Case study of the soundness diagnostic method by monitoring the time-dependent behaviour around the tunnel ground

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Abstract

The time-dependent deformation after the completion of tunnel construction has become a serious social issue in Japan. One of the problems is that most of these deformations could not be discovered by conventional rock evaluation methods. Therefore, a more rational method for rock estimation and maintenance systems required. A diagnostic method is required that is able to provide constant and reproducible monitoring from construction stage to maintenance stage. And it is necessary that any such method is applicable to in-use tunnels without harmful damage of structures, and can be carried out rapidly. We are carrying out a study to develop a diagnostic method to estimate the soundness of tunnel ground from time-dependent behavior from the perspective of geology, mineralogy and geophysics in an actual tunnel with time-dependent deformation. From the results of a series of laboratory tests and field experiments, we found it is possible to estimate the soundness of tunnel ground using seismic velocity. Moreover according to drilling survey, the seismic velocity is sensitive to current geological conditions. And the soundness of tunnel ground may be evaluated by a decrease in the ratio of surface seismic velocity to that deep zone. It is confirmed that decrease in P-wave velocity in the zone with time-dependent deformation is higher than other zones.

Keywords: time-dependent behavior, seismic refraction survey, soundness diagnostic method, P-wave velocity

1. Introduction

In Japan, much of the infrastructure was built during a period of rapid economic growth between the 1950's and 1970's, and maintenance of these aging structures is becoming a serious social issue. Recently, continuous ground degradations such as squeezing and swelling with time-dependent behaviour have led to damage of the linings or floor heaving in several in-service tunnels (JSCE, 2013, Sakuma et al., 2009). These time-dependent deformations in tunnels may cause serious social and economic losses such as an accident involving users and a traffic closure caused by lack of required clearance. Moreover, countermeasures in in-service tunnels are usually expensive and quite disruptive as they often require reinforcement or the addition of an invert arch. However, it is difficult to observe directly degrading ground conditions behind a lining or pavement and there is no diagnostic method for assessing these time-dependent behaviours at present (JSCE, 2005). Thus a new method is needed to evaluate the soundness of tunnel ground until its maintenance phase. For maintenance use, the new diagnostic method is required to enable continuous observation in tunnels that are in service.

We are undertaking a project study focused on these time-dependent behaviours of rock mass from the perspective of geology, mineralogy and geophysics. In previous paper, we reported that it might be a useful index to observe the time related changes of seismic velocity as a result of both laboratory experiments and field experiments (Niwa et al., 2015a). This paper describes the result of field experiment of actual tunnel with time-dependent deformation and the result of case study evaluating the soundness of tunnel ground using seismic velocity.

2. Diagnostic method

2.1 Concept of the diagnostic method

It is known that the stress released by excavating a rock mass often results in changes of physical properties such as strength reduction. Fig. 1 shows the concept of a diagnostic method using seismic velocity. This concept is based on the idea that the physical properties of rock mass should change as it degrades. For a rock mass that doesn't show time-dependent behaviour, the seismic velocity may show no decrease apart for a potential small decrease due to initial degradation during the construction phase. As the rock masses with time-dependent bahaviour, the seismic velocity may show continual decrease until late phase of maintenance stage. Based on this concept, it may be possible to evaluate the soundness of rock mass around a tunnel by continuous monitoring of seismic velocity.

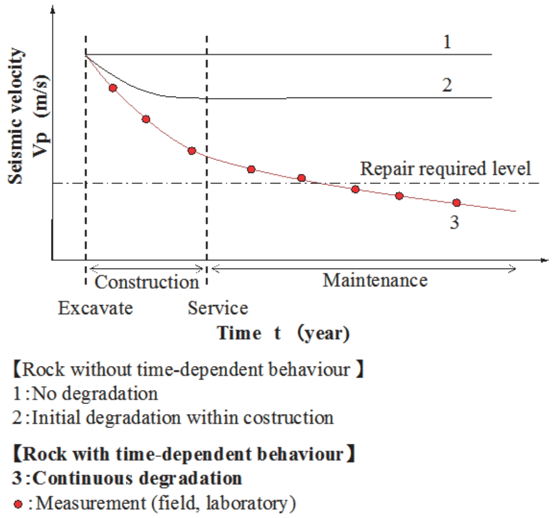
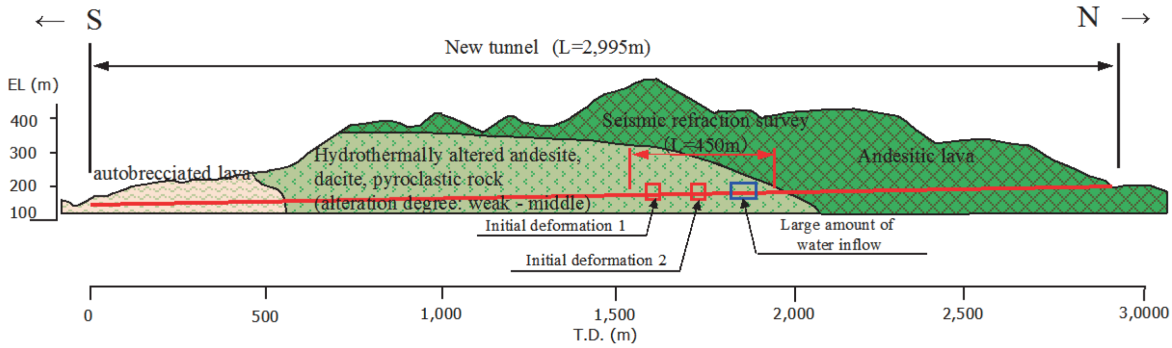


Fig. 1 Concept of diagnostic method using seismic velocity

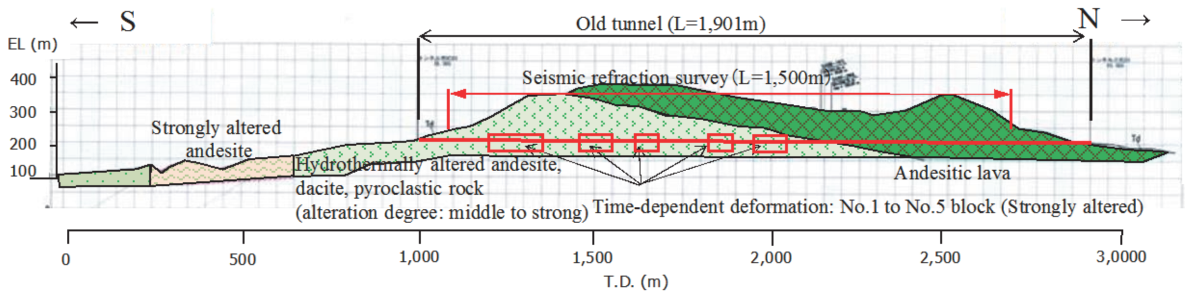
2.2 Outline of applied tunnel

The tunnels in this study are a pair of road tunnels in Hokkaido Japan. The first is the original tunnel in which time-dependent deformation has been occurring for the more than 30 years since completion, the other is a newly constructed relief tunnel. In the remainder of this paper we call the initial tunnel "Old tunnel" and the relief tunnel "New tunnel" The Old tunnel was completed in 1977 using the timbering support method and has length of approximately 1.9 km. The New tunnel was completed in 2014 with NATM and the length is approximately 3.0 km. The geology of both tunnels is mostly hydrothermally altered Neogene andesite or dacite (Okazaki, et al., 2015).

The Old tunnel has 5 sections of time-dependent deformation as shown in Fig. 2. These time-dependent deformations initially occurred rapidly in the No.4 block with over 300 mm floor heaving and a side wall extrusion within three years of completion. Though several series of countermeasures were taken, some slow-speed deformation is still occurring. On the other hand, though no time-dependent deformation was observed



(a) Geologic cross section of New tunnel



(b) Geologic cross section of Old tunnel

Fig. 2 Geologic cross section and survey line of Old tunnel and New tunnel for now in the New tunnel, there are 2 sections that showed an initial deformation of invert arch with about 100 mm floor heaving had occurred. This required re-excavation work and the replacement of support member.

2.3 Seismic refraction survey

A seismic refraction survey was carried out in both tunnels in order to evaluate the soundness of tunnel ground. In the New tunnel, it was conducted on a freshly paved floor immediately after construction before use. Whilst, in the Old tunnel, it was conducted after closure after opening of the New tunnel.

We used a hydraulic impactor as the seismic source and MEMS (Micro electro mechanical systems) sensors as seismic receivers. The recording system was a SERCEL 428XL DSU. The receiver was set on a tripod stand in order to ensure stability on the pavement. The hydraulic impactor was used to avoid damages to the pavement as a non-blasting seismic source. MEMS sensors enabled down-sizing of the survey equipment and to reduce the hours needed for receiver handling (Niwa et al., 2015b). P-wave generation was achieved using a vertical shot and S-wave generation using an inclined shot at a 35 degree angle. Each shot is stacked 3 times at each shot point in order to improve S/N ratio. The survey line is 450 m length in the New tunnel, 1,500m in the Old tunnel. The interval of receivers is 6.0m, and the interval of shot points is 3.0m- 6.0m. The configurations of the shot and receiver in both tunnels are shown in Fig.3. In the Old tunnel, single spread of survey line consists of 100 geophones over 594m and the whole survey is conducted while moving the spread with 150m lap. Using the above equipment, we finished seismic refraction survey without any damage to tunnel structures and were able to keep one lane of the tunnel open to traffic.

We applied tomographic analysis to the data obtained. To determine most probable initial model, we initially carried out a tomographic analysis using fifty randomly generated velocity models and averaged those fifty results.

2.4 Drilling survey

The drilling survey was conducted in the Old tunnel in order to grasp the geological distribution and condition of altered rock. Initially, several short drillings of less than 5m length were carried out as a brief survey. The equipment used for short drillings was a portable core drilling machine normally used

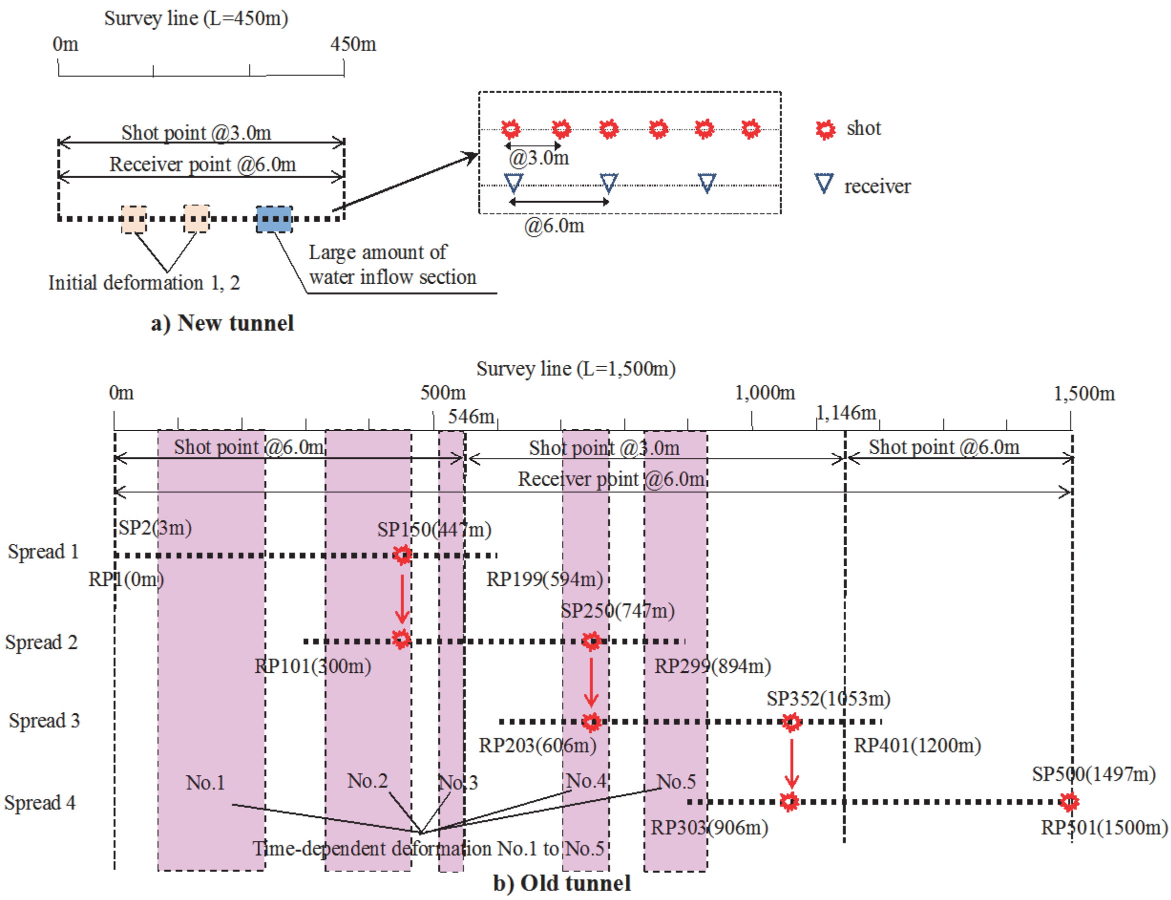


Fig.3 Configuration of shot points and receiver points

for concrete core sampling. Employed short drilling system were specially arranged in order to be able to use the core sampler which commonly used geological survey drillings. The short drillings are conducted in horizontal direction from side wall of tunnel as shown in photo. 1. Because this equipment is easy to set it up, it is able to achieve the maximum 5m depth in less than half a day. And long horizontal and vertical drillings carried out as part of a detailed survey of the No.4 block. The equipment used for long drilling was the hydraulic rotary drilling machine usually used for tunnel advanced drilling. The survey length is 40m for horizontal drilling and 30m for vertical drilling.

Photo. 1 The equipment of short drilling survey

3. Results and discussion

3.1 Survey results

Fig.4 shows the vertical distribution of seismic velocity obtained by the seismic refraction survey of both tunnels. It also shows the section where initial and time-dependent deformations had occurred. The deformation of New tunnel is mainly discontinuous initial floor heaving after completion of invert arch. And the deformation of the Old tunnel is continuous time-dependent deformation in No.1 to No.5 block. As shown in Fig.4, P-wave velocity is relatively lower between No.1 and No.5 block in which the time-dependent deformation was observed. While, P-wave velocity of north side of Old tunnel and New tunnel is higher than No.1 to No.5 block. As several significant deformations such as floor heaving and side wall extrusion are observed in No.4 block (Murayama et al., 2015), the survey result shows coincident tendency. On the other hand, in the New tunnel, a certain level of loosening must be going on due to initial discontinuous deformation in the zone of deformation 1 and 2. However the decreased level of seismic velocity is relatively less in the New tunnel than the Old tunnel.

We carried out several drilling surveys in order to better understand the geological distribution of the Old tunnel. The drilling survey confirmed that the geology of the Old tunnel consists mainly of altered andesitic rock including pyroclastic rock. Fig.5 shows the geological condition observed in each of the drilling samples. As shown in Fig.5, the geology around the No.4 block is strongly altered to clayey condition. Though it is unclear whether these clayey conditions caused the tunnel deformation or whether a huge deformation in the tunnel made geology

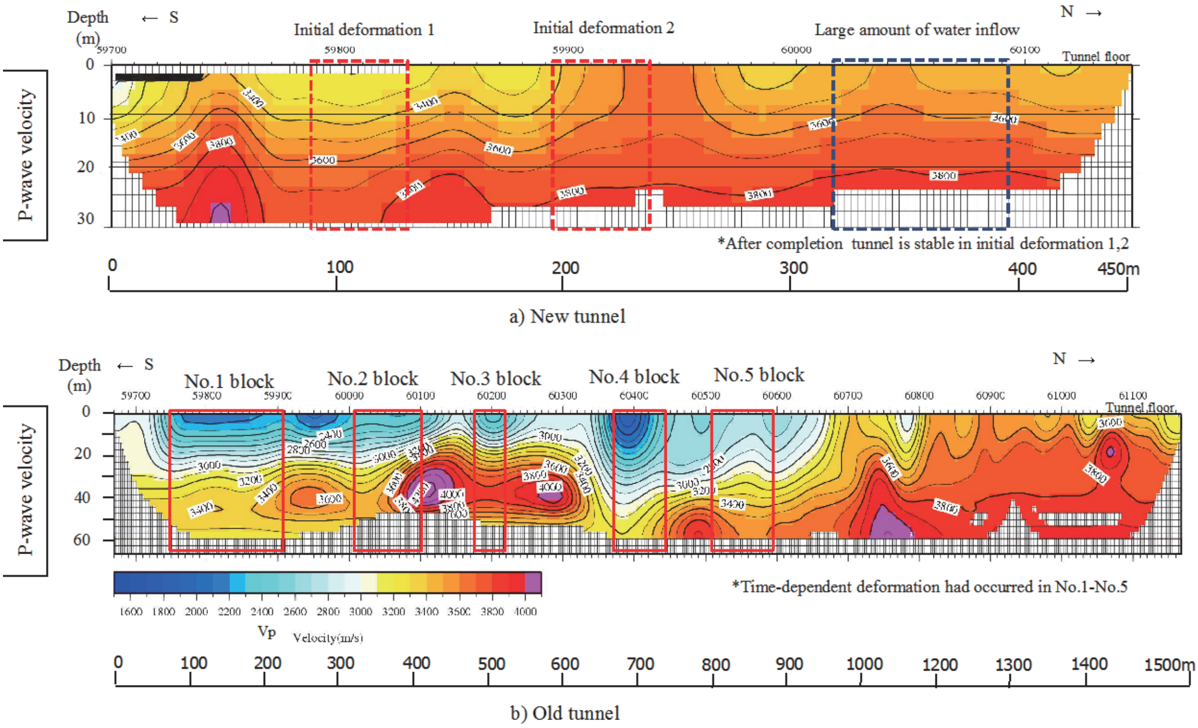


Fig.4 Results of seismic refraction survey in New tunnel and Old tunnel

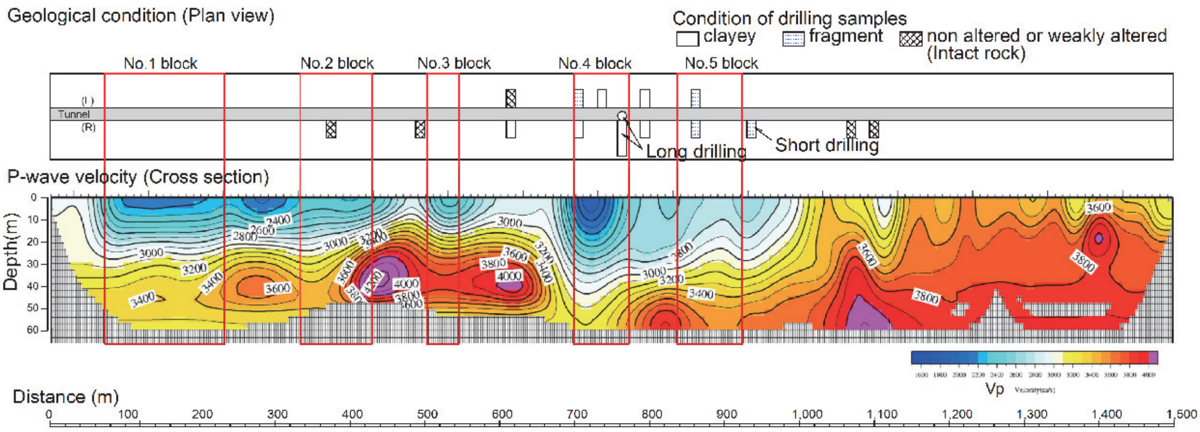


Fig. 5 Geological condition and P-wave velocity of Old tunnel

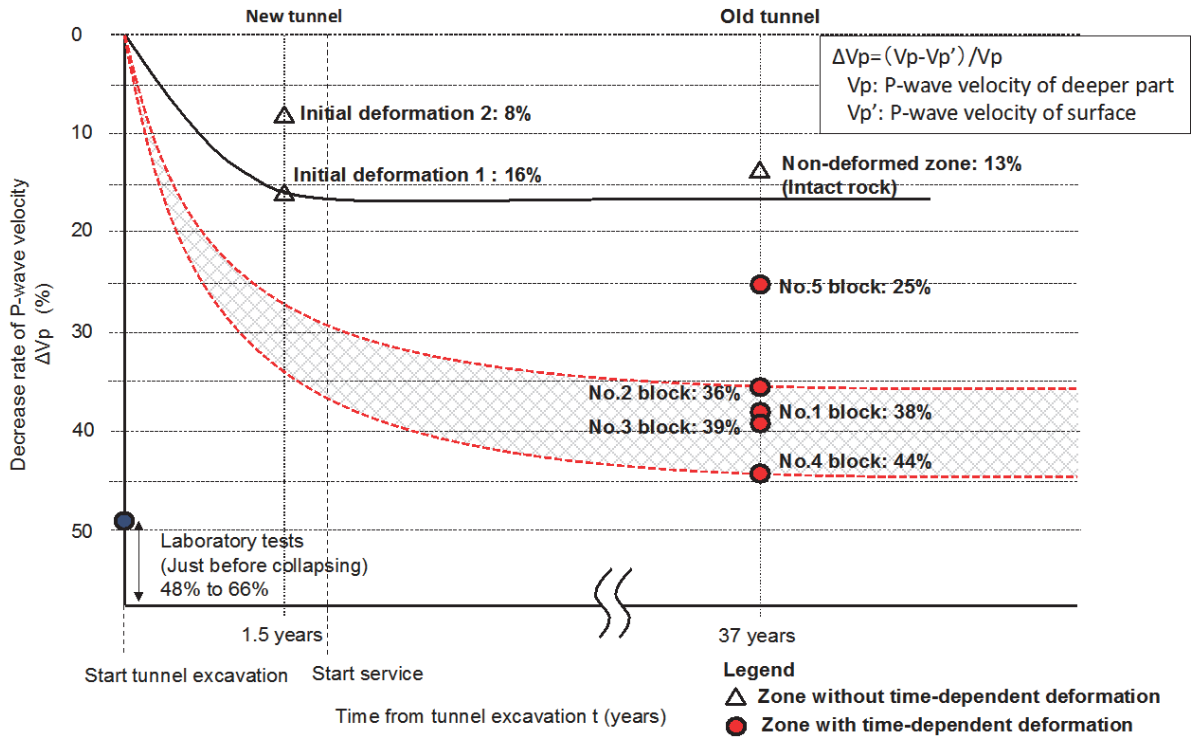


Fig. 6 Decrease rate of P-wave velocity of Old tunnel and New tunnel

clayey, it was confirmed that the seismic velocity is sensitive to current geological conditions.

3.2 Soundness evaluation of tunnel ground

If the decrease of P-wave velocity due to the time-dependent deformation or the loosening by stress release from the excavated surface, the seismic velocity in the deeper zone may be assumed to be indicate the original seismic velocity of ground because it is far from influence of the excavation. In other words, the surface part having lower seismic velocity originally had higher velocity but it decreased as tunnel excavation work progressed. Based on this assumption, the soundness of tunnel ground can be evaluated by a decrease in the ratio of surface seismic velocity to deep zone.

The decrease rate of P-wave velocity of No.1 to No.5 block and non-deformed zone of the Old tunnel and the zone of initial deformation 1 and 2 of the New tunnel is shown in Fig. 6. The horizontal axis indicates conceptually the time from tunnel excavation. And it also shows the decrease rate of P-wave velocity just before collapse obtained by laboratory tests using the New tunnel samples (Niwa et al., 2015a). As shown in Fig.6, the decrease rate of P-wave velocity of No.1 to No.5 block with time-dependent deformation is estimated 25% to 44%. While, the decrease rate of P-wave velocity of the other zone with no time-dependent deformation is 8% to 16%. Thus, it is confirmed that the decrease rate of

P-wave velocity in the zone with time-dependent deformation is higher than that in the other zones. And it is suggested that the threshold of this tunnel ground may exist between 16% and 25%. Furthermore the maximum decrease rate of P-wave velocity is 44% in the No.4 block. The current decrease rate of P-wave velocity in the Old tunnel is relatively lower than that obtained by laboratory test just before collapse, though direct comparison of values of seismic velocity may not be valid because of difference of measuring method between field and laboratory.

4. Conclusions

We carried out a series of experiments in the laboratory and in two actual tunnels, aiming to evaluate the soundness of tunnel ground using seismic velocity. The conclusions of this paper are summarized as follows.

1) The seismic velocity is relatively lower in the sections in which time-dependent deformation was observed.

2) According to drilling surveys, the seismic velocity responds to current geological condition.

3) The soundness of tunnel ground can be evaluated by a decrease in the ratio of surface seismic velocity to deep zone.

4) It is confirmed that the decrease rate of P-wave velocity in the zone with time-dependent deformation is higher than other zones.

We are now conducting continuous monitoring of the environment in the Old tunnel such as ground water pressure, air and ground temperature, humidity. And analysis of mineral composition of rock is also conducted. Through these studies, we aim to explain the mechanism of time-dependent behavior of rock mass now on.

Acknowledgements

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