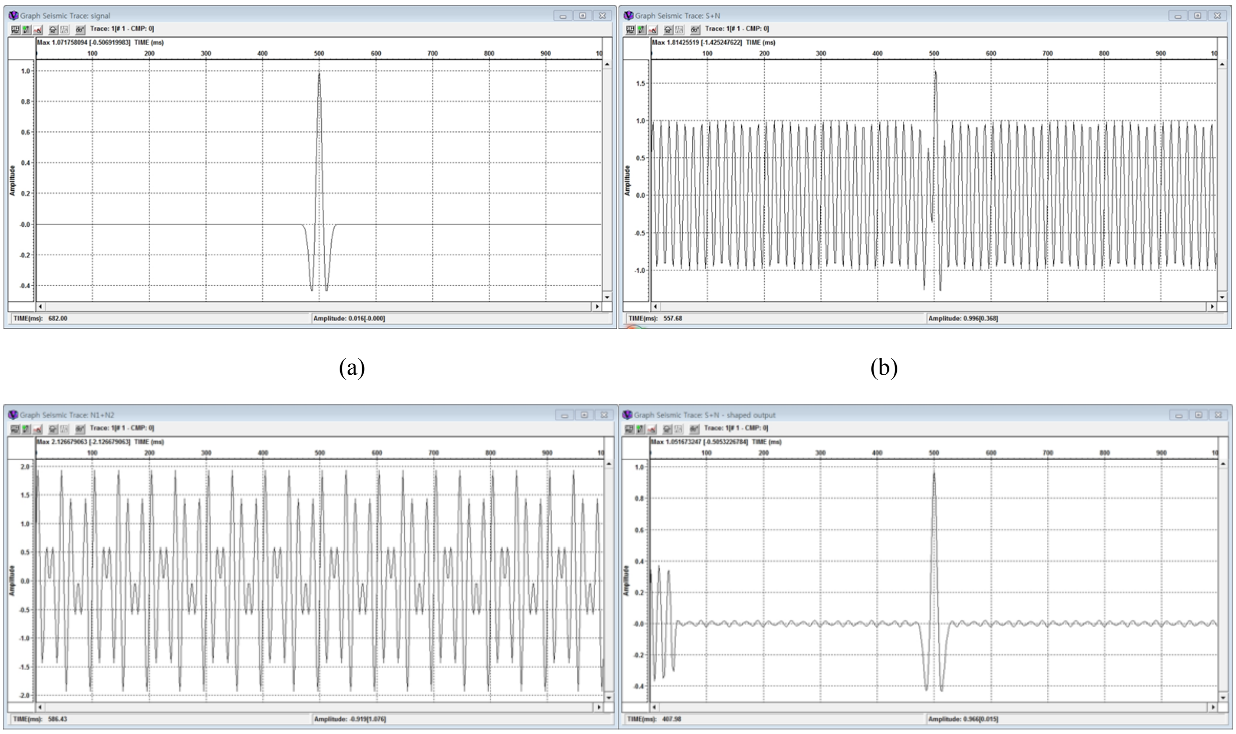
Adaptive noise subtraction assumes that signal and noise components are mutually exclusive so that they are not invertible to each other but noise components are mutually invertible. Then, if we record pure noise components in one sensor, the noise component from a signal-noise mixture could be inverted by the least-square method and subtracted from the mixture to obtain the original signal.

In the seismic data processing, adaptive noise subtraction can be easily implemented by using a shaping de-convolution filter. With the shaping de-convolution filter, we can make one signal resemble to another target signal in the least-square manner. Figure 7 shows that a simple synthetic test for adaptive noise subtraction with Ricker wavelet with 30 Hz main frequency and noise components (50 Hz and 70 Hz sinusoidal functions). By calculating shaping de-convolution filter for making the pure noise mixture (summation of 50 Hz and 70 Hz noises) resemble the mixture of Ricker wavelet and 70 Hz noise, Figure 7d would be obtained. Result shown in Figure 7d indicates that adaptive noise subtraction can work properly although there appear some errors in the early time and slight fluctuation.

For application of adaptive noise subtraction to SWD data, the BOP pilots, whose SNR were not satisfactory can be re-utilized as a noise recorder. Using vertical components of BOP pilots, an estimated noise and its amplitude spectrum are calculated and depicted in Figure 8.

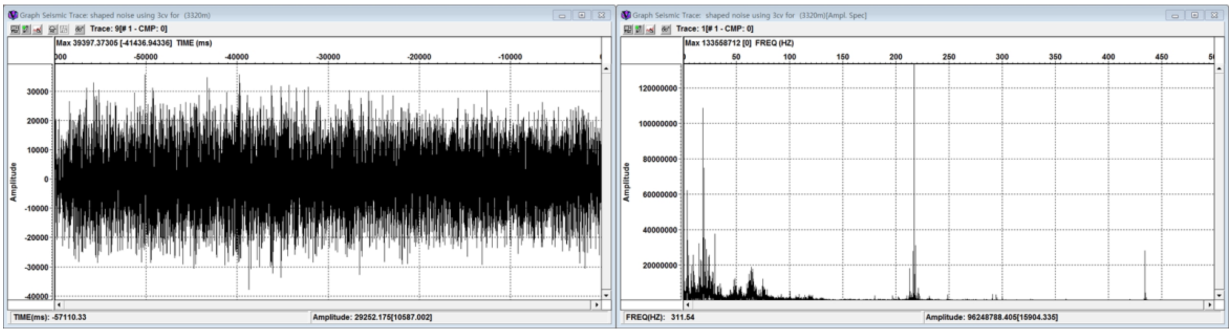
The nature of this estimated noise is difficult to be defined or refined as a time domain signal in Figure 8a. However, the amplitude spectrum of the estimated noise contains noise-like components in high frequency band around 200 Hz and 400 Hz.

Auto-correlation result of the top-drive pilot and top-drive pilot subtracted by the estimated noise are illustrated in Figure 9a. As can be seen, fluctuation of auto-correlation near the zero-lag peak is reduced. However, the cross-correlation result is slightly improved and not clearly seen in Figure 9b compared to Figure 6b.



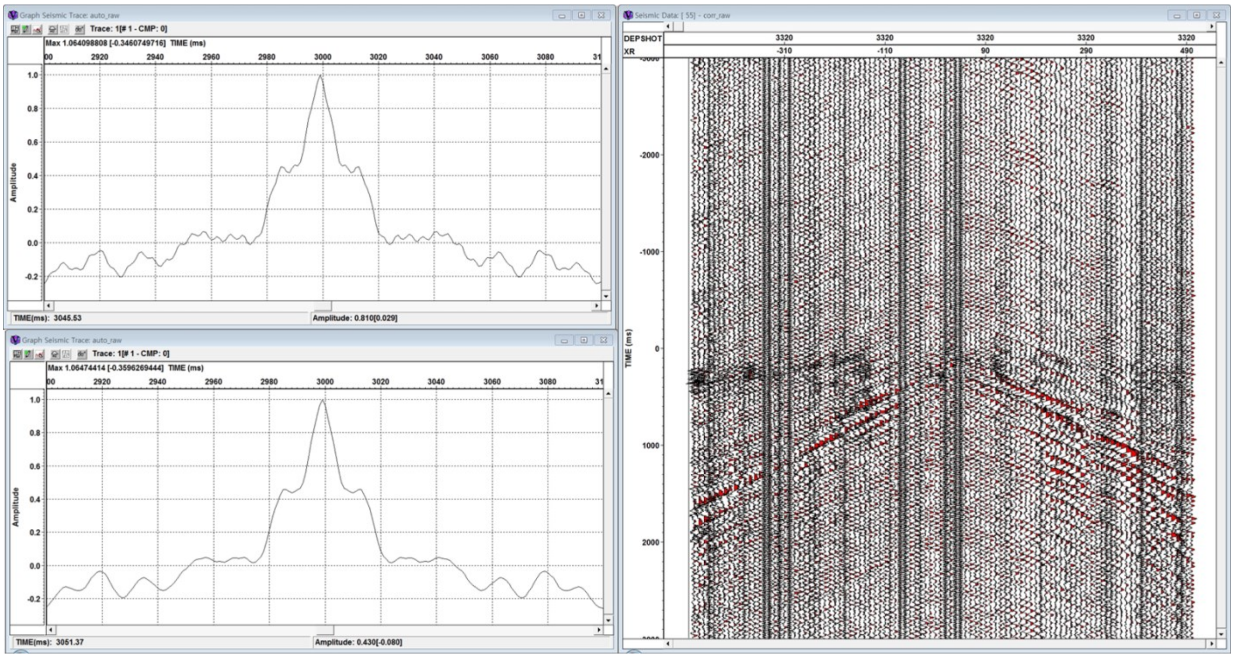
(a) (b) (c) (d)

Figure 7: Synthetic test for adaptive noise subtraction, (a) Ricker wavelet with 30 Hz main frequency, (b) mixture of Ricker wavelet and 70 Hz noise component, (c) 50 Hz and 70 Hz noise mixture, and (d) adaptive noise subtracted result



(a) (b)

Figure 8: (a) Time domain estimated noise of the top-drive pilot signal using the vertical component of BOP pilot as a noise source and (b) its amplitude spectrum



(a) (b)

Figure 9: Application of adaptive noise subtraction to the top-drive pilot when the drilling depth is 3,320 m, (a) the original auto-correlation (upper panel) and auto-correlation of the processed top-drive pilot (lower panel) and (b) the cross-correlogram with the processed top-drive pilot. The pilot and geophone signals used in Figure 6 are input data for this test.

5. PILOT DE-CONVOLUTION AND SELECTIVE STACK

After cross-correlation, pilot de-convolution is required for removal of anti-causal part of the cross-correlogram (Rector and Marion, 1991; Poletto and Miranda 2004). In addition, for improving SNR of cross-correlogram, a selective stacking should be carefully done because regardless of the selection of the relatively better top-drive pilots, SNR of some top-drive pilots and their correlograms are not satisfactory. In this case, excluding poor SNR cross-correlograms from stacking list in the given drilling depth point is necessary.

6. CONCLUSION

In this study, we tried to select top-drive pilot signals by assessment of the main frequency band of drill-bit vibration energy. Harmonic noise subtraction was tested for synthetic data and applied to reduce strong electronic noises. Adaptive noise subtraction was also tested for the simple synthetic data and applied to the top-drive pilot. After cross-correlation, pilot de-convolution for removing anti-causal part of the cross-correlogram and selective stack are implemented.

As a final result in this study, Figure 10 compares a raw cross-correlogram without any pre-processing and the cross-correlation result with selective stack, pilot de-convolution, adaptive noise subtraction, and harmonic noise subtraction. As illustrated in Figure 10, the SNR of the pre-processed cross-correlogram is critically improved to be enough for further RVSP processing.

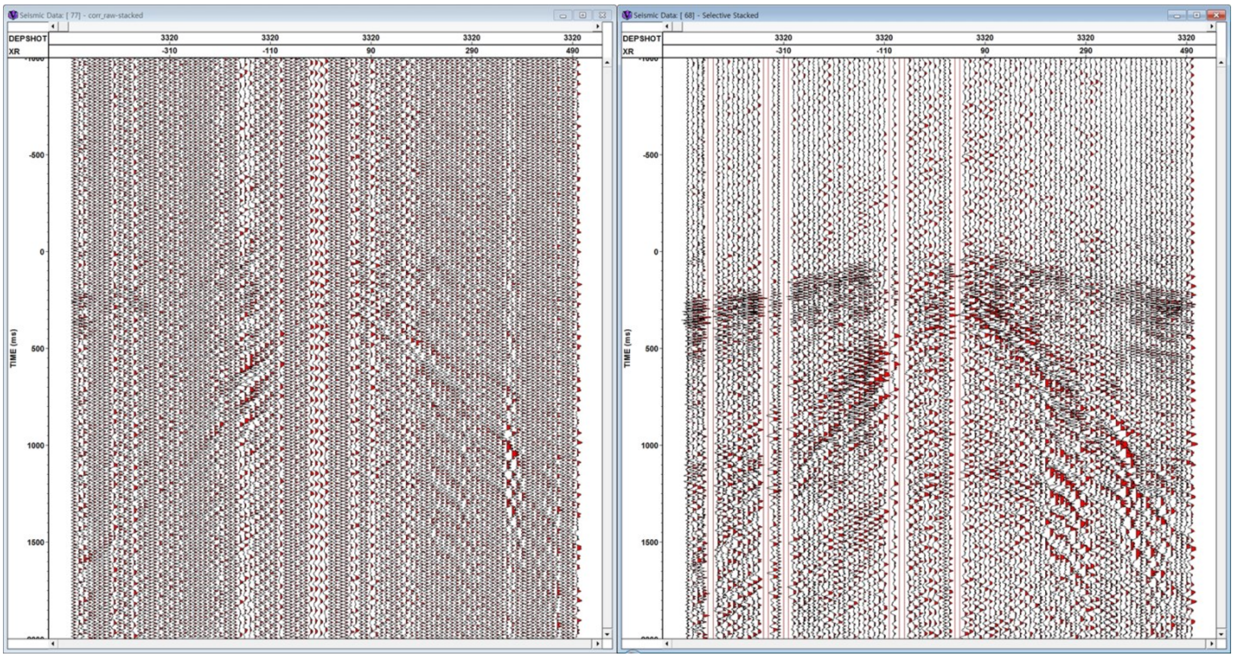


Figure 10: (a) Cross-correlogram when the drilling depth is 3,320 m (without any processing for comparison, just cross-correlate with raw top-drive pilot and geophone traces) and (b) Cross-correlogram with the top-drive pilot after selective stack, pilot de-convolution, adaptive noise subtraction, and harmonic noise subtraction (dead traces are removed for a display purpose)

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