Subsurface Imaging by Seismic Interferometry
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Summary
The pseudo-reflection shot records can be generated by the cross-correlation of the transmission responses observed at the sensors located on the ground-surface, which is called “seismic interferometry” or “daylight seismic imaging.” In this paper, we apply this technique to the field data observed by using several different types of micro-seismicity as seismic sources in order to appraise the practical applications of the seismic interferometry technology. Since this method requires a long record length, we newly developed a PC-based long-time seismic recording system with 96 channels. The experimental survey was carried out in a mountain area where two tunnels exists. Several micro-seismicity sources, for example running vehicles in the tunnel were adopted to make underground noise for the seismic interferometry. We acquired transmitted wave field generated by such sources moving in the tunnels. Obtained data were properly processed and it shows subsurface image clear enough to estimate underground structures and proved the seismic interferometry technology.

Introduction
Under the ground, there always exist various kinds of vibrations caused by social activities, such as the running of trains, subways, or cars and civil constructions and industrial factories. Also natural earthquakes and volcanic activities create vibrations. These vibrations are called as the micro-seismicity. In this paper we use these seismicities as the source signals for the reflection seismic survey. This reflection survey technique is called “Seismic Interferometry (Wapenaar, 2003)” or “Daylight Imaging (Claerbout, 1968).” The method intends to image the subsurface structure using the seismic waves observed on the ground-surface as a transmission wave field without using any artificial active sources and to simulate the pseudo reflective wave field by cross-correlation of transmission wave data.

Generation of Pseudo-Shot Records from Transmission Wave Field
The relationship between the transmission wave field and the reflective wave field in the one-dimensional multilayer structure was introduced by Claerbout (1968) and he called this as “Daylight Imaging.” Wapenaar (2003) extended this idea to the case of the three dimensional space and Wapenaar (2004) in the case of elastic medium. This relationship is obtained by using the reciprocity theorem and the Law of the conservation of energy.

When the seismic wave fields generated from a certain buried impulsive source are observed at two places A and B on the ground-surface (Fig. 1), we can simulate the pseudo reflection wave field which corresponds to the data which is propagated from source at location A to the receiver at location B. The expression of this relationship of the transmission wave record T and the reflective wave record R is as following (Wapenaar 2003, the equation (14)).

\[ R(x_A, x_B, t) + \frac{\partial}{\partial t} R(x_A, x_B, -t) = \delta(x_{HA} - x_{HB}) \delta(t) - \sum_i T(x_A, x_i, -t)^* T(x_B, x_i, t) \]  

(1)

Where \( T(x_A, x_i, t) \) and \( T(x_B, x_i, t) \) are the transmission wave fields detected at points A and B from the subsurface source point \( x_i \), respectively. \( R(x_A, x_B, t) \) is the reflection wave field corresponding to the receiver at \( x_A \) when the source is located at \( x_B \). Or \( R(x_A, x_B, t) \) can be considered as the Green function relating to the source at \( x_A \) to the receiver at \( x_B \). The symbol * denotes the convolution operation. Using this relationship, the reflection wave field can be simulated by the cross-correlation of two transmission wave fields.

The first term of left-hand side of Eq. (1) is causal part and the second term corresponds to the anti-causal part. Moreover the second term of the right-hand side of Eq. (1) expresses the sum of the correlation results of many buried sources, when two or more buried sources exist. In theory of seismic interferometry, number of the buried sources should be as many as possible and/or infinite and these should be randomly distributed.
From Eq. (1) we can understand the great advantage of the seismic interferometry which is that we can simulate the pseudo shot records with improved signal-to-noise ratio, once many receivers are deployed on the survey line. So the many geophones should be set on the survey line to simulate as many pseudo shot records as possible.

Field Test with Underground Random Noise

In order to estimate the applicability of the seismic interferometry using micro-seismicity, we carried out a field test in a mountain area where two tunnels exist under the survey lines. In order to generate the underground seismic noise, several methods were adopted using several different types of seismic sources.

(1) Survey Layout

The geological structures of the test site and survey liens are shown in Fig. 2. In this area, a prior geological survey shows the parallelly eastward inclining alternation of layered mudstone. The driveway tunnel and the sidewalk tunnel pass in the ground, and these tunnels are used for a pathway of the moving vibration sources. A geophone group (Line-1) has 96 receiver locations with intervals of 5m and these were deployed on the mountain right above the sidewalk tunnel.

In order to compare the seismic interferometry data with the regular seismic data in this line, we had also acquired the regular reflection records using 72 receiver positions (receiver #25 – 96).

(2) Data recording system

For the seismic interferometry, the long-time measurement must be required using many channels. For the purpose of long-time recording, the desktop PC-based recording system with 96 channel was newly developed (Fig. 3). Geophone signals enter into the A/D board of the PC and the data are stored on the hard disk. The PC-based data acquisition system is controlled by LabView™.

In the test survey, the sampling frequency was set to 1000Hz. After measurement started, the vibration source in the tunnel moved and stopped at the specified period of time (or the specified number of the shot times). Although the current maximum number of channel is 96ch, we are now developing the system up to 360 channels.

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Figure 2: Geology, topography, and survey line.

Figure 3. The picture of data acquisition instrument.
Table 1: The vibration sources and data acquisition length.

<table>
<thead>
<tr>
<th>Source</th>
<th>Set place</th>
<th>Data Length (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer</td>
<td>sidewalk tunnel</td>
<td>1,600</td>
</tr>
<tr>
<td>Air knocker</td>
<td>sidewalk tunnel</td>
<td>2,140</td>
</tr>
<tr>
<td>Digi-pulse</td>
<td>driveway tunnel</td>
<td>1,840</td>
</tr>
<tr>
<td>2t Track</td>
<td>driveway tunnel</td>
<td>1,600</td>
</tr>
</tbody>
</table>

(3) Data acquisition
As for the seismic source, there are 4 kinds of vibration sources (Table 1) used in a driveway tunnel and a sidewalk tunnel. The recording length of the each data acquisition is also shown.

Fig. 4 shows a picture of each source, a Digi-pulse, an air-knocker, and a 2-ton truck which we were used. The Digi-pulse and air-knocker hit the surface of the tunnel road moving at equal intervals (every 2.5m - 5m) from the entrance to the exit in the driveway tunnel and the sidewalk tunnel respectively. The 2-ton truck kept running in the driveway tunnel intently and drove with 10 times round trips.

The record lengths of each source is 1,840s (Digi-pulse), 2,140s (air-knocker) and 1,600s (truck). During recording, we never handled the recording trigger because of no information of the seismic source movement. Since a recording trigger was not applied during the data acquisition, the first break of each record is not the same. However, the seismic interferometry theory guarantees the unnecessary of first break matching of each record because of the cross-correlation operation.

(4) Data processing and Results
In the data processing, in order to remove the noises on the measurement and PC-based recording system, a median filter and a band pass filter were applied prior to the cross-correlation. Then, simulated shot records are generated by cross-correlation of the observed records, and the header information was added and finally converted to the SEG-Y formatted data. Fig. 5 shows the examples of the simulated shot records obtained from different seismic sources and several reflection events can be seen and these are corresponding to the geological boundary.

In order to image the subsurface structures, the conventional data processing was applied to the simulated shot records. The processed stacked sections are shown in Fig. 6. Geological structures parallel to the surface inclining to the east side can be visualized. This structure crosses the west side slope of the mountain. This result strongly supports the validity of the method of the passive record observation, seismic interferometry.

Discussions
In this paper, we showed the field examination towards the utilization of "Daylight Imaging" or "Seismic Interferometry." Since this method requires a long-time recording, we developed PC-base seismic instrument with 96 channels for this purpose. The method discussed here is a newly proposed reflection seismology technique by using positively the micro-seismicity and do not require artificial sources but has so far been considered to be a noise in reflection seismology. Also the application to three-dimensional survey is practically easy since we can generate the pseudo-shot records at any receiver positions.

References

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Fig. 5: Simulated shot records. From left to right: hummer, Digi-pulse, air-knocker, 2t truck.

Figure 6. Stacked sections corresponding, hummer, air knocker and 2t truck as sources of micro-seismicity.