# The relation between tunnel supports and elastic wave structures determined by the TFT system in a tunnel

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## Abstract

The design for a mountain tunnel is based on the results of preliminary surveys conducted on the surface above the planned tunnel route. One of the most useful surveys is seismic exploration by the refraction method, which is performed along the entire tunnel length. However, when the tunnel is deep under the ground, the precision of the survey usually decreases. It is important to conduct seismic exploration within the tunnel as construction progresses, and to verify the seismic velocity of rock mass near the tunnel. Accordingly, there is considerable interest in the development of a seismic-wave exploration system that enables accurate and safe measurements to be taken within the tunnel as it is being driven. We developed the Tunnel Face Tester (TFT), which measures the occurrence of seismic waves by tunnel excavation blasting. This paper discusses the seismic velocity of rock mass near the tunnel, and the results of in-site measurements.

**Keywords**: excavation blasting, seismic exploration, refraction method, mountain tunnel

## 1. Introduction

The new Austrian tunneling method is an excavation method that relies on the inherent strength of the surrounding rock as the main component of tunnel support. The method entails the prompt spraying of shotcrete (concrete) over each newly excavated stretch together with the setting of rock bolts. The support pattern for such work, such as the thickness of the shotcrete to be sprayed and the number of rock bolts, is selected to match the observed ground conditions.

Preliminary surveys are conducted on the ground surface over the full length of the tunnel route. The results of such surveys are combined with the findings of borehole drilling and other surveys to design a support pattern suitable for each section of the tunnel. With the surveys conducted from the ground surface, however, overburden depth and other factors can limit the accuracy and reliability of the results. Thus, when driving a tunnel, it is necessary to compare actual ground conditions as encountered at the cutting face with inferred ground conditions based on the survey results so as to confirm the suitability of tunnel design.

Seismic wave exploration is utilized as a method to quantitatively estimate the surrounding rock conditions of a tunnel. There are dangers entailed in utilizing this method at the cutting face, including the risk of collapse, and it can therefore be applied only under certain geological conditions. There is also the limitation that other work must be interrupted to conduct the measurement. With these issues in mind, we developed a seismic wave survey system, the Tunnel Face Tester (TFT, Fig.1), which utilizes the tunnel blast as a wave source, thereby promoting worker safety and enabling other work to progress during measurement. (Nakaya *et al.,* 2013, 2014).

## 2. Outline of measurement using TFT system

This development work was conducted to create a system that is easy to handle for tunnel engineers in the daily tunneling cycle. The system uses a seismic sensor fixed on a tunnel wall behind the tunnel face, utilizes excavation blasting as a wave source, and measures seismic waves automatically. As a result, all blasting can be measured. Figure 2 shows the wave data obtained with the TFT system. The travel time of elastic wave can be calculated from the difference between the blasting signal that triggers the exploration and the rise of the elastic wave.

The TFT system (Figs. 1 and 2) consists of a portable detector unit (a) and peripheral devices (b)–(d). A current sensor (b) has a noncontact connection with the blasting lead wire and detects the ignition current. A geophone (c;GS-20DH, OYO; natural frequency: 28 Hz) of a type commonly used for seismic exploration is mechanically fixed to the head of a rock bolt ($L$ = 3–4 m) in the tunnel wall, which performs as a waveguide. The ignition signal and seismic waveform are acquired by a 2 channel IC recorder (d; DR-05, TASCAM; WAV format; max. sampling frequency: 96 kHz; max. resolution: 24-bit).

This system can detect acquisition of the signal of the blasting and the waveform of the seismic wave propagated along the tunnel wall. The travel time of the wave ($t_i$) is determined from the time delay between onsets of the blasting signal and the seismic signal. The following equation gives the apparent velocity of seismic waves that traveled the distance between the geophone and the tunnel face:

$$V_{pi} = L_i / t_i \qquad (1)$$

As the tunnel face advances, the change in the seismic velocity is calculated from a combination of the velocities in the previous measurement interval and the face advance interval as the following equation:

$$V_{pi\sim i+1}{}' = (L_{i+1} - L_i)/(t_{i+1} - t_i) \qquad (2)$$

When the geophone position is unchanged, $V_p$ in the face advance interval can be determined from the travel time curve ($t$: arrival time of P wave; $L$: length between geophone and tunnel face), as shown in Fig. 3. The travel time curve and $V_p$ are determined by the following equations:

$$t = aL + b \qquad (3)$$

$$V_p{}' = dL/dt = 1/a \qquad (4)$$

## 3. Evaluation of ground around tunnel face by TFT survey

### 3.1 Measurement method

The TFT survey was conducted for construction work of Hanabuchiyama Tunnel No. 2 of National Route 108, as ordered by the Ministry of Land, Infrastructure, Transport and Tourism, located in Naruko Onsen, Osaki-shi, Miyagi Prefecture. The total length of the road tunnel is 1194 m and the internal cross section is 50.4 m$^2$. The geology of the tunnel consists mostly of granodiorite of the Cretaceous Period of the Mesozoic Era and a part of the ground at the end of the tunnel contains fine tuff from the Hosokura mine formed in the Neogene period. Also, the refraction elastic wave survey showed the existence of a fissure zone in the center of the tunnel. The elastic wave velocity at1.5D (1.5 x10.54 m = 15.8 m) from the tunnel's ground plane (F.H.) was 0.6-3.8 km/sec when measured with the tomography method and 0.3-5.1 km/sec when measured with the layer stripping method. Figure 5 shows the longitudinal geological profile at the

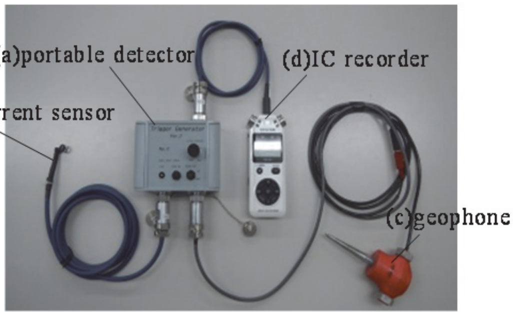

Fig. 1 Components of the Tunnel Face Tester

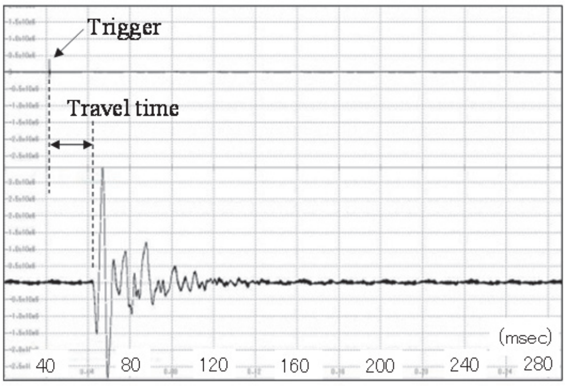

Fig. 2 An example of waveform

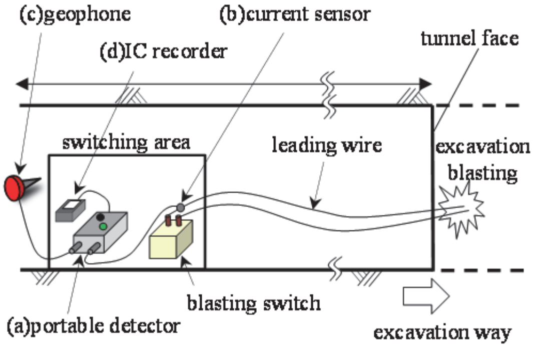

Fig. 3 Conceptual diagram of the measurement

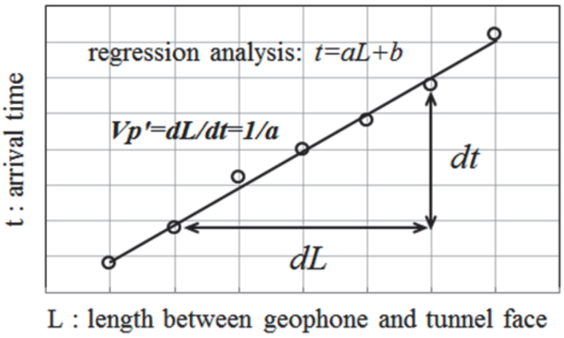

Fig. 4 Travel time curve

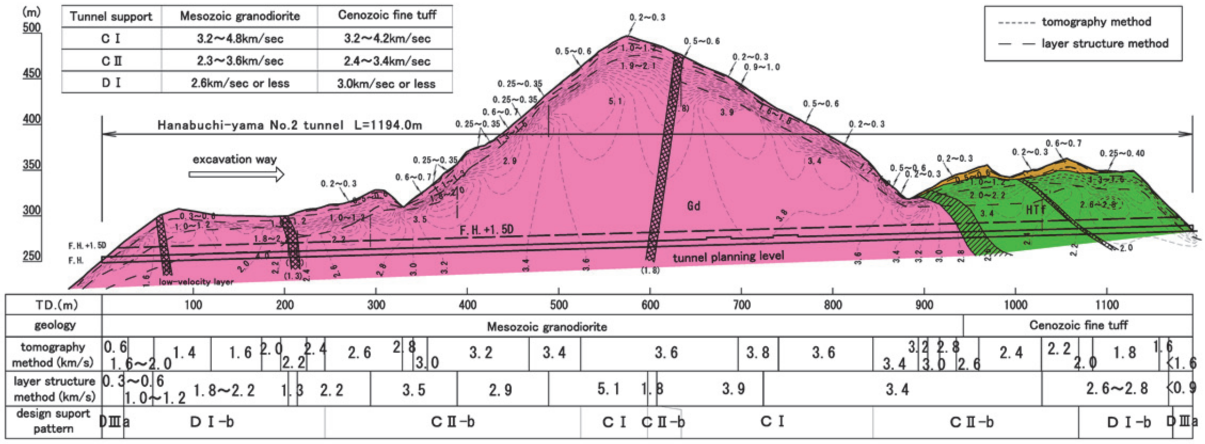

Fig. 5 Geological profile of Hanabuchiyama tunnel No.2

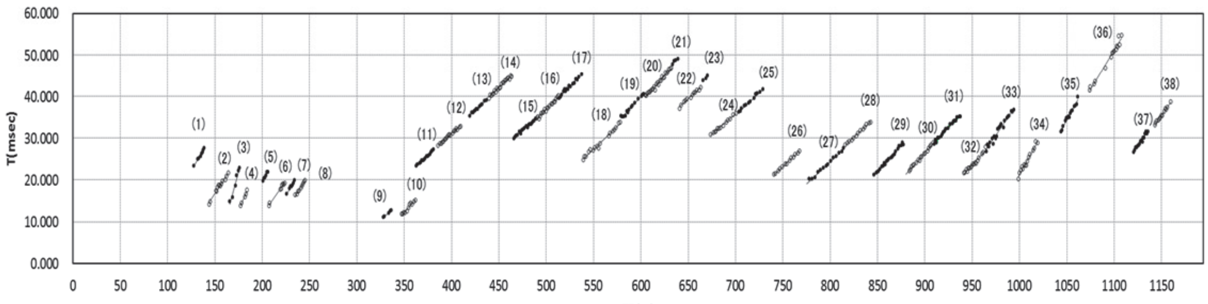

Fig. 6 Measurement result (travel time curve)

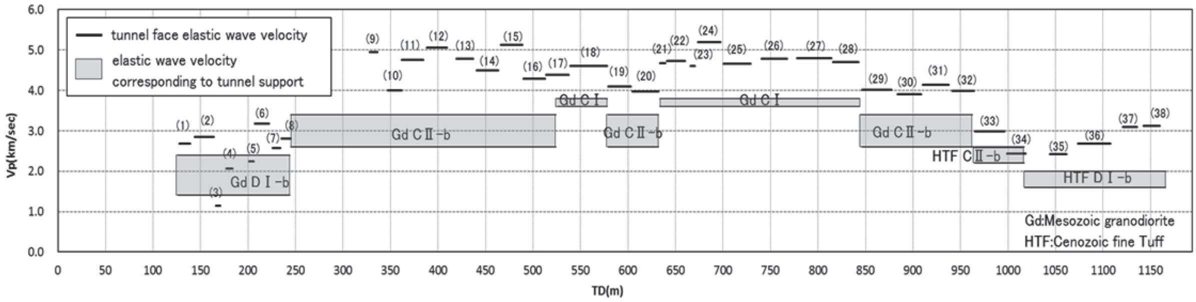

Fig. 7 Elastic wave velocity in tunnel face (TFT survey) and actual support pattern

design stage. For the survey, a seismometer was mechanically set on a rock bolt head on the wall 70-120 m back from the tunnel face. Other equipment was set near the seismometer after making the area explosion-resistant. When the drilling work advanced about 50 m, the survey equipment including the seismometer was moved forward for another survey. In principle the elastic waves that occurred by every blasting were measured and the travel time of the first waves was calculated.

### 3.2 Measurement result

As the drilling work advanced, the elastic waves produced at the working face (blasting point) that moved successively were continuously measured. The ground elastic wave velocity around the tunnel face was calculated from the obtained travel time curves. The travel time curves are obtained from the distance between the blasting point and the geophone and the first arrival time, and the tunnel face elastic wave velocity can be calculated from the slope. The travel time curves obtained in the measurement of the tunnel are shown in Fig. 6.

An approximate line is calculated for the straight line section of each travel time curve and the elastic wave velocity was calculated from the slope of the line. Table 1 shows the measurement result of each measurement section. In all the 38 sections where the TFT survey was conducted, the correlation coefficient of the approximate lines was r=0.920 or higher, indicating that the calculation of the tunnel face elastic wave velocity was accurate.

The average number of the measured blasting works was 13 and the average measurement section length was 21.6 m. Therefore, when the tunnel face advanced about 20 m, about 13 blasting data sets were obtained to accurately calculate the elastic wave velocity.

The calculated elastic wave velocity was $V_p$=1.2-5.2 km/sec, about the same as the one obtained in the refraction elastic wave survey made from the ground surface. The relation between the tunnel face elastic wave velocity obtained in the TFT survey and the actual support pattern is shown in Fig. 7. In the section where a heavy pattern was selected based on the result of the tunnel face survey, the tunnel face elastic wave velocity was relatively low. This indicates that the TFT survey can detect a change in the geological features of the tunnel face.

Next, Fig. 8 shows the results of the tunnel face elastic wave velocity for each actual support pattern. In the figure, the tunnel face elastic wave velocity obtained in the TFT survey are plotted for the lower limit of the elastic wave velocity for each support pattern (Fig. 5). The correlation coefficient of all the data is r=0.83 and the actual support pattern and the tunnel face elastic wave velocity have almost the same tendency. It also shows that the larger the lower limit of the elastic wave velocity is, the less variation the tunnel face elastic wave velocity has. This could be due to the influence of the excavating-caused loose area. Namely this relation is observed because the influence of the loose area would be small in a more robust rock bed.

## 4. Summary

A tunnel elastic wave survey system Tunnel Face Tester (TFT) where blasting is used as the vibration source was developed. With the system, one can accurately measure the elastic wave velocity around the tunnel face. In this study TFT survey was conducted for all blasting sections of a currently-constructed tunnel. The tunnel face elastic wave velocity calculated in the TFT survey showed the almost same tendency as the actual support pattern and reflected the geological change. Also, good agreement was found in comparison with the elastic wave velocity for the support pattern. There was a particularly strong correlation in the high-velocity region.

In future, the TFT survey method will be applied under various geological conditions and an evaluation method of loose areas will be studied.

Table 1 List of TFT survey results

| No. | mesurement section (m) | number of blasting | elastic wave velocity(km/sec) | correlation coefficient r |
|---|---|---|---|---|
| (1) | 12.0 | 8 | 2.7 | 0.991 |
| (2) | 21.0 | 13 | 2.8 | 0.988 |
| (3) | 11.0 | 6 | 1.2 | 0.977 |
| (4) | 8.0 | 5 | 2.1 | 0.986 |
| (5) | 6.0 | 6 | 2.2 | 0.983 |
| (6) | 18.0 | 8 | 3.2 | 0.995 |
| (7) | 9.0 | 7 | 2.6 | 0.987 |
| (8) | 11.4 | 9 | 2.8 | 0.989 |
| (9) | 9.6 | 5 | 4.9 | 0.991 |
| (10) | 15.6 | 11 | 4.0 | 0.971 |
| (11) | 25.2 | 16 | 4.8 | 0.994 |
| (12) | 22.8 | 17 | 5.1 | 0.994 |
| (13) | 20.4 | 12 | 4.8 | 0.995 |
| (14) | 25.2 | 21 | 4.5 | 0.989 |
| (15) | 24.0 | 18 | 5.1 | 0.990 |
| (16) | 24.0 | 19 | 4.3 | 0.990 |
| (17) | 25.0 | 16 | 4.4 | 0.989 |
| (18) | 40.2 | 17 | 4.6 | 0.992 |
| (19) | 25.2 | 14 | 4.1 | 0.990 |
| (20) | 29.1 | 24 | 4.0 | 0.988 |
| (21) | 7.5 | 4 | 4.7 | 0.920 |
| (22) | 23.5 | 12 | 4.7 | 0.987 |
| (23) | 6.0 | 3 | 4.6 | 0.943 |
| (24) | 25.5 | 12 | 5.2 | 0.994 |
| (25) | 30.0 | 13 | 4.7 | 0.995 |
| (26) | 28.5 | 13 | 4.8 | 0.997 |
| (27) | 37.5 | 14 | 4.8 | 0.996 |
| (28) | 28.5 | 13 | 4.7 | 0.996 |
| (29) | 32.4 | 22 | 4.0 | 0.995 |
| (30) | 26.4 | 17 | 3.9 | 0.996 |
| (31) | 28.8 | 19 | 4.1 | 0.991 |
| (32) | 24.0 | 17 | 4.0 | 0.981 |
| (33) | 30.0 | 21 | 3.0 | 0.982 |
| (34) | 21.0 | 15 | 2.4 | 0.982 |
| (35) | 19.0 | 15 | 2.4 | 0.987 |
| (36) | 35.0 | 15 | 2.7 | 0.990 |
| (37) | 16.0 | 16 | 3.1 | 0.985 |
| (38) | 18.0 | 13 | 3.1 | 0.992 |
| total | 820.3 | 506 |  |  |
| average | 21.6 | 13 | 3.8 | 0.986 |
| max | 40.2 | 24 | 5.2 | 0.997 |
| min | 6.0 | 3 | 1.2 | 0.920 |

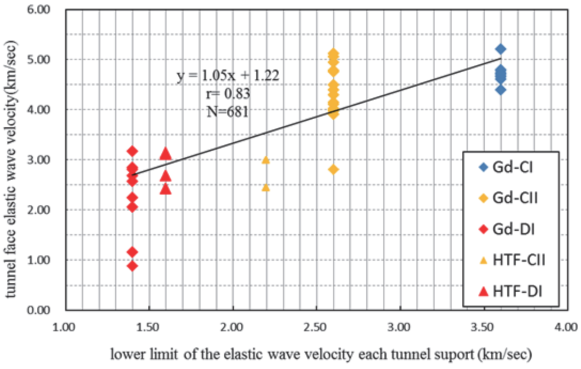

Fig. 8 Relation between support pattern and elastic wave velocity in face

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