Verification of seismic survey results ahead of a tunnel face using drilling vibration data of ultra-long controlled boring

Masahito YAMAGAMI(1) ,Tomoyuki AOKI(1),Yoshiaki YAMANAKA(2), Toru TAKAHASHI (3) and Kenichiro NANBA(4)

(1) TAISEI Corporation Technology Center, Yokohama, Japan
E-mail:ymgmsh01@pub.taisei.co.jp
(2) SUNCOH Consultants Corporation, Japan, (3) Fukada Geological Institute, Japan,
(4) West Nippon Expressway Company Limited, Japan

Abstract

In the preliminary investigations of mountain tunneling, a seismic refraction survey from the ground surface is conventionally conducted, and a tunnel support pattern is designed based on the seismic wave velocity of the ground, as evaluated by the survey. The resolution of the velocity profile by this technique, however, is poor as the tunnel overburden becomes large. In response to this problem, the authors developed a new survey method in which drilling vibration data were used, called tunnel seismic probe drilling (T-SPD), to estimate the seismic wave velocity distribution ahead of the tunnel face so that it could be used in the design of tunnel support patterns. We conducted field demonstration tests of the T-SPD at three tunneling projects (Yamagami et al., 2012a; 2012b; 2012c; 2014a; 2014b). In this study, we report the results from the project using a drill rig with a drilling capacity of 1,000m (ultra-long controlled boring). The P-wave velocity distribution estimated by the T-SPD was found to agree with those estimated by the seismic refraction surveys from the ground surface and from the tunnel floor. The T-SPD can be thus an alternate exploration method for seismic refraction in cases where seismic refraction from the ground surface is difficult due to large tunnel overburden. According to a comparison between the P-wave velocity distribution and drilling specific energy data, which indicates the energy required for drilling per unit volume of rock, it is evident that the T-SPD is capable of properly evaluating ground conditions even where borehole logging may result in misleading information in areas with cuttings in a drilled hole. We suggest that the detection accuracy of poor ground conditions such as fracture zones can be improved by simultaneously conducting the T-SPD and the borehole logging.

Keywords: Mountain tunnel, Survey ahead of a tunnel face, SWD, T-SPD

1. Introduction

In conventional planning of mountain tunnels, seismic refraction surveys from the ground surface are performed as preliminary surveys. Tunnel support patterns are then designed based on the seismic wave velocity of the ground, as obtained by the seismic refraction survey. The resolution of the velocity profile estimated by this technique, however, is poor as the tunnel overburden becomes large. In such conditions, a survey ahead of the face during tunnel construction is considered to be more effective than the seismic survey from the ground surface. Two methods are generally used in the surveys ahead of the tunnel face: seismic reflection method known as tunnel seismic prediction (TSP) or horizontal seismic profiling (HSP), and borehole logging known as drilling survey system (DRISS). We can obtain information on the position and direction of the discontinuous surface using TSP or HSP. However, it is not possible to obtain property information such as the width of the fracture zone, which is important for designing tunnel support patterns. The drill machine data based method provides the specific energy distribution (MJ/m^3), which is related to the strength of the rocks, and is defined as the energy consumed to drill the rock per unit volume. Although borehole logging method provides data and drainage for groundwater at the same time, its disadvantages are that the drilling cross-sectional area is small relative to that of the tunnel face, and that it is difficult to correlate the drilling specific energy with the rock classification.

Therefore, we developed the tunnel seismic probe drilling (T-SPD) as a new exploration method that can evaluate the seismic wave velocity distribution ahead of the tunnel face in order to assist properly designing tunnel support patterns. Using a drill rig with a drilling capacity of 100m, we conducted field demonstration tests at two tunneling projects to confirm the effectiveness of the T-SPD (Yamagami et al., 2012a; 2012b; 2012c). At another tunneling project, we previously presented the results of two field demonstration tests using ultra-long controlled boring with a drilling capacity of 1,000m, and have confirmed effectiveness to a total drilled length of 250m (Yamagami et al., 2014a; 2014b). In this study, we report and verify the results for the remaining section of the previously reported project and additional field demonstration tests for a total drilled length of 710m where the tunnel excavation has been completed. We also add drilling specific energy data from borehole logging to the verification data.

2. Principle of T-SPD

In the exploration of petroleum resources, the seismic while drilling (SWD) using the vibrations generated by the drill bit is used to investigate the distribution of seismic wave velocity of the drilled section on the basis of the direct wave and to generate subsurface images by the reflected waves (Ashida, 1997). The SWD principle with the use of direct waves is shown in Fig. 1. The vibration generated by the drill bit is measured by the sensor attached to the swivel of the drill rig (pilot sensor) and those placed on the ground surface at some distance away from the drill rig (receiver sensors).

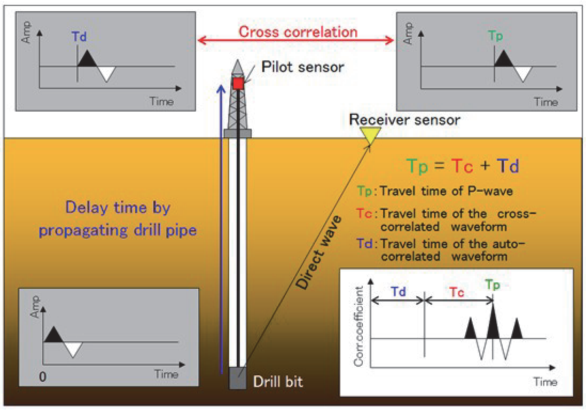

Fig. 1 Schematic chart of T-SPD（Sectional view）

In Fig. 1, Tp is the travel time of wave from the drill bit to the receiver sensor on the ground surface, while Tc is the travel time of the cross-correlated waveform, and Td is the travel time calculated from the auto-correlated waveform at the pilot sensor. A velocity profile of the seismic waves can be created from the arrival times obtained from these procedures. The T-SPD is a seismic method for estimating the seismic wave velocity profile ahead of a tunnel face and is based on the same principle as the SWD (Fig. 2).

3. Field Test

3.1 Site overview

The field test was performed in a road tunnel with a width of about 11m (Fig. 3). The maximum overburden was 150m. The geological features include mixed rock (shale, sandstone, and chert) in the Mesozoic age. Shale is mainly distributed over the survey area. Refraction survey results from the ground surface, conducted during a preliminary investigation phase, showed the presence of four low velocity zones ranging from 3.0 to 3.2km/s and those ranging from 4.4 to 4.6km/s along the tunnel alignment. In the section where the tunnel passed under rivers with a small overburden, a watertight

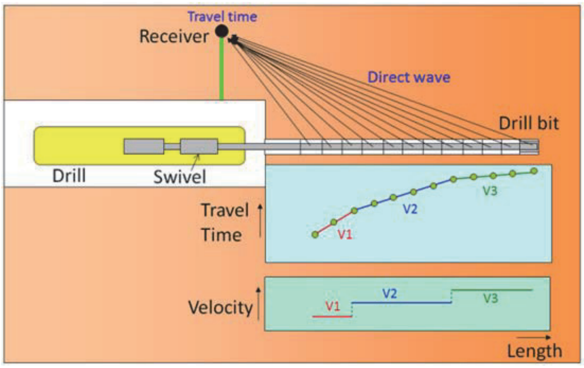

Fig. 2 Method for determining travel time in T-SPD by using SWD principle（Plan view）

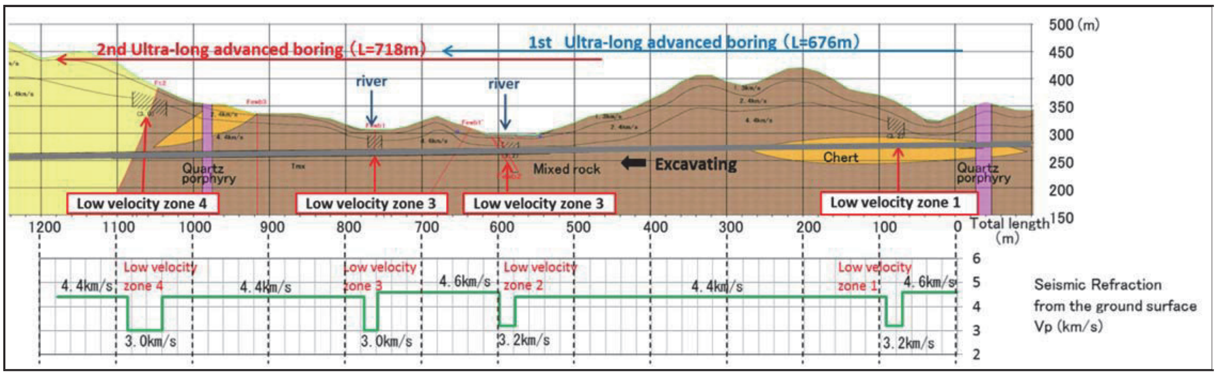

Fig. 3 Field test site and refraction survey results from the ground surface (longitudinal section)

structure is to be adopted to conserve the surrounding aquatic environment. To understand the hydrogeological structure of the sections, we conducted probe drilling twice (for total drill lengths of 676m for the first and 718m for the second, with an overlapping length of 217m) using an ultra-long controlled boring. In accordance with the specification requirements, the data to be acquired for the evaluation of ground conditions included the volume of groundwater inflow to the tunnel in a given section, the rock type determined using cuttings, and the drilling specific energy distribution. We also acquired P-wave velocity by applying the T-SPD to the ultra-long controlled boring.

3.2 Data acquisition

A T-SPD was conducted in the enlarged part of a tunnel. Schematic diagrams of the T-SPD are shown in Figs. 4 and 5. The experimental condition and a drill bit (inset) are shown in Photo. 1. To advance the exploration borehole, we deployed an ultra-long controlled boring. The drilling direction is controlled by managing the rotation of the string of the drill pipes. When drilling straight ahead, both the down hole motor and string are rotated (Fig. 6 left). When drilling in a curved trajectory, the down hole motor is activated without rotating the string, to direct the drilling in the direction of the bent sub equipped behind the drill bit (Fig. 6 right). All vibration data are continuously recorded whether drilling a straight or a curved borehole.

In the first test, we placed the receivers in a 21 m long borehole drilled from the right side of the tunnel wall looking toward the tunnel face. Seven 3-component geophones were placed at 3.0 m intervals in the borehole. Fig. 4 shows the layout of the receivers in this test. The length of forward drilling (=exploratory length) was 676 m.

In the second test, a 12 m long borehole was laid out 10m from the drill rig toward the tunnel face in order to reduce the machine noise. Two 3-component geophones were placed at 3.0 m intervals from the bottom of the borehole. Fig.5 shows the layout of the receivers in this test. The length of exploration borehole advanced was 718m. Seismic data processing was performed advancing the borehole 5m at a time to improve the S/N ratio. Regardless of the tunnel excavation work, measurements were conducted continuously during drilling. To verify the effectiveness of the T-SPD for a total drilling length of about 710m, we compared the P-wave velocity

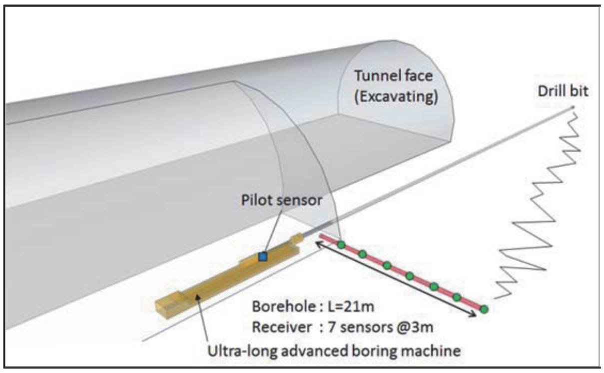

Fig. 4 First test layout of T-SPD

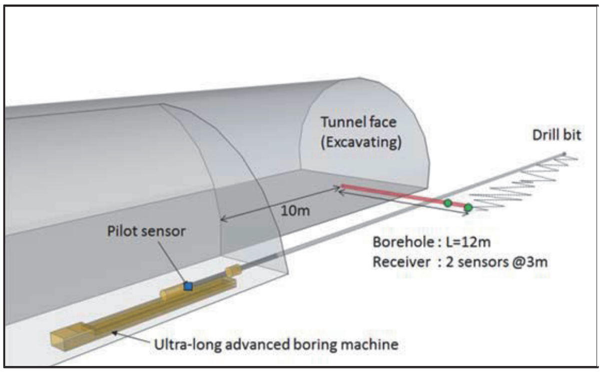

Fig. 5 Second test layout of T-SPD

Photo. 1 Experimental condition and a drill bit (inset)

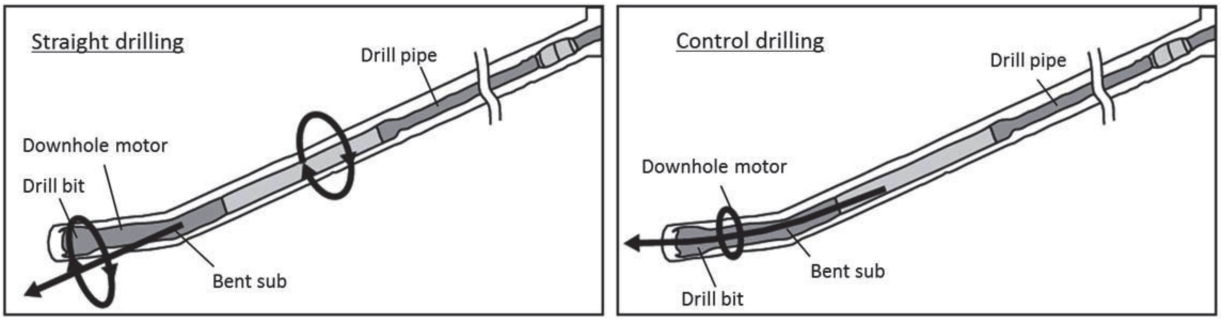

Fig. 6 Ultra-long controlled boring method (left: straight drilling, right: control drilling)

distribution predicted by the T-SPD with the results of the seismic refraction surveys from the ground surface and on the tunnel floor, the results of tunnel face observations, and the drilling specific energy distribution.

3.3 Field test results

Fig. 7 shows the spectrum of the pilot sensor, while Fig. 8 shows the auto correlation trace of the pilot sensor for the first test. In Fig. 7, two peaks may be observed at 20 and 80Hz. After removing the noise at these frequencies with a band-pass filter, we identified a peak at around 100Hz propagating through the string of the drill pipes, as shown in Fig. 8. We clearly observed this wave as it propagated along the string to a length of about 500m, and it appeared to have reciprocated three times between the swivel and the drill bit tip repeatedly. This multiple reflection indicates that string of the drill pipe propagating wave velocity was 4.8km/s.

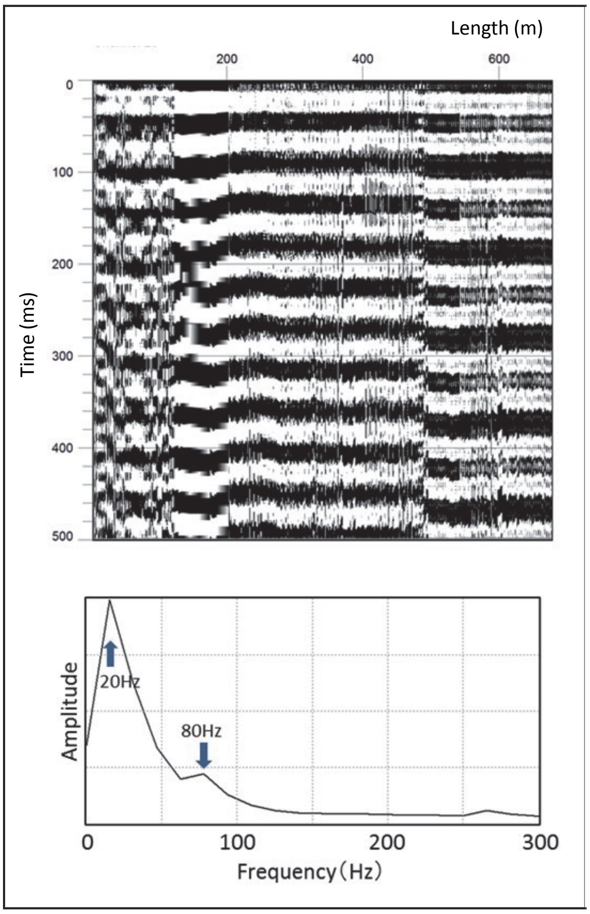

Fig. 7 Auto correlation traces and spectrum of pilot sensor (before applying band-pass filter)

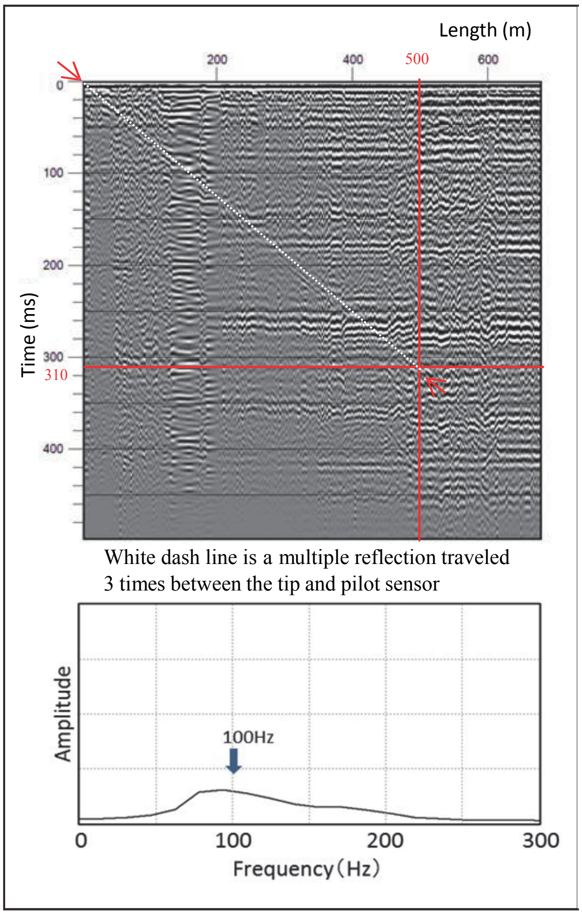

Fig. 8 Auto correlation traces and spectrum of pilot sensor (after applying band-pass filter 100-200Hz)

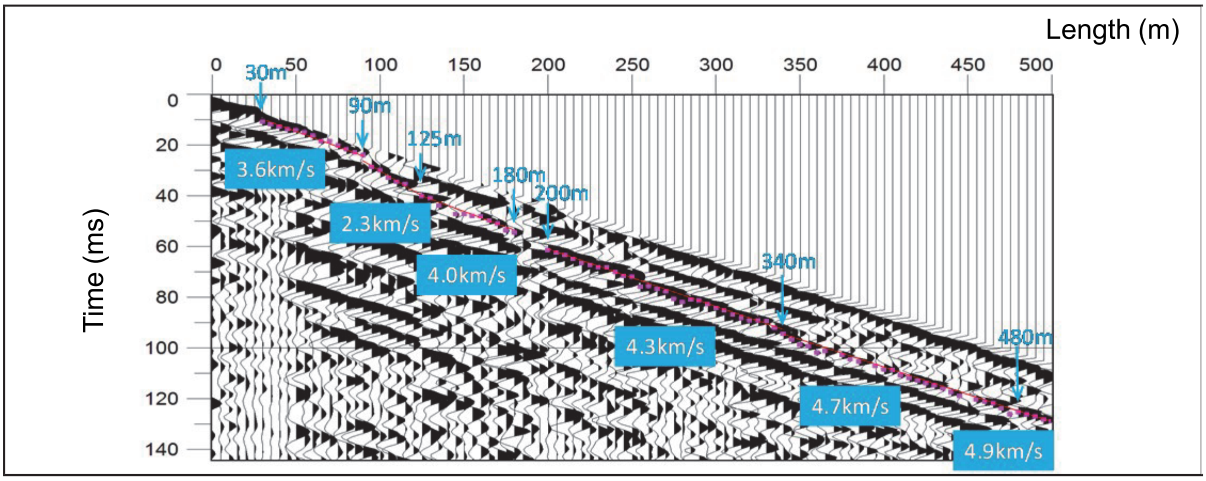

Fig. 9 Travel-time curve (first test)

Fig. 9 shows the clearest cross-correlated trace of the seven receivers at 21m in length along the borehole. To obtain the velocity profile shown in Fig.9, we corrected the travel times calculated by the velocity of the waves from their first breaks as they propagated to the string of the drill pipe. The first arrivals at the 0 -30 m and 180-200 m intervals were excluded in the determination of the velocity because they were either affected by the receiver offset (0-30m) or were unclear (180-200m).

Fig. 10 shows the spectrum of the pilot sensor, while Fig. 11 shows the auto correlation trace of the pilot sensor for the second test. In Fig. 10, a peak emerged at 20Hz. Using a band pass filter, we removed the noises, to reveal a spectral peak at around 100Hz that had propagated through the string, as shown in Fig.11. We clearly observed this wave propagating along the string to about 500m, and it also appeared to have reciprocated between the swivel and the drill bit tip, as in the first test. This

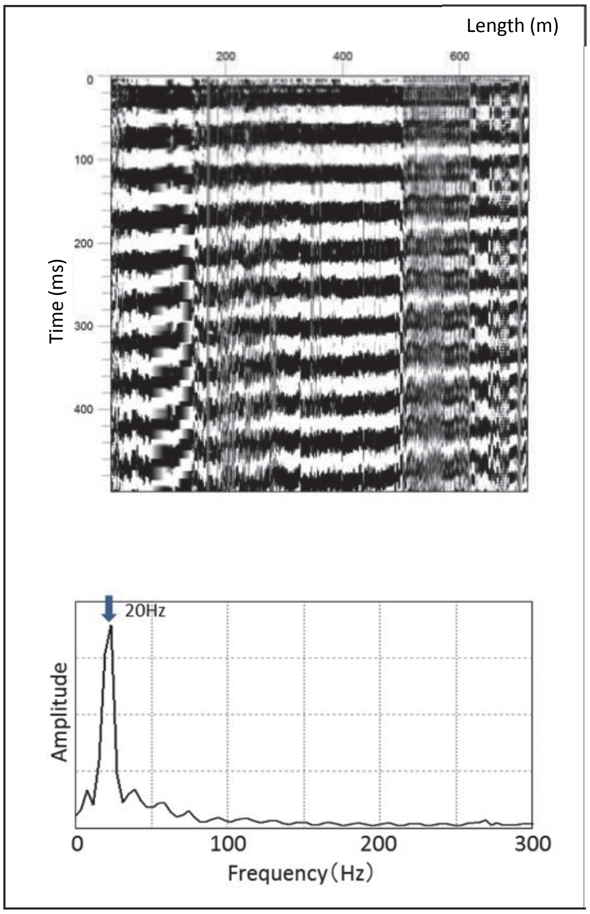

Fig. 10 Auto correlation traces and spectrum of pilot sensor (before applying band-pass filter)

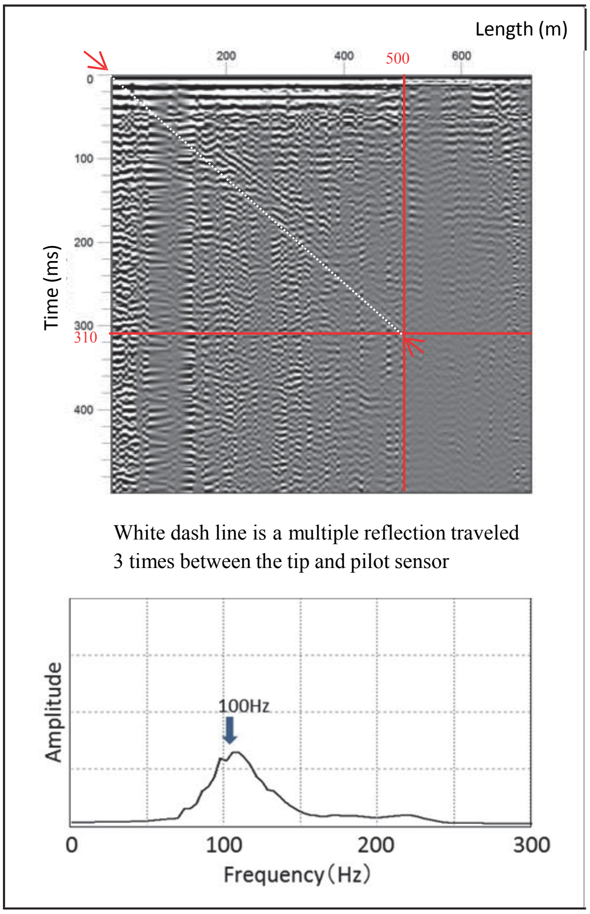

Fig. 11 Auto correlation traces and spectrum of pilot sensor (after applying band-pass filter 100-200Hz)

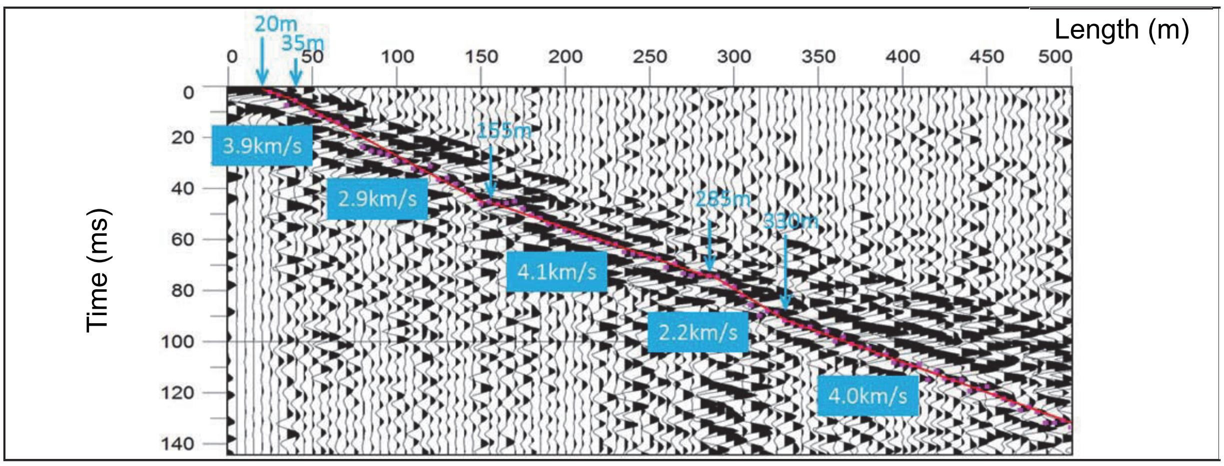

Fig.12 Travel time curve (second test)

multiple reflection indicates that the velocity of the wave propagating along the string of the drill pipe was 4.8km/s. It also suggests that direct waves from the drill bit reached a length of about 500m at the studied site. Therefore, the effective length was found to be 500m for the analysis of wave propagations.

Fig. 12 shows the cross correlated traces of the receiver installed at a length of 9 m in the borehole, which were clearer than those of the receiver installed at the borehole. Travel times calculated from their first breaks were corrected by the string propagating wave velocity to obtain the velocity profile shown in Fig. 12. The first arrival of waves at the interval of 0-20 m interval was not used for determining the velocity as they were considered affected by the receiver offset.

As to the reason the effective survey length was limited to about 500 m, we presumed that the S/N ratio became small when the length was longer than 500 m due to the use of smaller drill bits and the attenuation of the vibration of the drill bit.

4. Discussion

Fig. 13 compares the P-wave velocity determined from the T-SPD along the length of the exploration borehole with those from the seismic refraction investigations from the ground surface and on the tunnel floor. Correlations of the T-SPD results are also compared with the tunnel face observation and drilling energy observation.

It may be seen that P-wave velocity by the T-SPD varies from 2.3 to 4.9 km/s. We found three low velocity zones at total lengths of 30-125 m, 500-614 m, and 744-789 m.

P-wave velocity distribution by the seismic refraction survey from the tunnel floor varies from 3.7 to 5.2 km/s. We found the low velocity zones at total lengths of 50-120 m and 590-620 m. A low velocity zone at total lengths of 50-120 m agreed with that at total lengths of 30-125m by the T-SPD. While the other low velocity zone at total lengths of 590-620 m agreed with that of 500-614m by the T-SPD. It is clear that the T-SPD results are generally consistent with the results of the seismic refraction from the tunnel floor.

The seismic refraction survey from the ground surface gave three low velocity zones as shown in Fig.13. The low velocity zone 1 is consistent with the low velocity zone at total lengths of 30-125 m by the T-SPD. The low velocity zone 2 is consistent with the low velocity zone at total lengths of 500-614 m by the T-SPD. The low velocity zone 3 is consistent with the low velocity zone at total lengths of 744-789 m by the T-SPD. It is evident that the T-SPD results are generally consistent with the results of the seismic

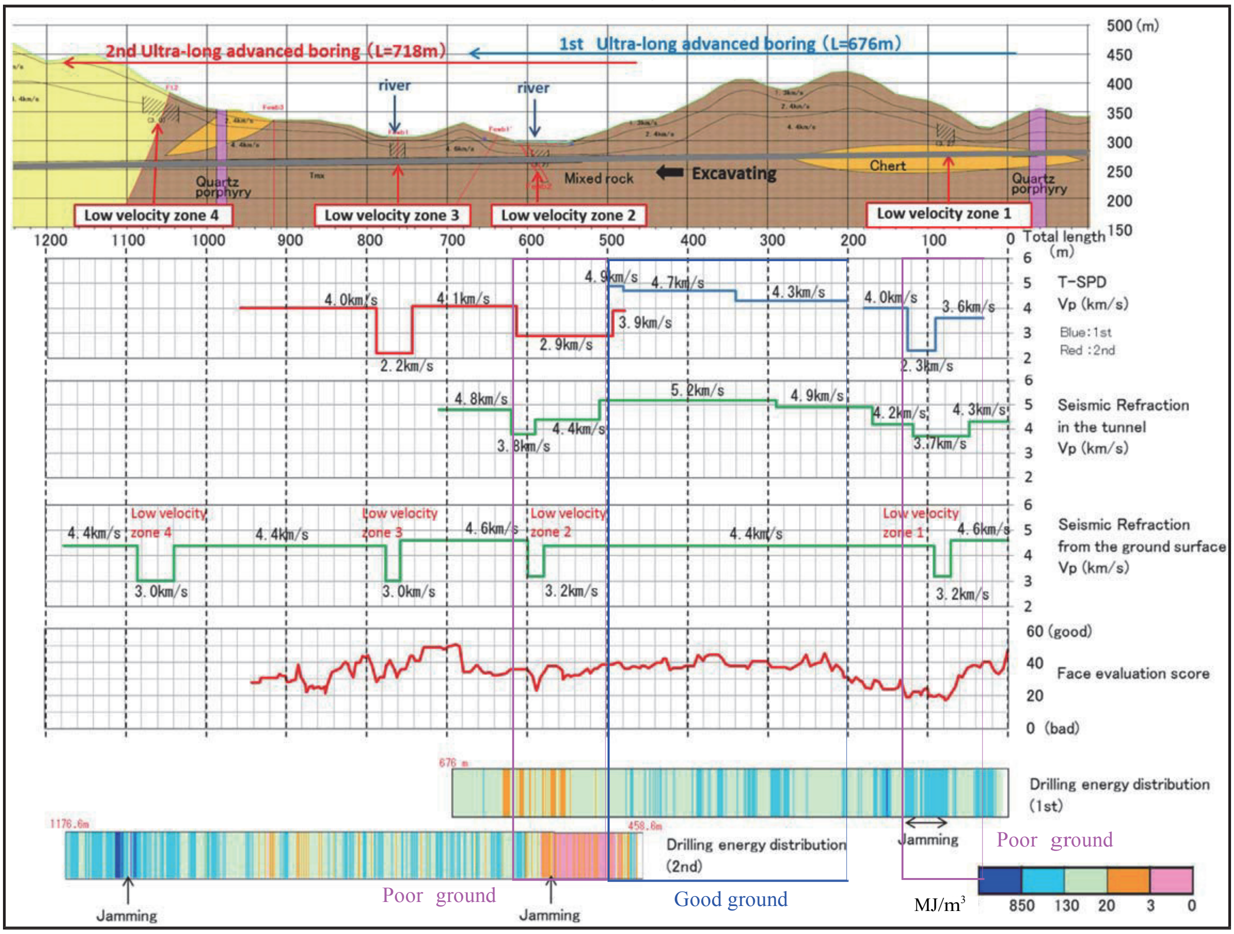

Fig. 13 Field tests results

refraction from the ground surface. T-SPD can therefore be utilized as an alternate seismic refraction method in cases where the use of seismic refraction from the ground surface is difficult due to a large overburden.

The face evaluation score by the tunnel face observation varies from 20 to 50. The low velocity zone at total lengths of 30-125 m by the T-SPD agreed with the section of face evaluation score around 20. The low velocity zone at total lengths of 500-614 m by the T-SPD agreed with the section of the face evaluation score 25-35. The low velocity zone at total lengths of 744-789m by the T-SPD agreed with the section of the face evaluation score 30-40. We found that the T-SPD results are generally consistent with the face evaluation score, and that the T-SPD could evaluate poor ground conditions as relatively low velocity zones (pink rectangles in Fig.13).

On the other hand, the relatively high P-wave velocity zone at the total lengths of 200-510 m by the T-SPD is generally consistent with the section of the face evaluation score around 40. We found that the T-SPD could evaluate the good ground condition as the relatively high velocity zone (blue rectangles in Fig.13).

In addition, we compared these results with the drilling specific energy distribution. On the basis of drilling specific energy, we identified a poor ground section at total lengths around 600m. However, we did not observe the poor ground section at total lengths around 100m. Since frequent jamming occurred around 100 m length, the drilling specific energy distribution might have presumably become high owing to the presence of cutting slime in the borehole, thus yielding a misleading result that the ground condition was good. We suggest that the detection accuracy of poor ground conditions such as fracture zones can be improved by simultaneously conducting T-SPD and borehole logging.

All in all, it is clear that the T-SPD method can be a very effective means of predicting and evaluating the ground geology and geotechnical property of the ground ahead of the tunnel face.

5. Conclusions

To evaluate a new seismic method, T-SPD, we performed field demonstration tests using the drill rig with a drilling capacity of 1,000m. We can draw the following conclusions from these two tests.

・We clearly observed a wave propagating along the string of the drill pipe to a length of about 500 m, which appeared to reciprocate between the swivel and drill bit tip. We therefore limited the effective exploration to length of about 500 m, on the assumption that the S/N ratio became small due to the influence of using smaller drill bits and the attenuation of the vibration from these drill bits at lengths greater than 500 m.

・Where verification has been completed, the T-SPD results using a drill rig with a drilling capacity of 1,000m, showed relatively good agreement with the face observations and P-wave velocity distributions estimated from seismic refraction surveys performed from the ground surface and from the tunnel floor for a total lengths of 710m. The T-SPD can be utilized as an alternate seismic refraction method in cases where the use of seismic refraction from the ground surface is difficult due to a large overburden.

・In addition the T-SPD results are generally in accordance with the drilling energy evaluation, except that at a depth about 100m, the drilling energy is evaluated rather high. Reviewing the drilling record, there were considerable jamming at that depth, and hence the drilling energy might have been overestimated.

・All in all, it is clear that the T-SPD method can be a very effective means of predicting and evaluating the ground geology and geotechnical property of the ground ahead of the tunnel face. We suggest that the detection accuracy of poor ground conditions such as fracture zones can be improved by simultaneously conducting T-SPD and borehole logging.

As a future study, we plan to validate the effectiveness of using T-SPD at total drilling lengths of 710 m and beyond, where low velocity zones have been observed. We also plan to adopt the use of T-SPD at other mountain tunnels using controlled boring.

References

Asida,Y. (1997): SWD(Glossary),Butsuri-Tansa,50,vol3,252-259 in Japanese.

Yamagami, M., Imai, H., Aoki, T. ,Tomono, Y. and Mitani,K. (2012a): Survey ahead of the tunnel by the use of SWD (Seismic While Drilling), Proceedings of the 67th JSCE Conference, Japan Society of Civil Engineers in Japanese.

Yamagami, M., Imai, H., Aoki, T. ,Yamanaka, Y. and Takahashi, T. (2012b): Case study on fracture zone evaluation by tunnel face survey with the use of drilling vibration data, JSEG, 2012 Meeting, 2012 in Japanese.

Yamagami, M.,Imai, H.,Aoki, T. ,Nakahara, F. (2012c): Development of survey Ahead of the

Tunnel by the use of Drilling Vibration DATA, Proceedings of tunnel engineering, JSCE, vol.22, 157-161 in Japanese.

Yamagami, M.,Imai, H.,Kato, H. ,Misumi, H.,Yamashita, M. (2014a): Development of survey ahead of the tunnel by the use of drilling vibration data with the ultra- long advanced boring, Proceedings of the 69th JSCE Conference, Japan Society of Civil Engineers in Japanese.

Yamagami, M.,Imai, H.,Aoki,T. ,Takahashi, T.,Yamanaka, Y.,Aizawa, T. (2014b): Seismic Survey Ahead of the Tunnel Face by the Use of Drilling Vibration Data, 8th Asian Rock Mechanics Symposium, 2014.