Case study of a tunnel with time-dependent behavior in a volcanic area of Hokkaido

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Abstract

Records of the construction and repair of a tunnel with time-dependent deformation were analyzed to develop judging method of time-dependent deformation. As a result, release of in situ stress of rock converged until about 80 days and time-dependent deformation was inferred to result from rock degradation by the change of rock surroundings mainly with groundwater inflow. The score of tunnel face estimation was found to be difficult to separate with and without time-dependent deformation part clearly. Although the displacement value at the part of time-dependent deformation of the tunnel had a tendency to be larger than those at the part without deformation, the boundary value was too small (about 4mm of crown settlement) to be adopted as threshold to determine tunnel support patterns. By the re-examination of geological description of advanced drilling at the time of construction, it was verified that the geological description should be more respected to predict time-dependent deformation parts.

Keywords: time-dependent deformation of tunnel, advanced drilling, displacement, geological description

1. Introduction

Tunnel deformation due to time-dependent behavior of ground is one of the most important problems for tunnel constructors. There are many cases of time-dependent deformation of tunnels in Japan (Table 1, JSCE (2003)). Though most constructors estimate and deal with rapid degradation of rock by monitoring, they sometimes underestimate gradual ones because of the luck of geological comprehension and result in time-dependent deformation of tunnels. Though some studies have reported on such degradation of rocks due to weathering and mineral leaching (Oyama et al., 1998; Kato et al., 2011), precise and in-situ estimation method for time-dependent deformation of tunnels has not been established sufficiently.

We are undertaking a project study focused on time-dependent behaviors of rock mass from the perspective of geology, mineralogy and geophysics and reported some important results (Murayama et. al (2015), Niwa et. al (2015a, 2015b), Okazaki et. al (2015a, 2015b)). In this study, detailed analyses were carried out for construction and research results on a tunnel with time-dependent deformations to clarify the mechanism of time-dependent behavior and to find the prediction method of time-dependent behavior of the tunnel.

2. Outline

The studied tunnel is 2.1-km in length, and was constructed using NATM and was opened in 2003. Figure 1 shows the geological section, geology, actual tunnel support pattern, displacement (convergence of upper half of the tunnel and crown settlement), convergent time, and the three repaired areas (A, B, C) of the tunnel. Geology of the tunnel was Miocene andesite (An), volcanic breccia (Vb), and tuff breccia (Tb).

Andesite was relatively hard and had cracks at several places. It had undergone minor hydrothermal alteration. Auto-brecciated part of andesite was relatively soft and had many cracks. Volcanic breccia was soft and had undergone minor hydrothermal alteration. Tuff breccia was distributed in the form of blocks, which were soft, friable, and partially fragmented. During construction, displacement of the

Table 1 Time-dependent deformation of tunnels in Japan (Compiled from Japan Society of Civil Engineers, 2003)

Name	Prefecture	Place	Method	Years until deformation revealed	Geology
Rebunge	Hokkaido	Road	Timbering support Method	0.5	Brecciated tuff, andesite
Sengan	Akita/Iwate	Road	Timbering support Method	20	Weathered granodiorite
Mikuni	Hokkaido	Road	Timbering support Method	15	Tuff breccia, altered andesite
Asamayama	Gunma	Road	NATM	1	Tuff breccia, Tuff, andesite, Mudstone
Enasan	Nagano/Gifu	Road	Timbering support Method	14	Granite with argillic alteration
Ureshino	Saga	Road	NATM	0	Tuff breccia, Shale
Tawarazaka	Nagasaki /Saga	Road	NATM	1	Andesite, tuff breccia
Kamui	Hokkaido	Railway	Timbering support Method	18	Serpentinite, black schist
Rebun-hama	Hokkaido	Railway	Timbering support Method	6	Andesitic tuff, Altered andesite
Usuitouge	Nagano	Railway	NATM	9	Andesitic lava, Volcanic breccia
Tsukayama	Niigata	Railway	Timbering support Method	4 months, 20 years	Neogene mudstone

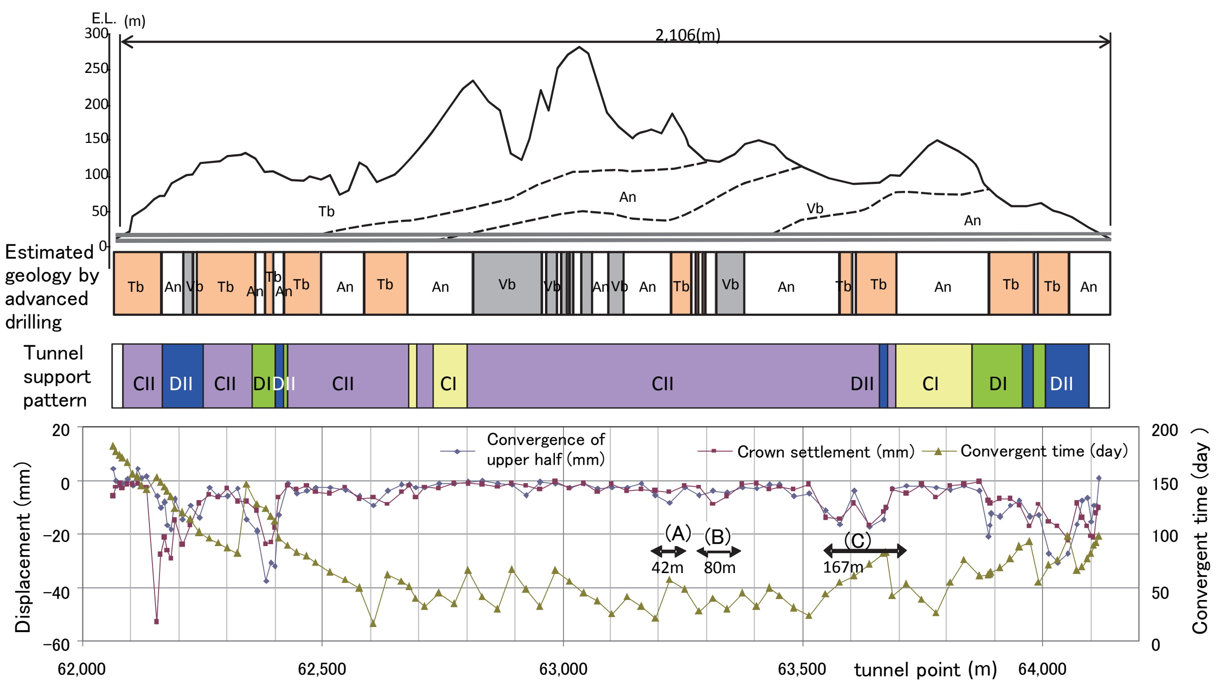

Fig. 1 Geology, displacement and three repaired area (A, B, C) of the studied tunnel

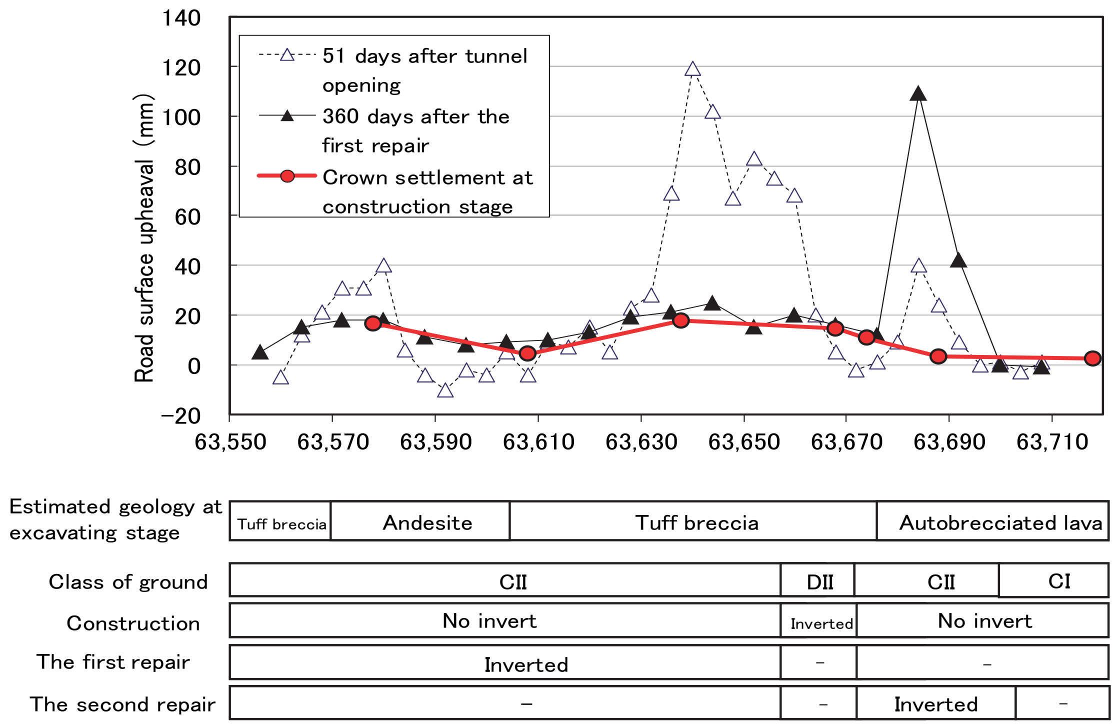

Fig. 2 Details of the area (C)

areas (A, B, C) was not particularly large (20mm at most).

At the tunnel, invert was settled for D I and D II of the tunnel support pattern, and not settled for C I and C II of it. From the geological observation of advanced drilling samples and cutting face, the geology of three areas was estimated too good to invert except some narrow part of the area (C). Also, convergent time of three areas was not so large compared with other areas without invert. There seemed no reason to settle invert there from the results of ordinary research.

Figure 2 shows the details of the area (C). The tunnel was opened in January, 2003. Just before the opening, upheaval and cracking was observed between tunnel point 63,565 and 63,663 of the area (C). 51 days after the opening, the maximum upheaval of road surface reached 120mm. The tunnel was closed and was repaired immediately. Near the repaired section, though small deformation was also observed between about 63,680 and 63,732 in March, 2003, the area was not repaired at that time.

360 days after the first repair, the maximum upheaval of this part reached 110mm, and the second repair was carried out. Repair work was also conducted at another two areas (A and B) where heaving lasted for a long period of time and maintenance of the tunnel structure was expected to be difficult.

The value of crown settlement was less than 20mm, and convergent time was less than about 80 days. Influence of stress release for rock of deformation part by tunnel excavation was thought to be convergent about 80 days at most. Comparing the value of road surface upheaval of 51 days after tunnel opening with crown settlement during construction, upheaval was remarkable at tuff breccia area between about 63,630 and 63,670 of tunnel point. Comparing value of road surface upheaval of 360 days after the first repair with crown settlement at construction stage, upheaval was remarkable at auto-brecciated lava area between about 63,680 and 63,700 of tunnel point.

In the tunnel, inverted section did not suffer from time-dependent deformation, while three time-dependent deformation sections were not inverted. Over-invert might be one of the methods to tunnels with similar geological condition. But it would result in overdesign and adequate threshold is needed.

3. Methods

During construction of the tunnel, geology, tunnel support pattern, crown settlement, convergence etc., were recorded at 99 sections of tunnel faces. Tunnel faces were estimated by a check sheet. Table 2 shows the check points and their scores from these sheets. Each check point was scored from 1 to 5, and these were then summed to the total score to estimate tunnel face. A high total score means bad conditions of the tunnel face, while low score indicates good conditions.

Table 2 Check points and scores of face observations

Score	1	2	3	4	5
Face condition	Stable	Small rocks fall off the face	Squeezing occurs at the face	Unable to support itself, the face collapses	The face flows out
Condition of unsupported excavation face	Standing (no support needed)	Loosening of ground and rock falls occur from time to time (ordinary support)	Barely able to stand and requires early support after excavation (immediate support)	Support before excavation needed	Others
Compressive strength	Withstands hammer blows	$100>\sigma_c\geq 20$MPa Crumbles when hit by a hammer	$20>\sigma_c\geq 5$MPa Crumbles when hit lightly by a hammer	$5>\sigma_c\geq 1$MPa A hammer head ends up lodged in	1MPa$>\sigma_c$ Crushable with a fingertip
Weathering/ alteration	No weathering; sound condition	Discolouring along rifts; slightly reduced in strength	General discolouration, considerably reduced in strength	Soil, clay, fractured, unconsolidated	Others
Crack/fissure frequency	Spacing $d\geq$1m	1m$>d\geq$50cm	50cm$>d\geq$20cm	20cm$>d\geq$5cm	5cm$>d$ fracture unconsolidated
Crack/fissure conditions	Tight	Partially open	General Open	Slickenside observed, unconsolidated sand and gravel	Interbeds of thick ($d\geq$5mm) clay, remarkable slickenside, soil, sand and gravel
Mode of Cracking/fissuring	Random, squares $d\geq$1m	Squares, massive	Layers, fragments, plates	Soil, fragmented, unconsolidated	Others
Water inflow	None, seepage 1little/min$>V$	Dripping $20>V$ 1little/min	Concentrated $100>V\geq$20little/min	Entire face $V\geq$100little/min	Others $V\geq$1000little/min
Deterioration due to water	None	Loosening	Softening	Collapse, outflow	Others

In this study, we correlated time-dependent deformation of the tunnel with the score of face estimation and measurement result of displacement. We also re-examined the geological description of drilling samples at the time of tunnel construction with respect to time-dependent behavior.

4. Results and Discussion

4.1 Relation between crown settlement and total scores of face estimation

Figure 3 shows correlation results of crown settlement and total score of face estimation for tunnel sections with and without deformation. There is a positive correlation between the two. From the figure, most parts with the score of more than 20 were inverted, while most scoring less than 20 were not. Whether invert settled or not was inferred to have been mainly determined by the score.

In the non-inverted area, scores from the sections with deformation (from about 20 to 12) overlapped those from the section without deformation (from about 20 to 10). Therefore, it is difficult to estimate whether the section would be deformed or not in the future only by the total score of tunnel estimation.

4.2 Relation between convergence and crown settlement of non-inverted section

Figure 4 shows correlation results between

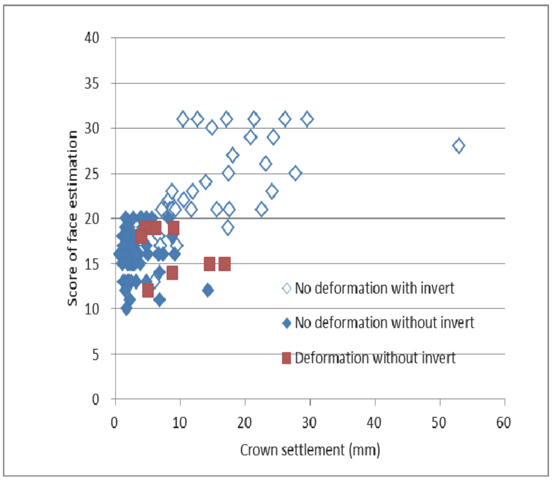

Fig. 3 Relation between crown settlement and score of face estimation

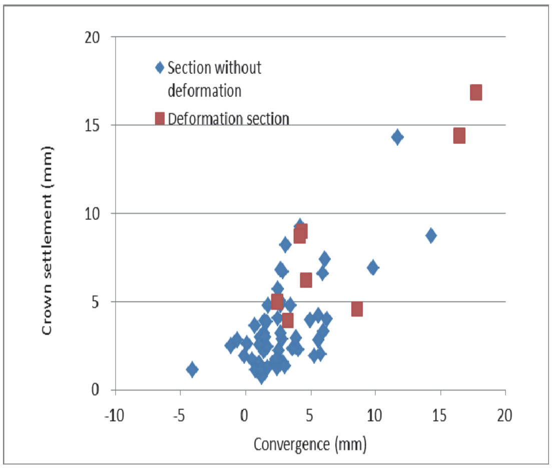

Fig. 4 Relation between convergence and crown settlement of non-inverted part

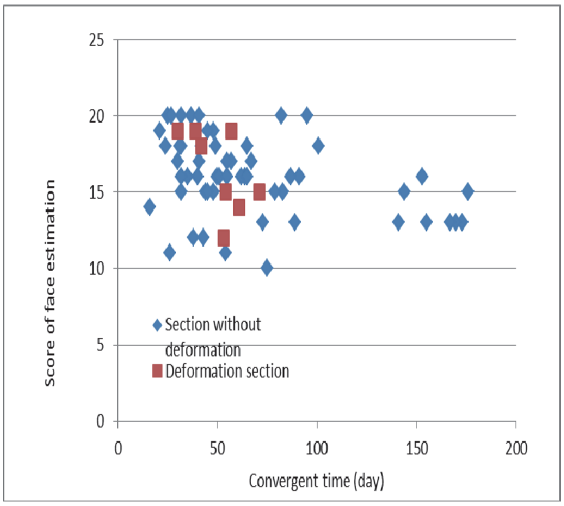

Fig. 5 Relation between convergent and score of face estimation in non-inverted part

convergence and crown settlement in the non-inverted section. There is a positive correlation between the two. Convergence value of the deformation section seems to be larger than that of the section without deformation. Therefore, we could adopt about 4mm of crown settlement or 2.5mm of convergence as the threshold to determine tunnel support patterns (whether invert was settled or not).

The threshold, however, is too small to be adopted compared with that of other tunnels. The estimation method might result in the overdesign of tunnel support pattern. However, there is a possibility that the value could be used for screening to find the section of time-dependent deformation of similar geological areas.

4.3 Relation between convergent and score of face estimation in non-inverted section

Figure 5 shows the correlation results between convergent time (day) and total scores of face estimation in non-inverted part. Convergent time of time-dependent deformation section is less than about 80 days, while section without it is from about 20 to 200 days.

This means that sections of small convergent time are not necessarily the section without time-dependent deformation. The figure also suggests that rock degradation by release of in-situ stress might end less than about 80 days at most, and time-dependent deformation occurred by other factors. Rock degradation by mineral change in rock by the change of temperature, water and air is one of the most important factors of time-dependent deformation.

4.4 Analysis of geological descriptions of drilling samples between convergence and crown settlement of non-inverted section

Geological features around the deformation part of tunnel was re-examined by checking the record of advanced drilling samples. We paid attention to the geological descriptions of the record to find the prediction method of time-dependent deformation part of the tunnel. That is descriptions such as “swelling” and “softening” (not “soft”). We also paid attention to the groundwater descriptions in it.

Table 3 shows the examination results from tunnel point 63,164 to 63,860. The zone was estimated as C II of the tunnel support pattern (without invert) except the area 4. The zone also includes three deformation areas (A, B, and C) and no deformation areas (1 to 5).

There were many descriptions with regard to time-dependent behavior such as swelling or softening in the area C. Only taking these descriptions seriously, we could easily estimate that there was a large potentiality of time-dependent

Table 3 Examination results from tunnel point 63,164 to 63,860

Area (Area A,B,C are repaired)	Tunnel Support Pattern and Tunnel Point	Descriptions with time-dependent behaviour	Other characteristic descriptions	Groundwater inflow (TP means Tunnel Point)(Litter/min)
1	63,164 C II 63,206	"Weakly swelling (2 parts:4cm and 110cm in sample length)"	"Soft"	TP=63,164-13204: 15
A (2nd Repair)	C II 63,248	-	"Fractured, muddy"	TP=63,216: Groundwater inflow TP=63,204-63,239: 12
2	C II 63,292	"Weakly swelling (3 parts:2.0m, 0.47m and 1.7m in sample length)"	"Soft and fragile"	TP=63,239-63,264: 85
B (2nd Repair)	C II 63,372	"Weakly slaking"	"Soft and fragile"	TP=63,292-63,314: No groundwater TP=63,314-63,364,: 24
3	C II 63,565	"Softening"	"Fragmental"	TP=63502: 80 TP=63,516: 130 TP-=63,528: 100 TP=63,542: 50 TP= 63,557-63,570: firstly 600, finally 170
C (1st Repair)	C II 63,663	Many descriptions (19 parts) of " weakly Swelling" or "Swelling"	"Rather soft and fragile"	TP= 63,581-63,587: 10.8 TP= 63600- 63660: No groundwater inflow
4	D II (Inverted) 63,680	"Softening"	"Matrix is soft"	-
C (2nd Repair)	C II 63,732	"Softening"	"Matrix is soft"	
5	C II 63,860	"Softening was not observed"	-	-

deformation in the area C. There were some descriptions with time-dependent behaviour in the area 1, 2, B and 3. Therefore, we could estimate that there was some potentiality of time-dependent deformation in these areas, though there was some possibility to overestimate time-dependent behaviour. There was no description with that in the area A. It might be difficult to predict that time-dependent deformation would occur in the area A.

Groundwater inflow was described in the area 1, A, 2, B, 3 and C (1st Repair), while no descriptions for that in the area 4, C (2nd Repair) and 5. Remarkable groundwater inflow was observed in the area 2 and 3, between the area A and B, and the area B and C, respectively. Though rock of the area A, B and C was originally dry or under stable circumstances of groundwater, it may become wet or become under unstable groundwater conditions by groundwater inflow from the area 2 and 3 after tunnel excavation. That might strengthen rock degradations, and result in time-dependent deformation of these sections.

By attaching importance to descriptions with regard to time-dependent behaviour and groundwater, we could estimate that where had a risk of time-dependent deformation, and could judge to change tunnel support pattern to avoid time-dependent deformation.

5. Conclusions

In this study, records of construction and repair of a tunnel with time-dependent deformation in Hokkaido were correlated with each other to develop judging method of time-dependent deformation. The results obtained in this study led to the following conclusions.

1) Most parts of the tunnel were not inverted when score of face estimation is less than 20, and time-dependent deformation of the studied tunnel occurred only in non-inverted parts. In such parts,

displacement value of deformation part tended to be larger than that of non-deformation part. Though the boundary value was too small (about 4mm of crown settlement) to be adopted as a threshold to determine tunnel support patterns, there is a possibility that the value could be used for screening to find the part of time-dependent deformation in similar geological areas.

2) Convergent time of time-dependent deformation section was found to be less than about 80 days. That suggests that rock degradation by release of in-situ stress of rock might end less than about 80 days, and time-dependent deformation occurred by other factors such as mineral change in rock by groundwater inflow or other condition change of temperature and air.

3) As there were many descriptions of time-dependent behavior in the area C, we could easily estimate that there was a large potentiality of time-dependent deformation by only taking them into consideration seriously. As there were some such descriptions in the area 1, 2, B and 3, we could estimate that there was some potentiality of time-dependent deformation although there was some possibility to overestimate time-dependent deformation. For the area A without such descriptions, it seems to be difficult to predict that time-dependent deformation would occur. By attaching importance to the descriptions of time-dependent behavior, we could mostly estimate that where had a risk of time-dependent deformation, and changed tunnel support pattern for that.

4) Remarkable groundwater inflow was observed in the area 2 and 3, between the area A and B, and the area B and C, respectively. Though rock of the area A, B and C was originally dry or under stable circumstances of groundwater, it may become wet or become under unstable groundwater conditions by groundwater inflow from the area 2 and 3 after tunnel excavation. That might strengthen rock degradations, and result in time-dependent deformation of these sections.

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