Case study of the reconsidering of the measurement data and geological survey results of the tunnel with time-dependent behaviour

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Abstract

In order to characterize the geological situation leading to the tunnel deformation with time-dependent behavior and in order to build a new evaluation method, we carried out long-term observations, swelling tests and X-ray diffraction tests using core samples obtained from deformed zones in two tunnels. These two tunnels are a new national road tunnel by NATM was opened in 2014, which provides an alternative route to a pre-existing tunnel that was constructed by conventional methods and opened in 1976. The geology of both tunnels is hydrothermally altered pyroclastic rock. Heaving occurred in two sections replaced by timbering in a hydrothermally altered andesite zone in the new tunnel after completion. In the old tunnel, countermeasures against deformation were carried out on three occasions. In this survey, we focus on the minerals involved in the degradation of the rocks for time-dependent behavior. The results of survey showed that the core samples degraded in 18 months after drilling. Most of this degradation occurred within one week of drilling. Therefore, it is useful to observe core samples in a one week just after drilling. Comparing results obtained by X-ray diffraction tests just after drilling with ones at a later period, we found differences in combination of mineral content.

Keywords: time-dependent behavior, tunnel, countermeasure, design, construction

1. Introduction

There have been many reported cases in which deformation, such as tunnel ground heaving and squeezing of sidewalls, occurred in a tunnel days, months or even decades after construction (JSCE 2003, 2013, Nakata and Ito 2000., Watanabe et al., 2007., Nihei et al., 2010). Even those tunnels that showed no evidence of problems with regard to the results of a conventional evaluation for the possibility of swelling (JSCE 2006), nor any increase in displacement resulting from excavation when they were constructed, still have the potential to undergo time-dependent behavior. Therefore, there is an urgent need to establish a method for evaluating and predicting such deformation during tunnel construction or in the early stages of maintenance.

In order to determine the effectiveness of countermeasures against deformation and the likely progress of such deformation, a ground degradation model has been formulated and numerical analysis has been conducted based on long-term measurement data on the amount of convergence (Matsunaga et al., 2009). However, few studies have addressed the basic geological factors and causes of time-dependent behavior.

In the past, the authors collected data on cases of deformation in tunnels and clarified the geological conditions. It was found that many of the tunnels with time-dependent behavior are in volcanic rock areas (Okazaki and Ito 2011, 2013). One of the causes of time-dependent behavior is the gradual release of stress in fresh bedrock and the swelling of the plastic zone due to tunnel excavation. In addition, this fresh rock is in contact with the air and ground water leading to changes in saturation and oxidation. In addition, the strength of rock decreased due to actualized cracks, grain refining and pulverizing. In addition, depending on the combination of minerals in rock, iron hydroxide and gypsum were produced by chemical changes, which these sometimes also promote the degradation or swelling of the rock (Tanaka et al., 1985, Oyama et al., 1998, Shikazono et al., 2002).

In this study, we compiled measurement data from tunnel construction through hydrothermally altered andesite in Hokkaido, Japan and examined the results of advanced drilling data (HRDB 2014) in cases where heaving occurred as the time dependence behavior after the tunnel completion. In addition, the mineralogical analysis, changes in the number of cracks and number of days up to the maximum swelling stress were examined using the drilling cores after the passage of a certain period from excavation to understand the relationship between time dependent behaviors.

In the present paper, survey results obtained during construction were compared with those obtained later, with the aim of clarifying the causes of time-dependent behavior. In addition, this paper discusses the results of a study that was conducted to clarify how to predict time-dependent behavior during construction.

2. Outline of study

2.1 Tunnel geology and deformation

(1) Tunnel geology

The present research was conducted on a new national road tunnel (about 3,000m in length) that was opened in 2014 as alternative to an older tunnel (about 1,900m in length) which was constructed by conventional methods and opened in 1976. The geology of both tunnels consists mainly of andesitic lava, dacite that includes auto-brecciated lava and pyroclastic rock (Fig.1).

(2) Deformation in the tunnel

The heaving occurred in the tunnel at two sections with maximum overburden near the tunnel piercing point (those parts in Fig.1 (a)), soon after the tunnel cleared; requiring re-excavation. The ground at both sections where deformation occurred had undergone hydrothermal alteration, and smectite was found in large amounts in those sections. According to the report of tunnel constructor (Sasaki et al., 2013), the deformation was caused by the combined action of the loosening of surroundings due to excavation and the swelling pressure of clay minerals. These deformations could not be predicted by the conventional rock estimation method. Therefore, more rational and economical method for both rock estimation and maintenance systems are required to mitigate such issues.

At the old tunnel, deformation occurred in five sections (those parts in Fig.1 (b)), and countermeasures against deformation were carried out three times. The ground at those sections where deformation occurred had undergone hydrothermal alteration, and smectite was found in large amounts in. According to the report of tunnel constructor (HRDB 1993), the deformation was caused by combined action of the loosening of surroundings due to excavation and the swelling pressure of clay minerals.

2.2 Test for mineralogical properties of rock

(1) Observation of long-term change in the cores

After deformation, the drilling cores excavated from the deformed sections in a new tunnel were observed in order to find out how those drilling cores would change in state over time, and in order to analyze the change in degradation state and the extent of degradation of rock. In addition, drilling cores also were also excavated from the deformed section in the old tunnel, in order to confirm the geology and understanding of aging degradation. The drilled cores were observed by mainly focusing on the number of cracks generated in succession until 17 to 23 days from the after digging. The number of cracks that occurred in drilling cores was compared with the

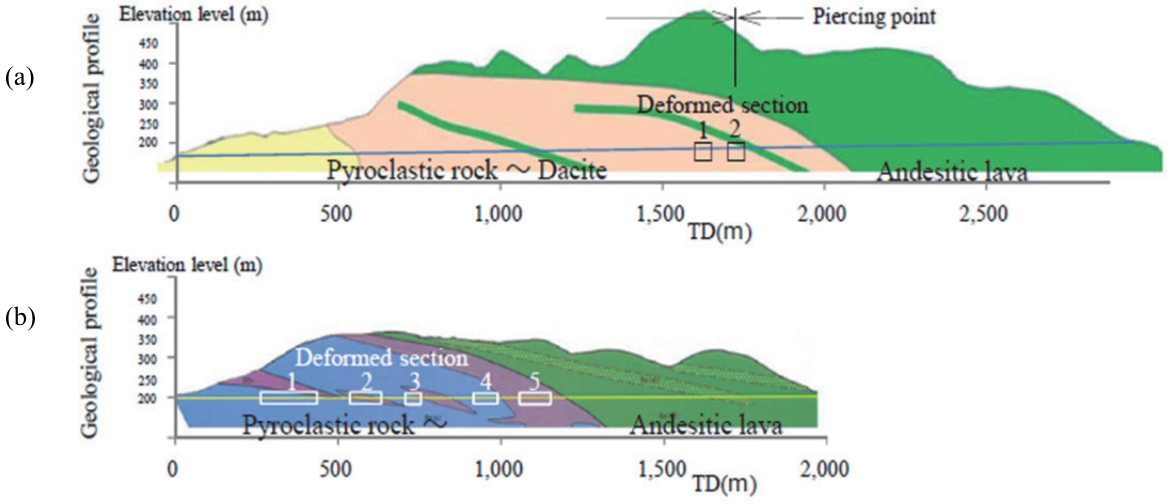

Fig. 1 Surveyed tunnels

difference of geology, the rock classification and RQD (10). The rock classification was divided into four grades as the C_H, C_M, C_L and D based on the state of cracks, the core hardness and shape (Table.1). Cores of each tunnel had been stored in a tunnel until approximately one month from their excavation. After that, cores of new tunnel were stored at the outdoor site of the tunnel operator by covering with vinyl sheet

(2) Swelling test of rock

A swelling test (JGS2121 1998) was conducted on cores excavated in the drilling survey conducted in the deformed sections of the new tunnel. In addition to the swelling rate being measured, the smectite, content was determined by X-ray diffraction test. The relation between the maximum swelling stress and the number of days that it took for the swelling stress to reach the maximum was examined.

(3) X-ray diffraction test

With regard to advanced drilling cores excavated including sections where deformation occurred, samples were collected from two types of sections: a section where swelling occurred, and a section where swelling did not occur in the new tunnel. Moreover, samples were collected from the drilling cores of the old tunnel. Then, an X-ray diffraction test was conducted on those samples. The smectite content was determined by X-ray diffraction using the internal standard method. After the minerals contained in the samples were identified, the strength ratio was determined based on the diffraction peaks of quartz and smectite. Then, the strength ratio, quartz intensity for smectite (hereafter, QISm) and the identified minerals were analyzed in combination. Quartz is found in many rocks. Thus, QISm is a value to indicate quantitatively the content of smectite relative to the content of the quartz. QISm shows the value of the smectite when the peak intensity of the quartz is 100. Among the identified minerals, Pyrite, Carbonate and Gypsum, were addressed in previous studies (Tanaka et al., 1985, Oyama et al., 1998, Shikazono et al., 2002) were carefully investigated; the relation between the combination of those minerals, the presence or absence of swelling of cores and QISm were compared.

Table .1 rock classification method

Rock Classification	Hardness	Shape	State of Cracks
C_H	B	II	b
	B-C	I	
		I-II	
C_M	B-C	I-II	c
		II	b
		II	c
		II-III	b
		III	
		III	c
	C	II	b
			c
C_L	B-C	III-IV	c
	C	II-III	
		III	
		III-IV	
		IV	
	C-D	II	
		II-III	
		III	
		III-IV	
		IV	
		IV-V	
	D	II	
		II-III	
		III	
		IV	
		IV-V	
D	D-E	II	c
		II-III	
		III	
		III-IV	
		IV-V	
	E	IV	c
		V	d
		VI	
		VII	
		VIII	

Item	Rank	Condition
Hardness (Hammer blow sound)	B	Piercingly
	C	Dingdong
	D	Subdued sound
	E	Silence
Shape	I	Over 50 cm
	II	15-50 cm
	III	5-15 cm
	IV	5cm or less
	V	Form of grabel
	VI	Form of sand
	VII	Form of clay
	VIII	Slime
State of Cracks	a	Not degradation
	b	Slightly degradation
	c	Degradation extends inside
	d	Not recognizable as a crack

3. Results and discussion

3.1 Observation of long-term change in the cores

(1) Degradation state and extent of the rock

Photo-1 shows the state of the drilling core immediately after excavation following deformation and the change in the state of the core after the passage of the time. Observation of the core immediately after excavation showed that, in places, some degradation had already occurred. When the core was re-observed 1week after excavation, it was found that the extent of degradation had increased. 586 days after that, it was found that the extent of degradation had increased along the cracks and had expanded from the location where degradation was found a one week after excavation. However, the extent of degradation found 586 days after excavation was roughly the same as that found at a one week after excavation. Thus it was shown that, in some cases, re-examining cores shortly after excavation may be a reasonable indicator of how further degradation will expand in the medium and long term.

(2) Number of generations of cracks

Table 2 shows the results of core observation for the number of generations of cracks. Drilling survey results showed the core is the andesite and tuff breccia, RQD is more than 80% in the C_H - C_M class, tending to 70% or less in the C_L - D class. On the other hand, the number of initial cracks number is not significantly different (between 4 and 8 per 1m) except for C_L class andesite. The ratio of the initial crack number to final crack number, is less than 2.0 in C_H - C_M grade, but increases to 2.0 or more in CL - D class.

Figure 2 shows the time variation of the crack number for each rock classification. A tendency to decrease in order of C_H, C_M, C_L, and D are seen in the number of cracks. When the much number of initial cracks exists, many cracks occur afterwards. The number of the cracks almost converges in five days after drilling. Re-observation of the core is possible to become one of the methods for predicting the degradation of rock due to the occurrence of cracking.

Photo. 1 Long term change in the drilling core.

3.2 Swelling and smectite content of rock

Table 3 shows the results of a swelling test of rocks, the smectite content and swelling ratio of rock

Table. 2 The results of core observation for the number of generations of cracks.

Geology	Rock Classification	Observation length (m)	Observation days of cores (days)	RQD(10) (%)	Initial cracks (numbers)	Final cracks (numbers)	Final/Initial ratio of craks
Andesite	C_H	10	22	98	4	7	1.8
	C_M	7	17	89	6	11	1.8
	C_L	11	23	54	15	37	2.5
	D	11	17	39	8	18	2.3
Tuff-breccia	C_M	6	18	81	8	15	1.9
	C_L	16	18	68	8	20	2.5
	D	6	20	16	4	15	3.8

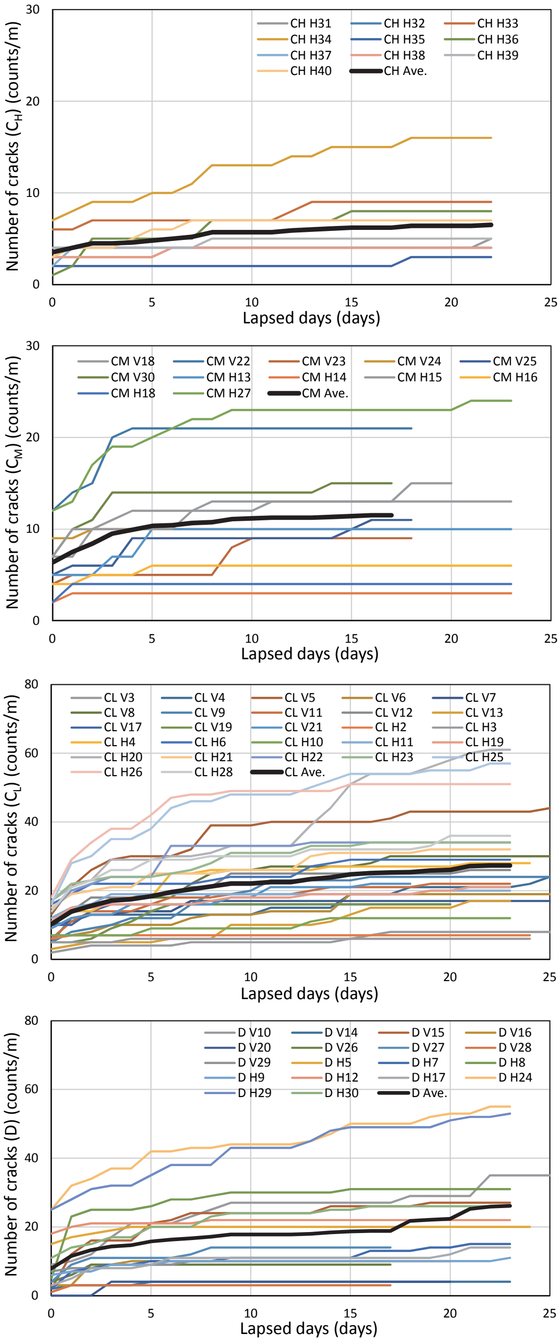

Fig. 2 The time variation of the crack number of each rock classification. (V: vertical borehole, H: horizontal borehole, figures shows drilled depth)

Table. 3 The results of a swelling test of rocks, the smectite content and swelling ratio of rock type.

Rock type	T.D. (m)	ND: Non -deformed D: deformed	Smectite content (wt%)	Swelling ratio (%) NT: Not tested
pyroclastic rock	603	ND	20	–
	614	ND	21	–
	1,100	ND	15	–
Dacite	900	ND	13	–
	950	ND	12	–
	1,000	ND	11	–
	1,050	ND	10	–
	1,150	ND	12	–
	1,200	ND	22	–
	1,250	ND	8	–
	1606-1	D	31	10.4
	1606-2	D	23	6.4
	1606-3	D	37	–
	1606-4	D	31	18.3
	1711-1	D	32	10.6
	1711-2	D	16	3.6
	1711-3	D	13	0.6
Andesite Lava	1,300	ND	4	–
	1,350	ND	4	–
	2,190	ND	4	–
	2,230	ND	13	–
	2,280	ND	8	–
	2,330	ND	5	–
	2,400	ND	4	–

type. The smectite was examined for each type of rock in tunnel. At the same time, the test results for the non-deformed section and the deformed sections were compared, and the swelling ratio of rock in the deformed sections was examined. The smectite was highest in dacite, followed by pyroclastic rock and then andesitic lava. The smectite content of all the rock was under 37-wt%, though, 20-wt% is used as an index for evaluating the swelling of rock. In contrast, the average value for smectite of dacite in the deformed sections was 26-wt%. Additionally, when smectite exceeds 30-wt%, the swelling rate exceeds 10%. However, some rock samples from the non-deformed sections did not experience deformation, despite showing high smectite of more than 20-wt%, which indicates the possibility of some factors other than smectite content contributing to deformation.

Figure 3 shows the relationship between the numbers of days until converge of swelling stress and maximum swelling stress by the swelling test of dacite cores out of the deformed sections. There are two cases relationship between the numbers of days until convergence of swelling stress and maximum swelling stress. One of the cases is fewer days and smaller maximum swelling stress, and another case is many days and larger maximum swelling stress. In the case of fewer days up to the maximum swelling stress can be evaluated by the existing test method. However, where swelling stress continues to increase for a long period, it is not possible to evaluate the time dependent behavior of rock degradation using the short-term existing methods. Therefore, it is necessary to develop longer-term indicators and test methods.

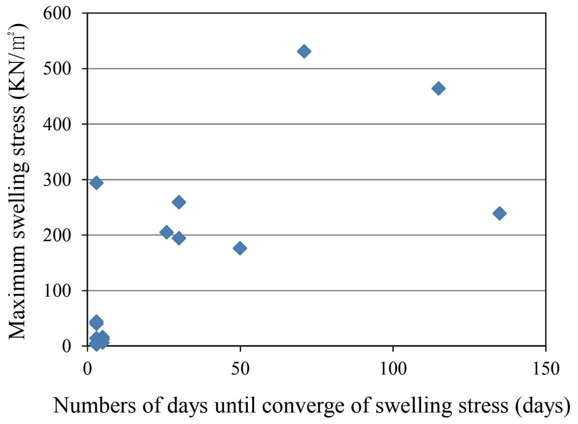

Figure 3 The relationship between the numbers of days until converge of swelling stress and maximum swelling stress.

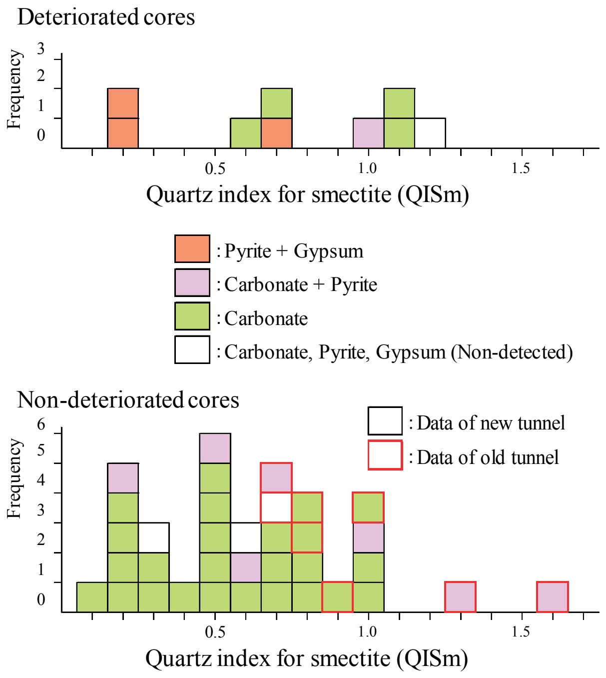

Figure 4 The results of an X-ray diffraction test.

3.3 X-ray diffraction test

Figure 4 shows the results of an X-ray diffraction test conducted on rock collected from the deformed section. The following minerals were identified in the X-ray diffraction test: Cb: carbonate minerals (Cal: calcite, Dol: dolomite and Sid: siderite), Si: silicate minerals (Q: quartz, Tri: tridymite, Cri: cristobalite), Sf: sulfide mineral (Py: pyrite), Su: sulfate minerals (Gy: gypsum, Roz: rozenite) and smectite.

QISm ranges between 0.1 and 1.6. From advanced drilling cores, 9 cores were found to be deteriorated core samples and 35 cores were found to be non-deteriorated core samples. QISm of the deteriorated core indicates the 4 samples of the 9 samples have a value of 1.0 or more. On the other hand, QISm of the non-deteriorated core indicates the 6 samples of the 35 samples have a value of 1.0 or more, and the ratio that QISm becomes more than 1.0 is smaller than deteriorated core. The investigation found that with regard to the deteriorated cores, when the Py+Gy was detected, QISm was 1.0 or less. With regard to the non-deteriorated cores, however, Py+Gy was not found in the samples in which Cb+Py was detected even when QISm was 1.0 or more. From this, it is presumed that when rock contains Cb and Py, the rock experiences the leaching of elements and the secondary formulation of Gy due to environmental changes resulting from excavation, which leads to changes in the density of the rock, promotes its degradation and lowers the physical strength of the rock. On the other hand, Py is detected in several non-degraded cores. However, chemical change from Py to Gy hardly proceeds to include the alkaline Cb at the same time, as a result the volume change might have been suppressed. Thus, even when the Sm is low, QISm is 1.0 or less; it seems to lead to the degradation of the rock.

Thus, the results of X-ray diffraction method and core observation, coupled with the reference value of the Sm content and focusing on the combination of Py, Cb and Gy is effective as an index to estimate the time dependent behavior of rock degradation.

4. Conclusions

The present research can be summarized as follows.

1) The results of the observation of long term changes in cores indicated that, in some cases, re-observation of cores at an early stage of degradation makes it possible to identify how degradation will develop over the medium and long term.

2) The results of the long-term observation of changes in the number of generations of cracks, many cracks occur at a relatively early stage, then, the occurrence of the crack decreases and changes to converge. The increase in the number of cracks increases after drilling tends to converge at about 5 days. Thus, re-observation of the core is a potential method for predicting the degradation of rock due to the occurrence of cracking.

3) The results of the test for mineralogical properties of rock indicated that, in some cases, the prediction of degradation and swelling can be made more effectively by considering the combination of minerals contained in rock, in addition to employing the traditional method of evaluating the swelling of the rock.

In the present research, the geological conditions and mineralogical properties associated with the occurrence of deformation were analyzed based on the results of geological surveys conducted in the tunnels where such deformation occurred. The ground heaving occurred due to the compound action of loosening of the tunnel ground and swelling of clay minerals; therefore, it is necessary to establish new methods for evaluating and predicting deformation during construction. To prevent deformation such as that which occurred in this case, the authors are determined to continue to conduct tests and analyses in order to develop methods for predicting the state of degradation on short-term and long-term bases.

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References

Hokkaido Regional Development Bureau, Takikawa road office (1993): Tunnel construction record magazine (in Japanese).

Hokkaido Regional Development Bureau (2014): The Guidelines of Road Design, Vol. 4, Tunnel (in Japanese).

Japan Construction Information Center Foundation (1999): The making point of the bowling columnar section (draft) (in Japanese).

Japan Society of Civil Engineers, Committee on Rock Mechanics (2003): Deformation Mechanisms of Tunnels (Collection of Deformation Cases), pp. 214-269 (Japanese).

Japan Society of Civil Engineers (2013): Invert for Mountain Tunnels, Tunnel Library No. 25 (in Japanese).

Japan Society of Civil Engineers (2006): Japanese Standard for Mountain Tunneling, (in Japanese).

Matsunaga, T., Yashiro, K. and Asakura, T. (2009): Study on Prediction of Long-term Tunnel Deformation by Ground Strength Reduction Model, Proceedings C of the JSCE, Vol. 65, No. 2, pp. 467-479 (in Japanese).

Nakata, M. and Ito, H. (2000): Ground Deformation in a Tunnel in Service and the Associated measures - Sengenzan Tunnel on the Joshinetsu Expressway, Tunnels and Underground, Vol. 31, 4, pp. 7-14 (in Japanese).

Nihei, N., Nakasono, S. and Ubukata, Y. (2010): A Case of Countermeasure for Deformation of Sengan Road Tunnel (National Highway No.46), JSCE, Vol. 1, pp. 23-31 (in Japanese).

Okazaki, K. and Ito, Y. (2011): Study on the Deformation and Its Time-dependent Changes in a Tunnel in Service, 23rd Proceedings of Tunnel Engineering, JSCE, pp. 23-31 (in Japanese).

Okazaki, K. and Ito, Y. (2013): Case Study of Deformation Factor and Rock Property of Deformed Tunnel After Its Services Commencement, Proceedings of the 13th Japan Symposium on Rock Mechanics, pp. 565-570 (in Japanese).

Oyama, T., Chigira, M., Ohmura, N. and Watanabe, Y. (1998): Heave of House Foundation by the Chemical Weathering of Mudstone, Journal of the Japan Society of Engineering Geology, Vol. 39, No. 3, pp. 261-272 (in Japanese).

Sasaki, T., Ujikawa, N. and Ishiguro, S. (2013): Overcome the Heaving in Construction due to Hydrothermal Alteration Soft Layer in the Re-excavation, Tunnels and Underground, Vol.44, No.11, pp.7-15 (in Japanese).

Shikazono, N., Kimura, S. and Iwai, S. (2002): Relationship between Gypsum Formation due to Chemical Weathering and Mineral Composition of Original Rocks, Journal of the Japan Society of Engineering Geology, Vol. 43, No. 3, pp. 134-142 (in Japanese).

Tanaka, Y. (1985): Changes in the Texture and the Property of Rocks due to Calcite Dissolution, Journal of the Japan Society of Engineering Geology, Vol. 26, No. 3, pp. 19-25 (in Japanese).

The Japanese Geotechnical Society (JSG2121-1998): Test method for axial swelling strain and axial swelling stress of rocks.

Watanabe, Y., Aigo, K. and Suzuki, T. (2007): Cause of the Track Bed Heaving in Shinkansen Tunnels Being Used, and the Countermeasures Taken, Tunnels and Underground, Vol. 38, 9, pp. 7-16 (in Japanese).