



Evaluation of geological conditions ahead of TBM tunnel using wireless seismic reflector tracing system[☆]



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ABSTRACT

The purpose of our work was to develop a new survey system which can evaluate a geological condition ahead of a TBM tunnel face accurately and rapidly, and to apply this system to an actual tunnel site to verify its effectiveness. The authors have compared their new wireless seismic reflector tracing system with the conventional 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. Furthermore, it is confirmed that it would greatly reduce the time and effort required for preparation and removal work, allowing more economical surveys.

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1. Introduction

For excavation by Tunnel Boring Machine (TBM), it is impossible to evaluate the geological conditions such as faults, fractured zones and geological boundaries like weathered layers, ahead of a tunnel face. This may hinder the high-speed and economical excavation, particularly in complex ground conditions.

Generally, seismic refraction survey conducted on the ground surface is normally carried out as a preliminary survey; however it does not provide accurate information of faults and fracture zones sufficiently. 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 has increased recently attracted more attentions of the survey techniques. This is because TBM excavation has advantages over conventional NATM in the rate of advance and safety, however it unable us to observe geological conditions ahead of a tunnel face.

From these points of views, several studies have been conducted both in- and outside Japan regarding survey techniques using seismic reflection waves to explore ahead of tunnel faces

(Sattel et al., 1996; Inaba et al., 1996; Kasa et al., 1996; Ashida, 2001; Ashida et al., 2001). For this investigation the authors conducted seismic surveys using three-dimensional seismic Reflector Tracing technique (TRT). TRT creates a 3-D isometric map of geological structures up to 100–150 m ahead a tunnel face and up to 30 m around a tunnel alignment (see Fig. 1). 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 (Yamamoto et al., 2003, 2007). However, the original TRT technique used wired installation to conduct seismic surveys. This contributed to some problems such as limitations in the array of sources and receivers in narrow TBM tunnels, increased personnel and time required for preparation work, and decreased SN ratio of the acquired waveforms due to a coupling noise.

To address these problems and the needs of the tunnelling operators to be able to predict geological conditions ahead of the TBM driven tunnel face, a new wireless TRT system has been developed, and was applied by the authors at actual tunnel sites to verify its effectiveness.

2. Development of the new system

2.1. Principle of TRT system

The concept of using seismic reflection for imaging ground conditions in three-dimensions is shown in Fig. 2. For each source and

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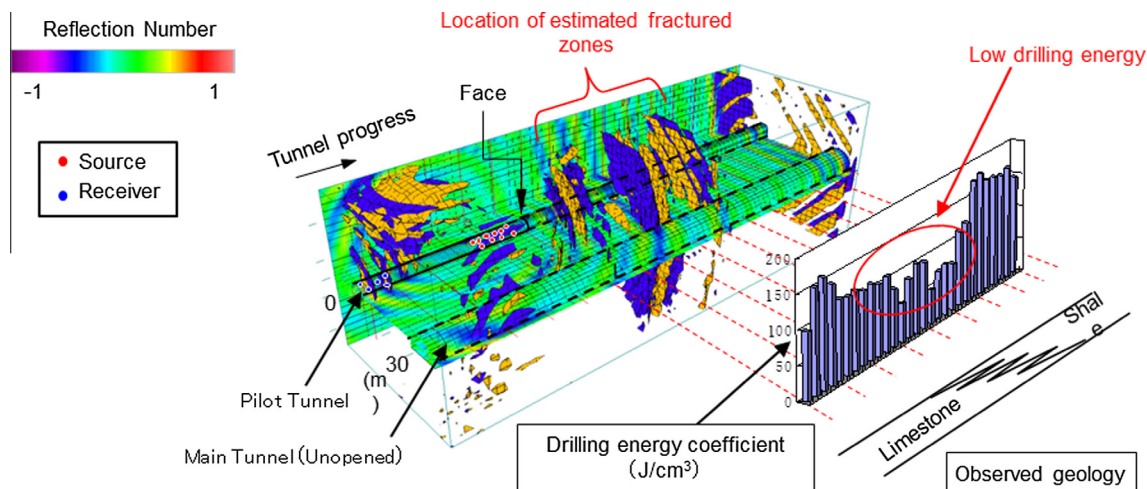


Fig. 1. TRT volumetric image with drill energy coefficient and observed geology (Yamamoto et al., 2003).

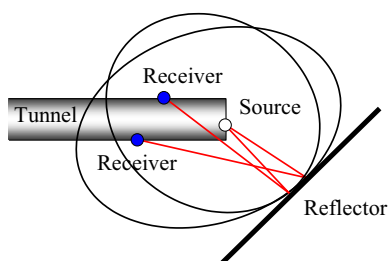


Fig. 2. Conceptual image of TRT.

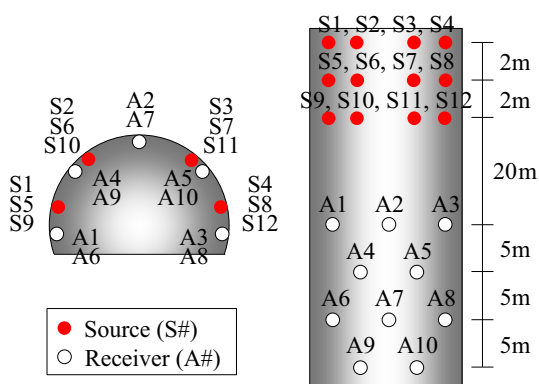


Fig. 3. Standard array of sources and receivers.

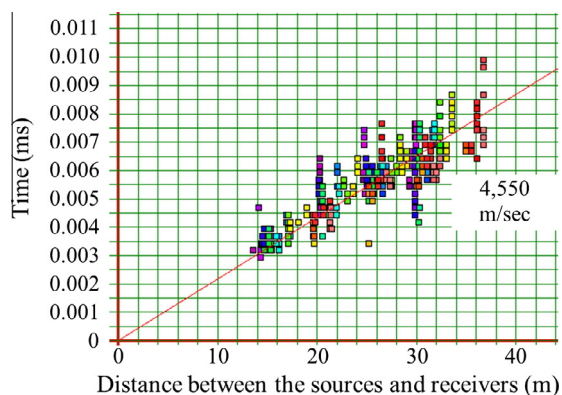


Fig. 4. Calculation of the velocity of the direct waves.

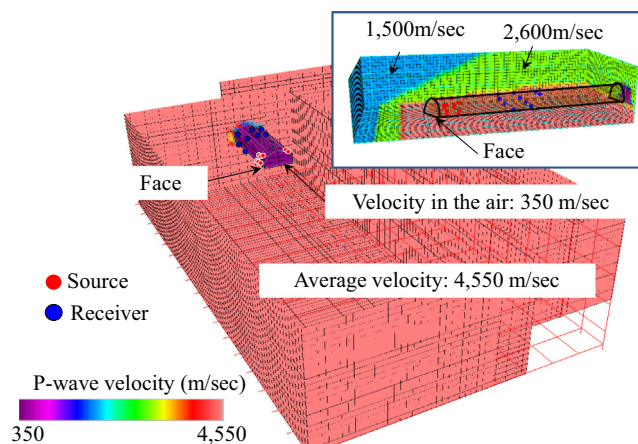


Fig. 5. Initial velocity model.

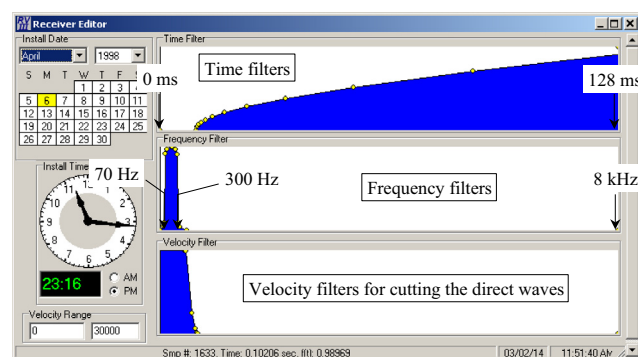


Fig. 6. Filtering window.

receiver of known location, the locus of all possible reflector positions defines an ellipsoid. For a sufficient number of sources and receivers forming a three-dimensional array, each boundary/reflecting horizon can be identified as an area where a majority of ellipsoids intersect. This system usually uses ten accelerometers as receivers and twelve sources arrayed three dimensionally as shown in Fig. 3, so that innumerable ellipsoids, which are enough to define reflecting horizons, can be drawn through the combinations of source/receiver points in the explored space. Reflecting

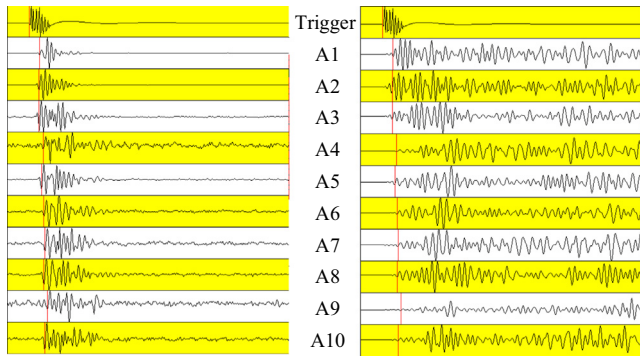


Fig. 7. Original waveform (left) and filtered waveform (right).

Table 1
Wireless TRT system specifications.

	System specification
A/D conversion	24-bit
Sample interval range	0.0625–0.5 ms (16–2 kHz)
Maximum record length	174,762 samples
Radio specifications	2.4 GHz (FHSS)

horizons, which are likely to be faults, fractured zones, rock boundaries and cavities, are described as the distributions of the “reflection number” which is the ratio between the average level of measured amplitude for reflected signals and the source signal.

The original TRT developed by the authors was wired system. As a result of its applications to many sites, some problems were 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 survey.

2.2. TRT data analysis processing

The iterative process for producing the images of anomalies ahead of the tunnel face is as follows;

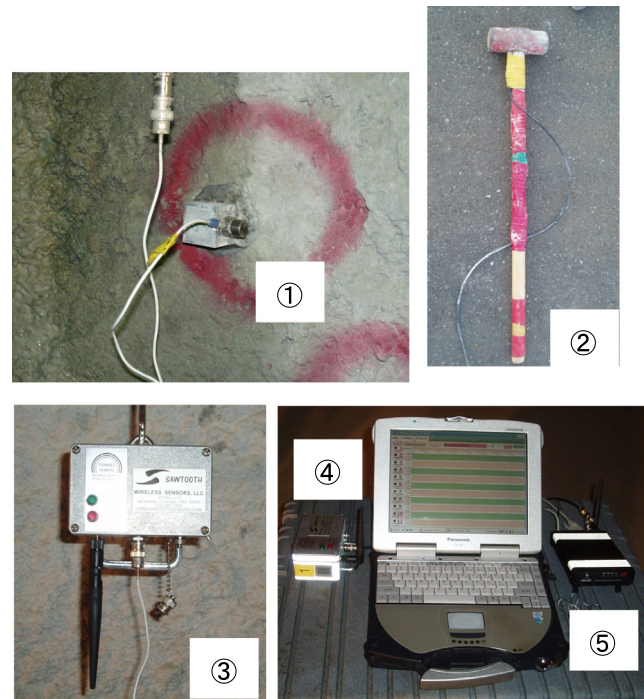


Fig. 9. Components of wireless TRT system.

- The image volume boundary (including sources and receivers) and the pixel size are established taking the resolution of the ground images, which is inversely proportional to the distance from the array and directly proportional to the shortest detectable wavelength, into consideration.
- Velocity model is calculated using direct waves travelling from sources to receivers along the tunnel (Fig. 4), and the average velocity is expanded over all the remaining pixels of the image volume (Fig. 5). In addition to this, detailed velocity model obtained by other preliminary surveys such as refraction survey from ground surface and seismic velocity logging survey is also available (Upper right at Fig. 5).
- The existing tunnel is “excavated” by changing velocity within perimeter of the tunnel to the velocity in the air (Fig. 5).

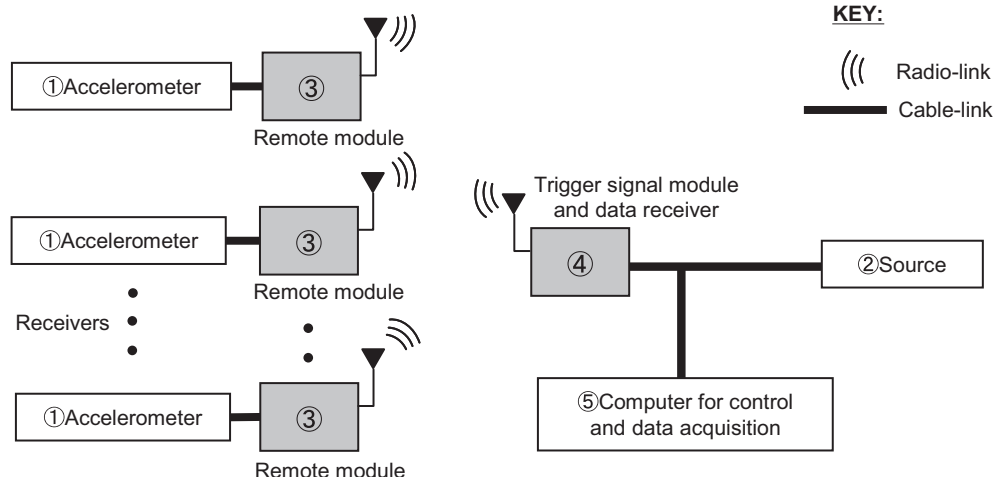


Fig. 8. Block-schematic of wireless TRT system.

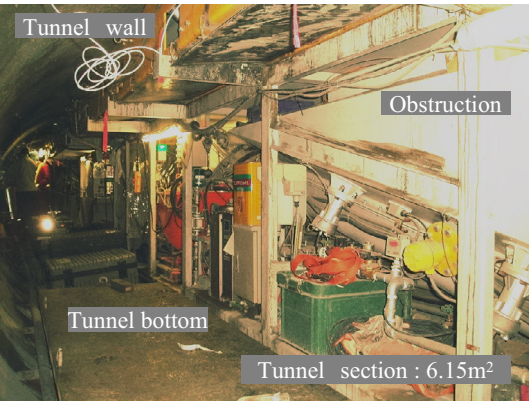


Fig. 10. View of tunnel internal.

- The trigger time and direct wave travel times are used to determine the common time delay at source for all reliable records. Records showing unstable trigger time have to be eliminated.
- Average attenuation parameters are assessed, and proper time filters to compensate for attenuation and weigh records dependent on their number are defined. Also optimum frequency filters are defined (Figs. 6 and 7).
- Spatial stacking of all seismic waveforms is conducted.
- Image is analysed for balanced spread of reflective anomalies throughout the image volume. Decision is made if the image is balanced indicating that attenuation and frequency filters are appropriate, or they need to be changed and the spatial stacking needs to be repeated.
- The reflection numbers generated by the system are relative and are normalized with respect to the average of 1.

2.3. Overview of the wireless TRT system

Table 1 shows the specifications of the wireless TRT system. Figs. 8 and 9 show the system configuration and components. This system does not require long transmission cables as the original

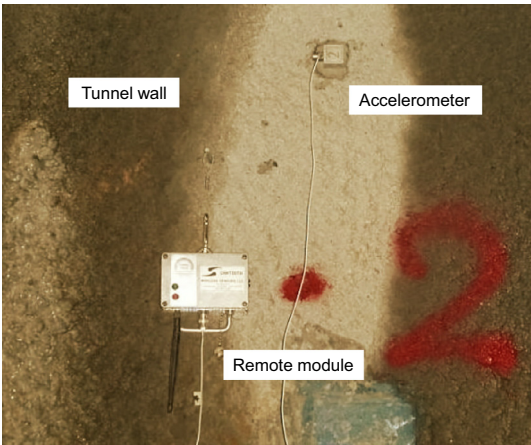


Fig. 12. Wireless remote module connected to accelerometer mounted tunnel wall.

system has. It does eliminate the abovementioned problems; however, it was also necessary to address the following new problems:

- Deterioration of waveform analysis accuracy due to synchronization problems of the wireless transmitters
- Influences of construction machinery and equipment, etc. on wireless transmissions (directional problems of high-frequency radios)
- Interference of multiple reflection waves (multipath) on wireless transmissions
- Compliance of 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 hammer 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

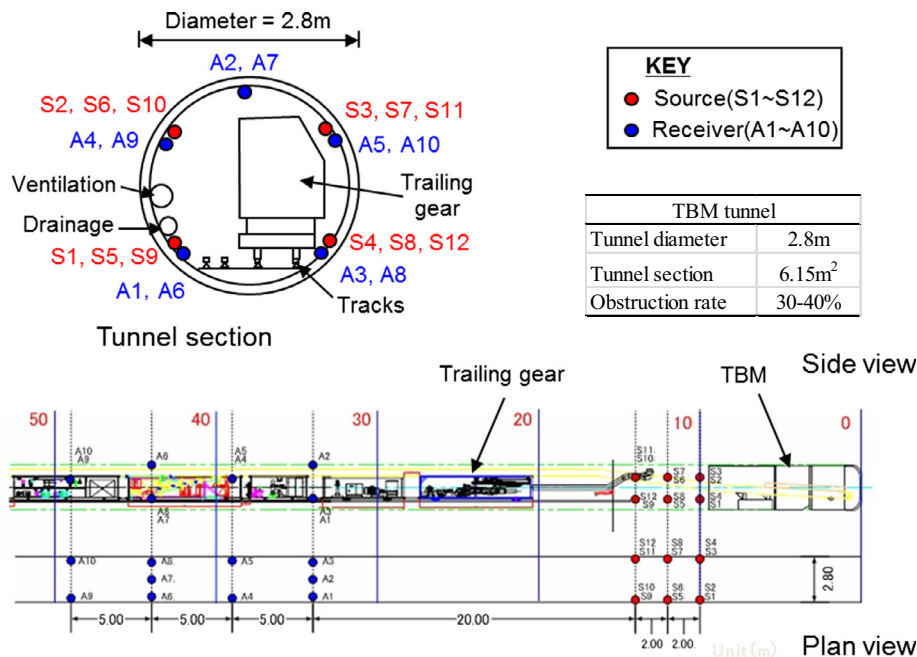


Fig. 11. Layouts of seismic sources and accelerators for TRT Survey.

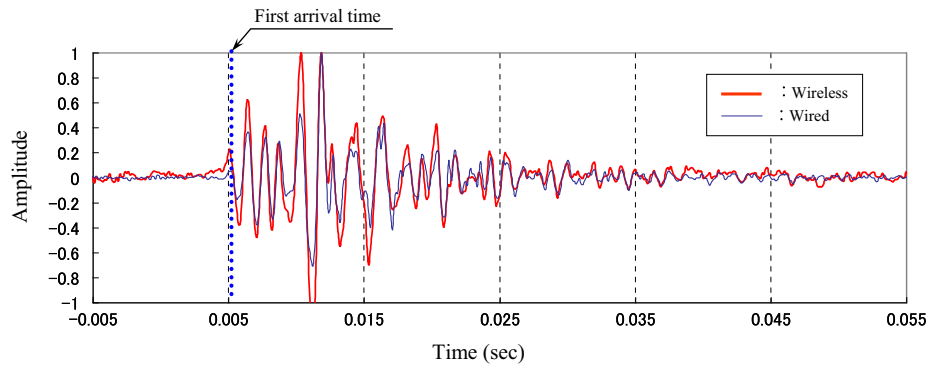


Fig. 13. Comparison of waveforms acquired by wireless and wired system.

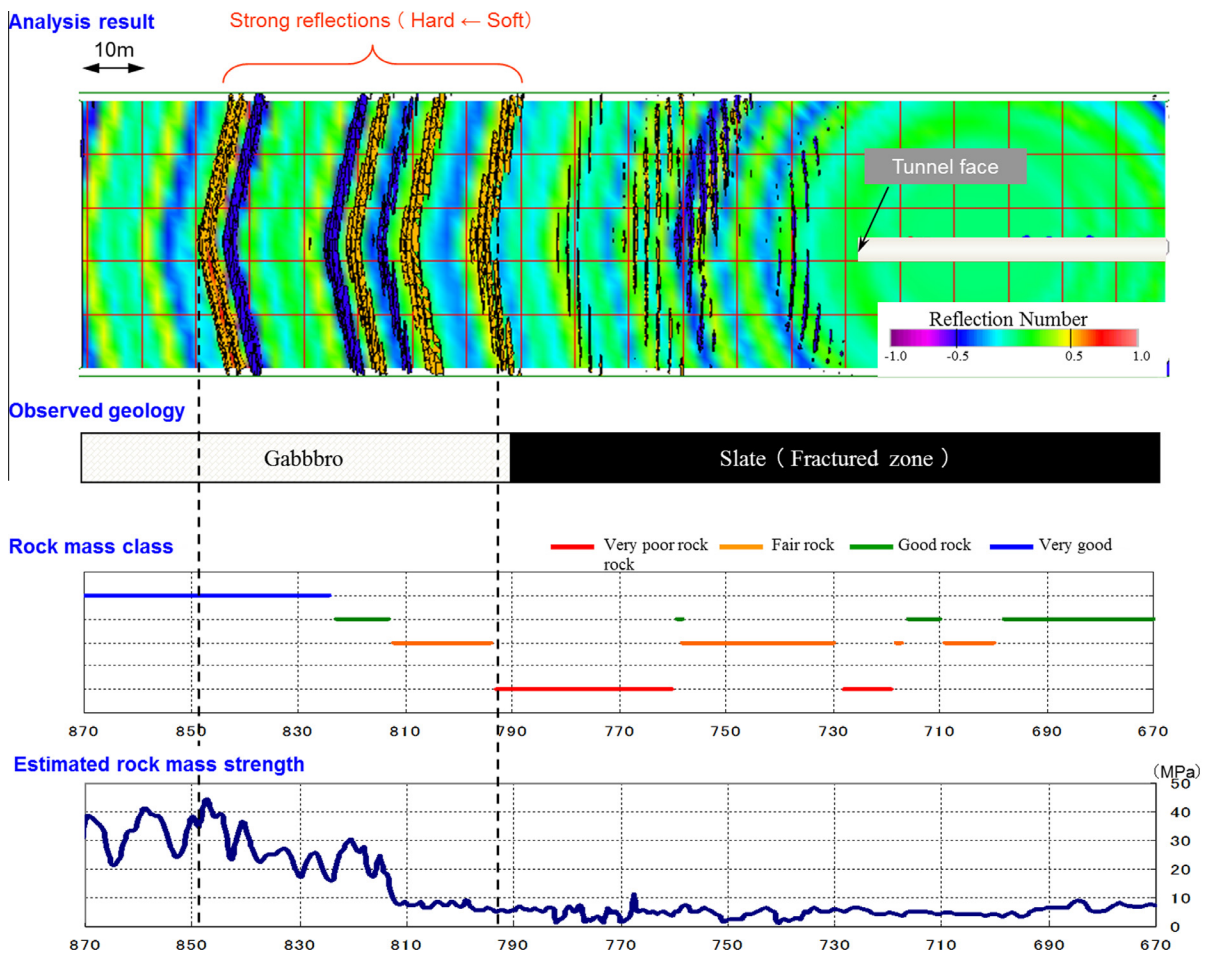


Fig. 14. Comparison of TRT image with geology, rock mass class and rock mass strength.

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.

3. Verification test in a small TBM tunnel

The field test was designed to verify fitness and reliability of the Wireless TRT surveying system versus the Wired TRT system in possibly the toughest and most disruptive conditions for radio communication. The evaluation was conducted in a small cross-section (6.15 m²), highly obstructed TBM tunnel (Fig. 10).

3.1. Site characteristics

The length of the extracted small TBM tunnel at the time of survey was 4.2 km. This tunnel is excavated by a TBM with a cutting

diameter of 2.8 m (Fig. 11). The tunnel path cuts mostly through slate interrupted sporadically by gabbro. The preliminary seismic survey done from surface along the projected tunnel alignment yielded P-wave velocities between 3.8 and 4.6 km/s. This led to prediction of relatively competent rock and good geological conditions for tunnelling. However, the investigation also detected some lower-velocity zones, possibly fractured ground. An intrusion of very competent gabbro into the tunnel path was considered possible as well.

3.2. Survey layout

The layout of seismic sources and receivers comprises 12 source points and 10 receiver points (Fig. 11). The Wired TRT system test was followed by the test of the Wireless TRT system. Each system used the same layout of sources and receivers. Fig. 12 shows the wireless Remote Module connected to an accelerometer coupled to the tunnel wall. A 3-m long cable connecting accelerometer to the Remote Module allowed some flexibility in positioning the Module further from the ferromagnetic components in the tunnel profile, and closer to the optimum line-of-sight to mitigate possible disruption of radio communications with the data acquisition equipment. This was particularly important as the steel structure of the trailing gear occupied approximately 30–40% of the tunnel profile (Figs. 10 and 11).

3.3. Survey result

In spite of the small diameter of the tunnel, which was additionally reduced by the components of the tunnelling equipment, there were no indications of any difficulties in radio communication between the components of the Wireless TRT survey system. Multipath fading, electromagnetic radiation and other sources of radio interference did not adversely affect the seismic records produced during the wireless TRT survey. Fig. 13 shows a comparison between waveforms acquired using the Wireless TRT system (Red¹) and waveforms acquired using the Wired TRT system (Blue). The records appear very similar with no difference in the travel times measured for the direct waves coming from the same source points. The matching travel times also confirmed that all the Remote Modules were precisely time synchronized. Additionally, the SN ratio of obtained waveforms can be improved because it is free from coupling noises.

Fig. 14 shows the volumetric image of the ground produced by processing seismic records acquired by the wireless TRT survey. The image is compared with the geology observed, and with the “Rock mass rating” and “Estimated rock mass strength from TBM machine data” parameters defined as the tunnel advanced. The weaker mostly negative anomalies correspond with the fractured rock zone. The strong mostly positive anomalies appear to match a competent gabbro formation.

4. Conclusions

This paper reported on the principles, the overview of the wireless TRT technique and one case study. The wireless system was developed and compared with the wired TRT system.

The results of verification test show;

- 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.
- It is confirmed that it would greatly reduce the time and effort required for preparation and removal work, allowing more economical surveys.

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¹ For interpretation of color in Fig. 13, the reader is referred to the web version of this article.