Imaging geological conditions ahead of a tunnel face using
Three-dimensional Seismic Reflector Tracing System

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ABSTRACT

This paper describes the tunnel seismic reflection survey which has been developed by the authors in order to three-dimensionally detect geological conditions such as faults, fractured zones and geological boundaries ahead of a tunnel face using reflected seismic waves. In addition, the applicability and the accuracy of a result of this system have been validated by comparing with geological observation results at a tunnel face and the result of the drill logging system. This surveying system is called Three-dimensional Seismic Reflector Tracing System (TRT). TRT creates a 3-D isometric map of geological structures 100-150 m ahead a tunnel face and up to 30 m around a tunnel alignment. Kajima has applied TRT to about 100 times since its introduction in February 1999 to predict rock conditions ahead of tunnel faces. The images produced by TRT have been used satisfactorily to manage the risk caused by encountering unforeseen geological conditions.

Keywords: Tunnel, Seismic reflection survey, Exploration of geological conditions ahead of a tunnel face, 3-D isometric map

1. INTRODUCTION

1.1 Background of this research

Assessing and accurately predicting the geological conditions ahead of a tunnel face are important in constructing mountain tunnels reasonably and safely. The survey techniques, for instance, enable us to avoid unexpected collapses at a tunnel face. Seismic refraction survey conducted on the ground is normally carried out as a preliminary survey; however it does not provide sufficiently accurate information of faults and fracture zones. While horizontal boring conducted from a tunnel face provides good accuracy, they are infrequently conducted because they are costly and time-consuming. Further, the fact that the use of TBM (Tunnel Boring Machine) has increased recently attracted more attentions of the survey techniques. This is because TBM excavation has advantages over conventional NATM (New Austrian Tunnelling Method) in the rate of advance and safety, however it unable us to observe geological conditions of a tunnel face.

Research has been conducted so far both in- and outside Japan regarding survey techniques using seismic reflection waves to explore geological conditions such as faults, fractured zones and geological boundaries ahead of tunnel faces. However, there have been drawbacks to previous techniques in terms of accuracy and practicality. The three-dimensional seismic reflector tracing system developed and be introduced in this paper attempts to achieve both high accuracy and on-site practicality

1.2 Literature review and the purpose of this study

The first technique for searching ahead of a tunnel face using seismic reflection is the TSP (Tunnel Seismic Prediction) proposed by Sattel et al.(1996). This system was introduced in Japan, and various application tests have been conducted by Inaba et al.(1996), Kasa et al.(1996) and Yamamoto et al.(1995). This system was applied by the authors and was understood to have several drawbacks such that the strike of the strata must be assumed, and small variations in analytical accuracy appear from person to person and based on experience. Additionally, since evaluation results remain two-dimensional, only the reflection surface on the tunnel line is generated in order to simplify analysis. On the other hand, the three-component seismic reflection survey developed by Ashida (2001) and Ashida et al.(2001) utilizes a specialized analytical program, and is therefore quite versatile. An advantage of this technique is that it, unlike TSP, allows three-dimensional display of the reflection surface, thereby making it possible to determine the strike and dip of discontinuous surfaces. However, these methods for probing ahead of a tunnel face require a great amount of boring due to the fact that they involve special blasting work and geophone installation. Not only must measurements be constantly made when excavation is not occurring at the face, but a great amount of time for preparation and analysis is also required.
A new Three-dimensional Reflector Tracing (TRT) system was developed by the authors in an attempt to develop a technique that would accurately and simply predict the geological conditions ahead of a tunnel face in parallel with tunnel excavation. This technique does not require boring for geological conditions ahead of a tunnel face in parallel with a technique that would accurately and simply predict the magnetostrictive sources. Additionally, as it can also utilize the vibrations that occur from blasting, breakers, and TBM, etc., during excavation work, the only preparation required is the installation of accelerometers, and it is not necessary to stop excavations for long periods of time for surveys. Moreover, assessment results are displayed in three dimensions, and exploration range can be determined at-will, thereby allowing for geological assessment of the surrounding tunnel area at any range.

In this paper, the principles and development overview of this TRT system is reported as well as one example of applied results from nearly 100 on-site surveys conducted so far.

### 1.3 Principles of TRT

The basic concept of the system is shown in Figure 1. If the seismic wave velocity of the ground is already known, it is possible to draw an ellipsoid, which represents an isochronic surface, from recorded propagation time of a reflected wave between a certain source point and various receiver points. Therefore, as long as there are enough three-dimensionally positioned sources and receivers, a reflector can be depicted as the section that touches the majority of the ellipsoids drawn from a combination of the various sources and receivers.

This method utilizes reflection magnitude as an index for determining the dimensions and the phase (positive/negative) of reflection surface. Reflection magnitude as defined in this method is a normalised amplitude of each received reflected wave in the range from -1 to +1. This can be seen as proportional to the reflection coefficient of the reflection surface defined by Watters (1978) and Aki & Richards (1980). Reflection magnitude has been added to each of the ellipsoids drawn in Figure 1, and a greater number of ellipsoids converging on the same grid point indicate a strong reflection surface existing at that grid point. Therefore, the phase and the intensity of the reflection surface are depicted by adding the reflection magnitude of ellipsoids existing over a single grid (Ashida (2001), Ashida & Sassa (1993), Neil et al.(1999)).

### 2. DEVELOPMENT OF THE SYSTEM

#### 2.1 Optimum array of sources and receivers

As Ashida et al (2001) have indicated, when tracing ahead of a tunnel face, there is a major restriction on positioning sources and receivers because tunnels are generally narrow. Additionally, if optimum array of sources and receivers is not chosen, improved accuracy cannot be expected even with the addition of more sources and receivers. Therefore, in this chapter, the most logical array of sources and receivers with high accuracy is examined by conducting surveys with a horizontal array and three-dimensional array under the same conditions, as shown in Figure 2 (Shirasagi et al.(2004)).

Figure 3 shows a comparison between the results based on horizontal array and the results based on three-dimensional array. The figure shows that the reflection surface (1), where a massive groundwater inflow took place, was detected via both arrays. However, the poor geological location (fault fracture zone) from 1800m in tunnel distance from the portal (TD) onward determined from the results of advanced boring conducted beforehand is detected as only one prominent reflection surface (2) by horizontal array. On
the other hand, the results of three-dimensional array detected three reflection surfaces ((2)-1, (2)-2, (2)-3) from TD 1800m onward. In addition, a greater number of reflection surfaces occur in the vicinity of the source and receiver points in the horizontal array result than in the three-dimensional array result. Actual geological observations did not reveal such clear discontinuous surfaces that would act as reflection surfaces in this area. Thus, the horizontal array is not able to detect reflection surfaces that actually exist in positions far from the face, and also generates artefacts around the source and receiver points. This is attributed to the fact that the horizontal array restricts wave path to particular directions compared to multiple independent wave paths by three-dimensional array, and thus produces less information on reflection surfaces. This in turn causes problems such as artefacts and the convergence of reflection surfaces located far from the face into a single location.

Consequently, it is clarified that geological conditions far away from the face can be predicted in greater detail through three-dimensional array and is verified that the three-dimensional array is more effective for exploring a wide range of geological conditions not only ahead of the face but also in the surrounding tunnel area because it allows for greater suppression of artefacts.

2.2 Comparative study of receiver sensor and installation method

The TSP system employs three-component geophones and they are installed in holes drilled into the tunnel walls, whereas the TRT system is composed of one-component accelerometers and they are pasted on the tunnel walls with cement. Then, the comparative study is conducted whether or not the TRT system is equivalent to the TSP system in terms of signal acquisition.

(1) Comparative study of sensors

Our first step in examining receiving sensors is to compare one-component accelerometers (Endevco Model 752A13) and three-component accelerometers (Endevco Model 65) shown in Figure 4. As a result, three-component accelerometers are approximately 1/10 less sensitive than one-component accelerometers. Three-component accelerometers would be effective in determining complicated geological conditions nearby the face. However, the most important thing is to predict geological conditions along tunnel axis with high accuracy. Therefore, it is reasonable to use one-component accelerometers for the TRT system. It is also possible to construct a three-component sensor by three one-component accelerometers, however, it is troublesome and time-consuming to handle three times as many cables. Although one-component accelerometers are sensitive to a wave from only one direction, the three-dimensional array can provide three-dimensional images as mentioned in 2.1.

(2) Comparative study of installation methods

Next, following three options for installing receiving sensors as shown in Figure 5 are compared:
(a) Installed on special base bonded to shotcrete surface.
(b) Installed on the head of fibre bolts inserted into the bedrock.
(c) Installed on the head of rock bolts

The first method is concerned that acquired waveforms would deteriorate as a result of installation on the shotcrete surface. However, it is the superior method in terms of workability for preparation and removal. The second method is expected to result in the acquisition of waveforms with superior SN ratios due to use of fibre bolts, which have low propagation loss as a medium. The third method is considered to reduce preparation work by means of pre-installed rock
bolts. In addition, fine signals are expected to be acquired because seismic waves can be directly received via the rock bolts.

Figure 6 shows the comparative test results of the waveforms acquired through the three installation methods from the same source. As shown in the figure, there are hardly any differences between each installation methods.

According to this comparative study, the first method is selected as the most practical and reasonable method. In this case, it is important to select locations where the bedrock and shotcrete contact well without any voids.

2.3 Development of a new source

P-waves have been mainly used for seismic reflection survey because it is easy to read their initial motions. However, they show significant attenuation due to the existence of voids and changes in density in rock mass, and also they are affected by water. Especially in soft ground, P-wave exploration results in images with low accuracy and short distance. On the other hand, S-waves have an advantage in terms of the resolution due to their shorter wavelengths than P-waves. Besides, they have nothing to do with water even in soft ground.

Thus, a new TRT oscillator shown in Figure 7 was developed. This oscillator composed of a magnetostrictive actuator is able to dominantly generate S-waves with high repeatability as shown in Figure 8.

To confirm the effectiveness of this oscillator, a comparison test with conventional hammer strikes on a friction plate is conducted. Hammer blows are administered to a side of the friction plate and also to the other side of it, receiving S-waves of one and the other polarity. The oscillator is also laid down on the same ground in the same direction as the plate. After some oscillations, it is reversed for the same reason as the hammer strikes.

Figure 9 shows the comparison of waveforms acquired on the ground. As a result, it is confirmed that using this new oscillator for TRT would allow us to generate and observe S-waves with high frequencies and short wavelengths, and to conduct a survey with superior resolution and higher accuracy.

Next, P-wave analyses and S-wave analyses are conducted by using the same data containing both P and S-waves, and
are compared with actual geological conditions in order to find the effectiveness of S-waves. Figure 10 shows a comparison of RQD (Rock Quality Designation) with the P-wave analyses and S-wave analyses. From this figure, it can be seen that in both the results of P and S-wave analyses, reflection surfaces (4) are detected from TD 1660 to 1705 m, being almost identical to the area of low RQD. However, regarding the low RQD area between TD 1605 to 1640 m, accumulations of reflection surfaces are detected in (1) and (2) in the S-wave analysis result, while significant reflection surfaces are not detected in the P-wave analysis result as (3). It is believed this is caused by differences in the resolution between P and S-waves. Consequently, it is confirmed that S-wave analyses are higher in resolution than P-wave analyses, and would provide more complex and detailed understanding of geological structures.

Figure 9. Comparison of waveforms acquired by new TRT oscillator (left) and hammer strike (right).

Figure 10. Comparison of TRT images using P-wave (top) and S-wave (bottom).
3. INSTALLATION OF A WIRELESS SYSTEM

The original TRT system developed by the authors is wired. As a result of its applications to many sites, it revealed some problems such as limitations in the array of sources and receivers in narrow tunnels, increased personnel and time required for preparation work, and decreased SN ratios of the acquired waveforms due to coupling noise. Thus, a wireless system was developed in order to achieve more accurate and economical TRT (Yamamoto et al. (2009)).

3.1 Overview of the wireless TRT system

Table 1 shows the specifications of the wireless TRT system. Figure 11 and Figure 12 show the system configuration and components. This system does not require long transmission cables as the original system has. It does eliminate the abovementioned problems; however, it was also necessary to address the following new problems:

   i) Deterioration of waveform analysis accuracy due to synchronization problems of the wireless transmitters
   ii) Influences of construction machinery and equipment, etc. on wireless transmissions (directional problems of high-frequency radios)
   iii) Interference of multiple reflection waves (multipath) on wireless transmissions
   iv) Compliance with national radio standards

For the first issue, the methodology given below makes it possible to synchronize each wireless transmitter: firstly, a seismic generation time signal is immediately and simultaneously sent wirelessly from the trigger signal transmitter wired to the hummer switch to all the wireless transmitters wired to the accelerometers when the hammer is used to generate seismic waves. As soon as the wireless transmitters receive the time signal, they start to acquire seismic signals with accelerometers. Finally, the wireless transmitters send obtained seismic signals to the computer via radio waves.

Regarding the second and third issues, spread spectrum (SS) communication system with a 2.4 GHz specific low-power band is adopted for the wireless module. The SS technique is a method wherein the signal information is spread over a wide frequency band, and the original information signal is extracted from the spread signal at the receiving end. It is characterized by low power flux density and high resistance to interference, etc. The fourth issue was overcome by the manufacturer undergoing standard examinations at testing organization.

Table 1. Wireless TRT system specifications.

<table>
<thead>
<tr>
<th>A/D Conversion</th>
<th>Sample interval range</th>
<th>Maximum record length</th>
<th>Radio specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-bit</td>
<td>0.0625msec(16kHz) - 0.5msec(2kHz)</td>
<td>174762 samples</td>
<td>2.4GHz (FHSS)</td>
</tr>
</tbody>
</table>

3.2 Verification test in a small TBM tunnel

Figure 13 shows the internal conditions of a small TBM tunnel. As can be seen, several pieces of machinery and equipment were installed in such a way as to obstruct the wireless transmission. The goal of this verification test was to confirm the practicality of the wireless TRT system in small tunnels and tunnels with many obstacles, where wireless communication conditions are considered to be bad. For the test, the performance of the wireless system is compared with that of the original wired system in the tunnel.

As a result, it is confirmed that using the wireless TRT system allows waveforms to be obtained in all channels, and communication failures and communication errors due to multipaths do not occur even in such a narrow and crowded tunnel. Figure 14 shows a comparison of the results of waveforms obtained by the wireless TRT system and the original wired system. This shows that there are no gaps in the time axis for both waveforms. Therefore, it is demonstrated that the synchronization of each wireless transmitter is carried out correctly. Additionally, it is verified that the waveforms obtained by the wireless TRT system have both higher signal levels and SN ratios than that by the original wired system.
Figure 15 shows a comparison of the wireless TRT result with the geology, the rock mass class and the rock mass strength calculated from TBM machine data. The TRT result shows a group of strong reflection surfaces which indicates the change from soft to hard rock from 70 m ahead of a tunnel face, corresponding to the boundary between the slate and the hard gabbro, and also to the start of "fair rock". To conclude, the wireless TRT system allows to set optimal arrays of sources and receivers even in narrow and crowded tunnels without concern for transmission cable lines.

Additionally, the SN ratio of obtained waveforms can be improved because it is free from coupling noises. Finally, it cuts back on personnel and hours needed for measurement preparation and removal, and makes it possible to significantly reduce the costs.

Figure 13. View of tunnel internal. Figure 14. Comparison of waveforms acquired by wireless and wired system.

Figure 15. Comparison of TRT image with geology, rock mass class and rock mass strength.
4. APPLICATION TO AN ACTUAL SITE

4.1 Site overview

The pilot tunnel in this site was excavated parallel to the main tunnel and advanced 1.0 km ahead of it. At the time of exploration, mainly limestone occurred up to the face. Geological investigations such as geological reconnaissance and seismic refraction surveys conducted before the excavation predicted the existence of a relatively large fault in the vicinity, being concerned that this would present a large obstacle during excavation. Then, the TRT was conducted from the pilot tunnel in order to confirm the presence of the fault and understand its continuity to the main tunnel. Simultaneously, drill loggings were conducted from the face in order to validate the prediction accuracy of the TRT (Yamamoto et al., 2003).

4.2 Discussion on the results

Figure 16 shows a comparison of the results of the TRT, the drill loggings and the geological observation after excavation. The TRT result indicates three areas of geological concern in which reflection surfaces in block form appear together: (1) around TD 570 m, (2) around TD 595 m, and (3) around TD 610 m. Because the dark blocks appearing closer to the face represent “hard to soft” discontinuous surfaces, and the light blocks appearing closer represent “soft to hard,” the area of geological concern (1) is predicted as the “hard to soft” boundary, and the areas of concern (2) and (3) are predicted as deteriorated zones approximately 15m wide. In addition, it is interpreted that the large blocks visible from TD 650 m onward are artefacts, and those from the area of concern (3) onward is hard rock. Regarding the continuity to the main tunnel, clear continuity would not be found around area of concern (1), whilst the areas of concern (2) and (3) would continue to the positions approximately 15m before their appearance in the pilot tunnel.

Table 2. Result of each survey and geological observation.

<table>
<thead>
<tr>
<th>Distance from the portal (m)</th>
<th>Result of the seismic reflective survey</th>
<th>Drill energy coefficient (J/cm³)</th>
<th>Geological observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 570</td>
<td>Transition to softer rock</td>
<td>Decreasing from 150 to 100</td>
<td>Beginning of sedimentary complex zone with limestone and shale</td>
</tr>
<tr>
<td>(2) 590</td>
<td>Transition to softer rock</td>
<td>Decreasing from 100 to 50</td>
<td>Interfingering zone, relatively clay rich</td>
</tr>
<tr>
<td>(3) 610</td>
<td>Transition to harder rock</td>
<td>Increasing from 50 to 150</td>
<td>End of sedimentary complex zone, relatively hard shale rich</td>
</tr>
</tbody>
</table>
Table 2 presents a comparison of the TRT, drill logging results and the observed geological result after excavation, based on Figure 16.

As shown in Table 2, the positions of the areas of geological concern from the TRT result are consistent with the change of the drill energy coefficient derived from the drill loggings. In addition, a comparison with the observed geology reveals that the TRT result matches the area from around (1) TD 570m, where the limestone begins to interfinger with the slate layer, to TD 630m, where it completely shifts to slate. In fact, thin clay layers by weathering and alteration were often observed in (2) and also relatively hard slate appeared at (3).

5. CONCLUSIONS

This paper reported on the principles, the overview of the development of the TRT and one case study.

At the beginning of the development, the performance of the TSP system was tested. As a result, some inherent problems were found; namely, the strike of the strata must be assumed, and small variations in analytical accuracy appear from person to person and based on experience. Also, the evaluation results remain two-dimensional and output only the reflection surface on the tunnel line in order to simplify analysis.

Next, in an attempt to overcome the problems in the abovementioned two-dimensional TSP system, the TRT was developed, which does not require boring for the installation of sources and receivers, and makes it possible to assess geological conditions 100-150m ahead of a tunnel face via hammers and magnetostrictive sources. Moreover, assessment results are displayed in three dimensions, and exploration range can be determined at-will, thereby allowing for geological assessment of the surrounding tunnel area at any range.

The principle of the reflection coefficient, which is a normalised amplitude of each reflected wave, and imaging concept based on isochronic surfaces were introduced to analyses of reflected waves. This allows to specify three-dimensionally the position of geologically discontinuous surfaces ahead of a tunnel face.

In order to achieve three-dimensional imaging, three-dimensional array of sources and receivers was selected as a result of comparative study with the horizontal array. It was also demonstrated that the three-dimensional array contributes to obtain more accurate results than the horizontal array.

The apparatus for sources and receivers and the installation method were studied. The comparative study between one-component and three-component accelerometer clarified that the former had about 10-fold sensitivity and the three-dimensional array could compensate the difference between one-component and three-component. Next, three installation methods were compared. From the results, it was verified that the method to paste the accelerometers with special bases on shotcrete surfaces provided sufficiently excellent waveforms as well as it was practical and rational.

Regarding the source, magnetostrictive actuator was applied as a new oscillating apparatus. The results of the test showed that compared to conventional hammer strikes, the apparatus had high repeatability. In addition, it was able to generate S-waves dominantly besides P-waves. This could contribute to achieve accurate and detailed exploration because of their shorter wavelengths than P-waves.

Finally, the wireless system was developed and compared with the wired TRT system. The results showed that the wireless system made it possible to conduct the survey with optimal positioning of sources and receivers even in narrow and crowded TBM tunnels, and that coupling noise was eliminated, thereby allowing more accurate exploration. Additionally, it is confirmed that it would greatly reduce the time and effort required for preparation and removal work, allowing more economical surveys.

This system has been tested on-site in approximately 100 times in Japan and approximately 50 times in the US and other countries. As given in the case study, its accuracy and adaptability have been rather proven, however, it remains a matter of research on filtering technology, methods combined with other explorations, and expanding into vibration monitoring technology, etc. The authors would like to apply the developed TRT system for reasonable and safe tunnel construction as well as to improve the system in terms of accuracy and practicality.

REFERENCES


