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Deformation characteristics of tunnel bottom after construction under geological conditions of long-term deformation

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Abstract. Mountainous areas cover more than 70% of Korea. With the rapid increase in tunnel construction, tunnel-collapse incidents and excessive deformation are occurring more frequently. In addition, longer tunnel structures are being constructed, and geologically weaker ground conditions are increasingly being encountered during the construction process. Tunnels constructed under weak ground conditions exhibit long-term deformation behavior that leads to tunnel instability. This study analyzes the behavior of the bottom region of tunnels under geological conditions of long-term deformation. Long-term deformation causes various types of damage, such as cracks and ridges in the packing part of tunnels, as well as cracks and upheavals in the pavement of tunnels. We observed rapid tunnel over-displacement due to the squeezing of a fault rupture zone after the inflow of a large amount of groundwater. Excessive increments in the support member strength resulted in damage to the support and tunnel bottom. In addition, upward infiltration pressure on the tunnel road was found to cause severe pavement damage. Furthermore, smectite (a highly expandable mineral), chlorite, illite, and hematite, were also observed. Soil samples and rock samples containing clay minerals were found to have greater expansibility than general soil samples. Considering these findings, countermeasures against the deformation of tunnel bottoms are required.

Keywords: tunnel bottom; long-term deformation; tunnel construction

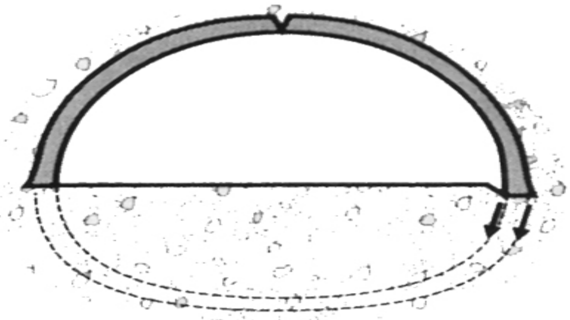
1. Introduction

Recent trends in tunnel construction include extended tunnel lengths and longer construction periods, leading to diverse ground conditions being encountered. Excavation of tunnels in areas with faults and fractures tends to cause serious engineering problems, such as excessive deformation. Of particular concern is the deformation at the bottom of tunnels, according to the physical properties of the single-layer fracture zone (Son *et al.* 2015). Thus, the most important prerequisite for tunnel excavation is to provide sufficient support to ensure stability of the tunnel during excavation and support installation.

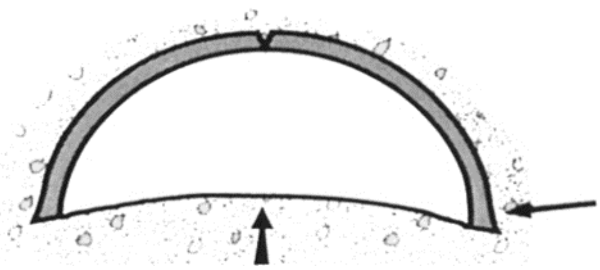
Insufficient ground forces cause ground relaxation occurs, which gradually increases the load, thereby causing phenomena such as spalling, squeezing, and sudden popping, all of which eventually induce tunnel collapse (Chang *et al.* 2014, Yoo 2016).

The types of collapse that occur before support installation include collapses due to a lack of bearing capacity, increase in side pressure, and fracture of the branch joint, as shown in Fig. 1.

Collapse due to a lack of bearing capacity occurs mainly when soft ground appears in the lower part of the tunnel (Laver *et al.* 2016). In case of deformation due to subsidence of the first support material installed on the upper part of the tunnel, which occurs owing to the lack of



(a) Deformation due to lack of bearing capacity



(b) Upheaval due to increased lateral pressure

Fig. 1 Deformation and upheaval due to lack of bearing capacity

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bearing capacity, it is difficult to maintain the inner section, and cracks in the support material may directly lead to collapse.

Collapse due to an increase in lateral pressure occurs when the horizontal stress is greater than the vertical stress. Cracks in the ceiling section of the primary support material and uplift of the lower ground may occur owing to excessive displacement in the side wall section (Wongsaroj *et al.* 2013, Yang *et al.* 2016), which may lead to collapse.

This study aims to investigate the behavior of tunnel bottoms under geological conditions of long-term deformation. This will determine the most important factors to be considered during tunnel construction to avoid collapse.

2. Characteristics of tunnel deformation in the fracture zone

2.1 Definition of fracture zone

Through geological changes, faults are formed in rocks with very low tensile strength and very high permeability coefficients. An area defined as a "fractured zone" exhibits the characteristics of rocky ground with the development of large-scale cracks due to weathering and fracturing.

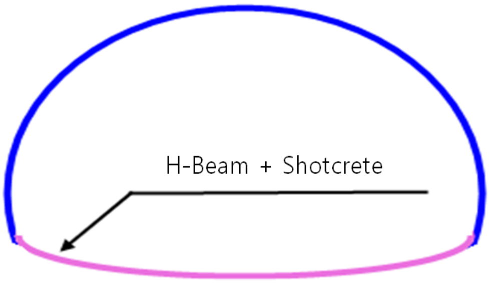
2.2 Characteristics of fracture zone

Generally, tunnels constructed in a fractured rock layer within a fracture zone are mechanically weak (Son *et al.* 2015, Yang and Li 2016). Fault fracture zones formed by single-layer fractures, hydrothermal alteration zones formed by hydrothermal solutions, and dykes due to penetration are relatively unfavorable for engineering activities, compared with surrounding rocks (Yang and Yan 2015, Yang and Zhang 2017). This is because the former have weaker characteristics. These rocks are more sensitive to weathering and can deteriorate rapidly owing to weathering by groundwater and rainfall. Therefore, when crushed rocks appear on the front of the tunnel during excavation, excessive deformation and collapse often occur. This is especially likely when crushed rocks are accompanied by groundwater, resulting in sudden collapse of the upper section of the closure surface; therefore, appropriate measures are required during excavation (Li *et al.* 2015, Zheng *et al.* 2017).

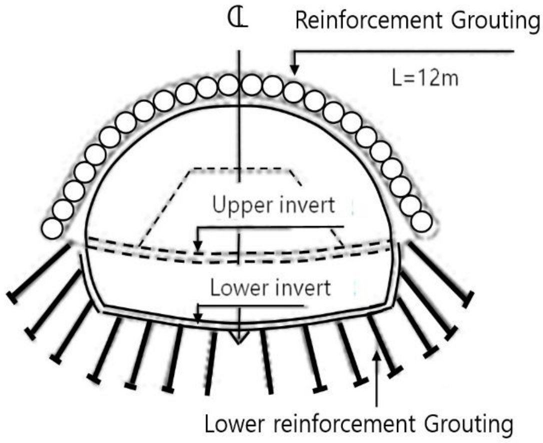
The crushed rock mass can cause long-term plastic deformation and is responsible for several engineering problems, not only during tunnel construction but also during later maintenance work. Therefore, the characteristics of crushed rock masses should be analyzed and incorporated into tunnel design and construction.

2.3 Tunnel bottom invert and reinforcement

In a tunnel exhibiting long-term displacement behavior, if groundwater leaching gradually increases with the time variation of a single-layer fracture zone, further displacement gradually occurs. Long-term displacement tends to occur at the bottom of the tunnel.

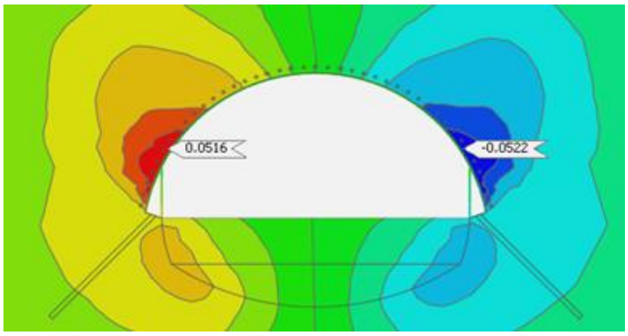


(a) H-Beam reinforcement method

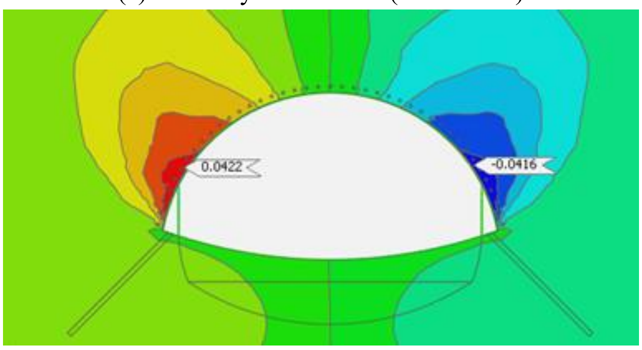


(b) Steel pipe reinforcement method

Fig. 2 Invert reinforcement for suppressing the displacement of tunnel bottom



(a) Plasticity distribution (Non-invert)



(b) Plasticity distribution (Invert)

Fig. 3 Invert behavior characteristics (displacement reduction effect)

In response to stability problems at the bottom of the tunnel resulting from excessive displacement, the invert or reinforcement is strengthened by being installed at the tunnel bottom, to control tunnel deformation against continuous displacement (Fig. 2).

As shown in Fig. 3, the incidence of plasticity due to stress concentration tends to be relatively reduced when applying a curve invert section.

In the case of weak tunneling, curved steel inverts and early ring closure due to shotcrete casting can increase the stability of the tunnel by reducing the stress concentration in the tunnel-deformation area and the surrounding ground. The tunnel invert should maintain a curved shape to maximize the stress relaxation and prevention of tunnel deformation. The thickness of the shotcrete installed in the invert should be greater than the designed shotcrete thickness.

In summary, rapid tunnel over-displacement occurs owing to the squeezing of a fracture zone after an inflow of a large amount of groundwater to the fracture zone during tunnel excavation.

3. Long-term deformation analysis of tunnel bottom

3.1 Damage of ceiling support and deformation of bottom section during tunnel construction

In the tunnel shown in Fig. 4, after excavation, deformation of the tunnel crown and side wall occurred during construction. The rock mass rating (RMR) is a geomechanical classification system for rocks. It combines the most influential geologic parameters and represents them as a single overall comprehensive index of rock mass quality, which is used for the design and construction of excavations in rock, such as tunnels, mines, slopes and foundations. Six parameters are used to classify a rock mass using the RMR system: uniaxial compressive strength of rock material, rock quality designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater conditions, and orientation of discontinuities. Each of the six parameters is assigned a value corresponding to the characteristics of the rock. These values are derived from field surveys and laboratory tests. The sum of the six parameters is the “RMR value”, which lies between 0 and 100. An RMR analysis of the tunnel that was analyzed in this study suggested that rock separation and the support damage zone are in very poor conditions, because the RMR was below 20 (Fig. 5). Clay fillings in the joints were found to be interlinked with the joints and spaced densely. Likewise, the fault and fault fractures are distributed in the sections of rock mass removal and support.

A re-evaluation of the ground condition, observational data of the tunnel excavation surface, and the present state of rock debris in the ceiling reveled separation of the rock mass and damage to the support material, which occurred through the following mechanism.

In the right part of the tunnel, as shown in Figs. 6-8, the deformation and strength characteristics became abruptly degraded when the rocks came in contact with groundwater. The slaking durability index, which was 27.6-35.4% as shown in the following Table 3, represents “low durability to extremely low durability”, according to Gamble’s classification system.

(a) Collapse of tunnel crown

(b) Collapse of tunnel side wall

Fig. 4 Shotcrete cracking of tunnel

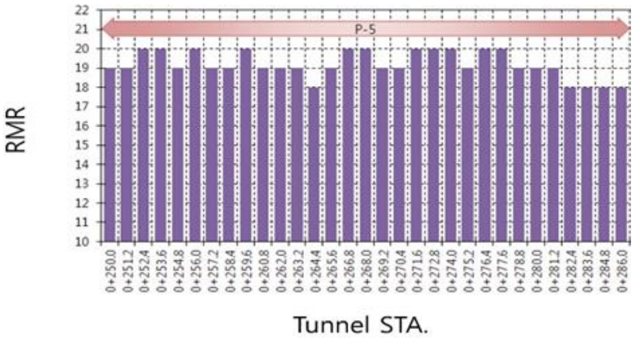


Fig. 5 RMR analysis results of face in shotcrete crack zone of tunnel crown

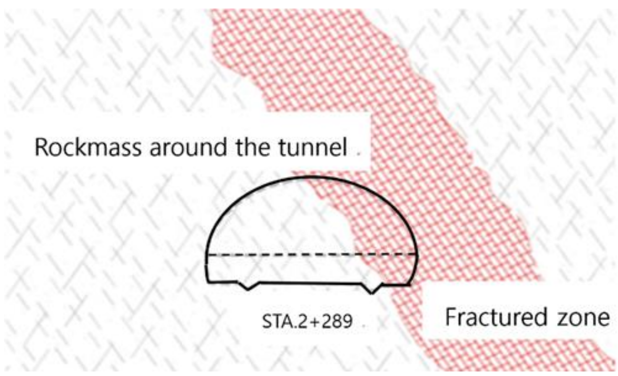


Fig. 6 Shape of fractured zone (before tunnel excavation)

The ground is vulnerable to weathering as its durability is significantly lower than the durability of rocks,

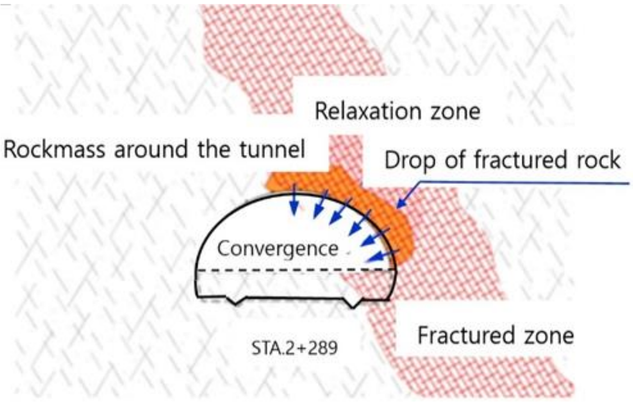


Fig. 7 Shape of fractured zone (after tunnel excavation)

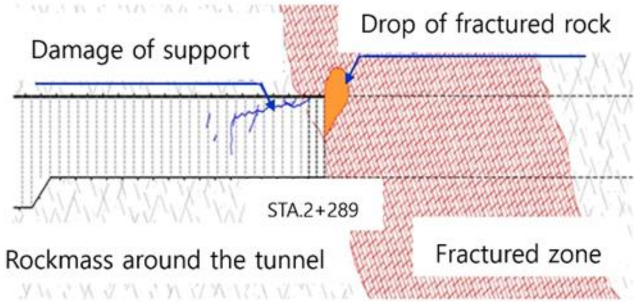


Fig. 8 Damage of tunnel support

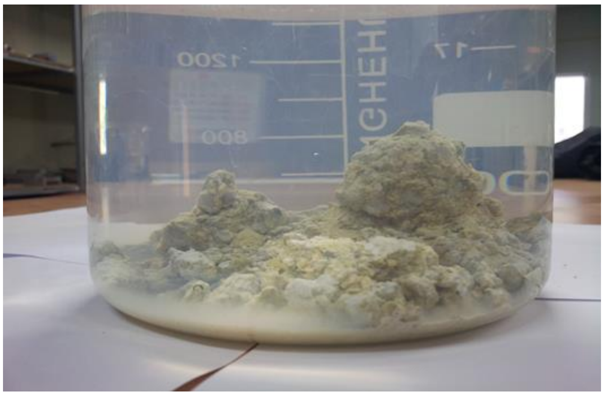


Fig. 9 Result of immersion test in upheaval zone of tunnel

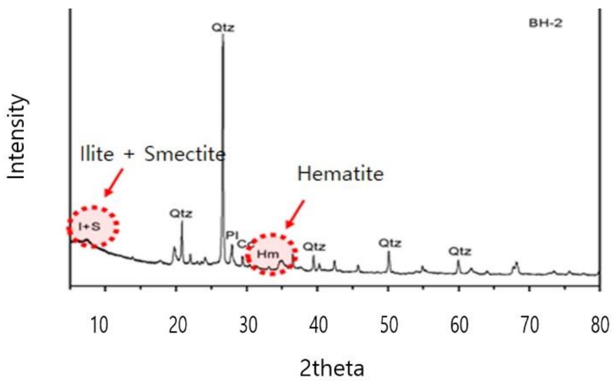


Fig. 10 Analysis result of X-ray diffraction

sandstones, mica schist, and unconsolidated rocks, which are also vulnerable to weathering. An immersion test was conducted using samples collected from the upheaval


Fig. 11 Upheaval of tunnel bottom under construction

zone of the tunnel. Particle separation started 2 h after immersion; 6 h after immersion, the original sample completely collapsed to become fragmented and partially liquefied. After 8 h, it changed completely into the soil form (Fig. 9).

The samples were analyzed using X-ray diffraction (XRD), which is a non-destructive test method used to analyze the structure of crystalline materials. The results revealed the formation of smectite, chlorite, illite, and hematite through hydrothermal alteration of tuff (Fig. 10). Note that smectite is a mineral with a large expansibility. Swelling tests of the soil and rock samples were also conducted, and samples containing clay minerals showed a larger swelling capacity (2.4 times that of earth and 3.3 times that of rock) than general soil samples did. Furthermore, based on weathering durability analyses, the rocks were evaluated as having very low to low durability.

As shown in Fig. 11, ridge-like damage appeared in the reinforcement support material used to suppress the bump in the tunnel bottom. The damage was caused by the decrease in strength due to the occurrence of slaking in the ground surrounding the tunnel (fracture zone).

3.2 Upheaval of tunnel bottom

Fig. 12 shows a graphical representation of the tunnel, which is a typical road tunnel. As shown in Fig. 13, cracks and other damages appeared in the tunnel pavement owing to the upheaval of the tunnel bottom.

According to field survey results and observational data on the tunnel face during construction, the weathering


Fig. 12 Section of typical road tunnel

Fig. 13 Upheaval and underwater flow of tunnel pavement

Fig. 14 Geological condition of the tunnel bottom under construction

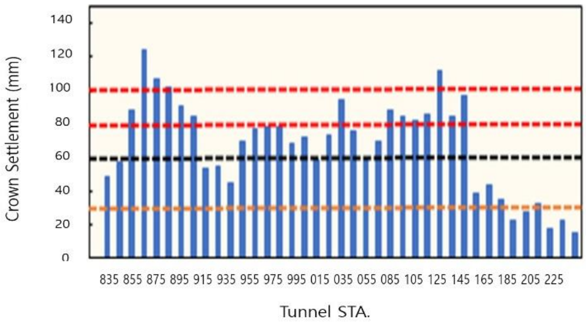


Fig. 15 Crown settlement of the tunnel under construction

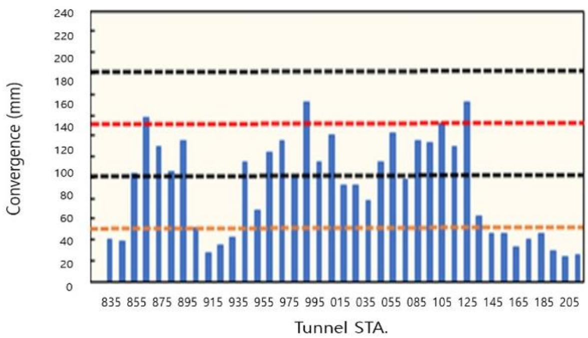
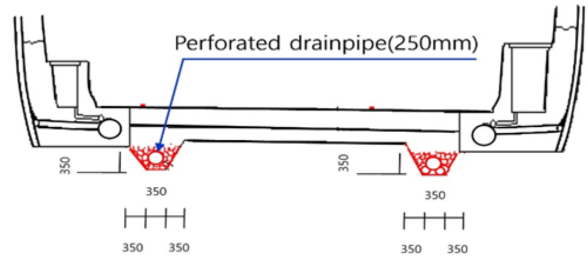
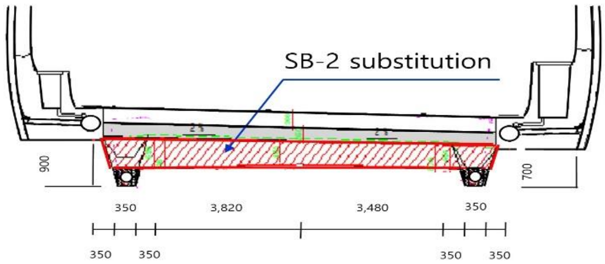


Fig. 16 Convergence of the tunnel under construction

condition of the rock mass around the tunnel is dominant, with the partially weathered state being distributed as shown in Fig. 14.



(a) Typical cross section of tunnel pavement



(b) Applying SB-2 substitution at the tunnel bottom

Fig. 17 Deformation suppress at the tunnel pavement

In this tunnel, the majority of the fault clay and coal shale layer are developed, and dropping occurs frequently at the crown under construction. Field measurements showed that the crown settlement occurred up to 120mm, as shown in Fig. 15. Fig. 16 shows that convergence occurred up to 200 mm.

The upward-penetrating water pressure of tunnel roads due to high groundwater levels causes serious pavement damage (Shen. *et al.* 2014). The deformation can be suppressed by applying SB-2 substitution at the tunnel bottom to reduce the upward penetrating water pressure, as shown in Fig. 17(b) (red zone).

3.3 Analysis of the cause of excessive deformation in tunnel floor

3.3.1 Analysis of ground strength ratio

Nakano (1974) suggested that the phenomena presented in Table 1 occur depending on the ground strength ratio (*Gn*), which is calculated as follows:

$$G_n = \frac{\sigma_c}{\gamma_t \ H} \tag{1}$$

where H: depth (m)
σ_c: uniaxial compressive strength
γ_t: unit weight

Table 1 Tunnel phenomena according to ground strength ratio

Ground strength ratio	Phenomena of tunnel
Gn ≤2	· Extrusion ~ expansibility
2 <Gn≤4	· Large earth pressure is estimated ~ extrusion
4 <Gn ≤6	· Large earth pressure can be estimated
6 <Gn ≤10	· Earth pressure can be estimated
10<Gn	· Almost no earth pressure can be estimated

Table 2 Analysis of ground strength ratio

Case	During Design		During Construction	
	σ_c (tf/m^2)	Gn	σ_c (tf/m^2)	Gn
1	5,650	50.4	88	3.67
2	3,210	34.1	132	5.07
3	3,210	43.3	44	0.61
4	3,450	71.8	132	1.38
5	-	-	110	2.29
6	-	-	176	8.8
7	-	-	44	2.2

Table 2 shows the results of applying the ground strength ratios suggested by Nakano (1974) during tunnel design and construction. The design ground strength ratio was 34.1-71.8, and the fault fractured zone was supposed to have no extrudability. However, the Gn value obtained from the measurement of uniaxial compressive strength during construction was 0.61-8.8, and the values were lower than 2 with the average value of 3.43. This suggests that the fault fractured zone has a very large extrudability. The cause of the significant decrease in Gn during construction compared with that during design is presumed to be the reduction in the uniaxial compressive strength due to a low depth of the damaged section and the inflow of surface water and underground water during construction.

3.3.2 Slaking test

The slaking test was performed to analyze the degrading consolidation phenomenon of rocks due to underground water-level fluctuation, stress change, absorption expansion, and weathering.

Specimens were prepared by placing 10 representative rocks weighing 40-60 g in a test device and drying them at 105℃ for 2-6 h. The weight was measured after cooling at least three to four times. The weathering index was determined by dividing the final dry weight by the initial weight. A total of five cycles were performed, and the slaking index in the second cycle was determined (I_{d2}). Eq. (2) shows the equation used for the slaking test.

$$I_{d2} = (C - D)/(A - D) \times 100(\%) \qquad (2)$$

where I_{d2}: Slaking index
A: Initial weight
C: Final weight
D: Drum weight

The results showed a slaking durability index of 27.6-35.4%, as shown in Table 3. According to Gamble's classification, this corresponds to "low to extremely low durability." This value is substantially lower than the durability indexes of coal, sandstone, mica, and unconsolidated mudstone, which are vulnerable to weathering. Thus, it is considered to be very vulnerable to slaking and weathering. When the strength decreased owing to slaking in the ground around the tunnel, the relaxation area is believed to have been enlarged to increase the hole displacement in the tunnel. This led to a large support pressure acting on the support, thus degrading the stability of the tunnel.

Table 3 Slaking test results

Classification	Slaking index I_{d2}(%)
Specimen1	35.4
Specimen2	34.1
Specimen3	27.6

Table 4 Swelling test results

Rock type	Swelling ratio(%)	
Granite	Axial	0.74
	Lateral1	0.18
	Lateral2	0.18
Granite	Axial	0.26
	Lateral1	0.03
	Lateral2	0.04
Granite fractured zone	Axial	0.063
	Lateral1	0.029
	Lateral2	0.025
Granite fractured zone	Axial	0.069
	Lateral1	0.040
	Lateral2	0.035
Granite fractured zone	Axial	0.090
	Lateral1	0.054
	Lateral2	0.044

3.3.3 Swelling test

The swelling test measures geometric changes in the specimens due to water absorption. The water absorption swelling ratio can be determined using Eq. (3). Rocks with large expansibility show significant swelling when the surcharge load is removed in the water absorption state, which softens the rock and decreases its strength. When swelling is restricted, a significant inflation pressure is generated. Furthermore, swelling is caused by progressive mechanical and chemical weathering due to stress release and water supply. The swelling ratio is closely related to the slaking and swelling pressure, which leads to problems owing to rapid softening. Eq. (3) shows the equation used for the test.

$$\text{Swelling ratio} = \frac{\alpha}{L} \times 100(\%) \qquad (3)$$

where α: Maximum swelling displacement (㎜),

L: Initial height of specimen (㎜)

The results revealed swelling ratios of 0.03-0.74%, as shown in Table 4. The swelling phenomenon does not occur in general rocks. The development of a large-scale fault fractured zone can cause swelling of clay minerals. When the strength decreases owing to an increase in the moisture content of the ground around the tunnel, tunnel damage may occur owing to increments in the hole displacement in the

Fig. 16 Convergence of the tunnel under construction

tunnel and a large support pressure on the support. Therefore, swelling is considered to be a cause of excessive displacement when there is a certain degree of expansion.

The underground water condition was estimated by examining the water condition in the damaged tunnel section. Several traces of water that had not been observed in the working face during the excavation were found after deformation occurred, as shown in Fig. 18. Soils were found in shotcrete cracks and dropouts in the pit, indicating that water had entered the pit. In some sections, small-scale silty soil inflow due to water was observed to occur continually. Moreover, water was observed to have entered at the point of excessive displacement.

In summary, a ground strength ratio(Gn) lower than the design value was found during construction, thus suggesting large extrudability. The fundamental reason for this change in the ground strength ratio is considered to be the decreased uniaxial compressive strength of the fractured zone. The reduction in the uniaxial compressive strength is believed to be caused by slaking due to the inflow of surface water or underground water. Water absorption expansion test results showed that swelling does not occur in the granite of plutonic rocks in general, but is observed when clay minerals are formed along a fault fractured zone. Furthermore, several water traces were found inside the tunnel. Surface water can flow into the tunnel owing to the geographical features at the top of the tunnel. Furthermore, tunnel excavation also led to the inflow of underground water, which was a fractured zone connected with tunnels and weathered rocks.

4. Conclusions

The behavioral characteristics of under-construction and public tunnels showing upheaval of the tunnel bottom were analyzed. The main conclusions can be summarized as follows:

- Rapid tunnel over-displacement occurs owing to the squeezing of a fault rupture zone after an inflow of a large amount of groundwater to the fault rupture distribution area during tunnel excavation. Excessively increasing the support member strength resulted in support member damage (shotcrete cracking and dropping), as well as damage to the tunnel bottom. An upward infiltration pressure on the tunnel road caused severe pavement damage, which can be suppressed by applying SB-2 displacement at the bottom of the tunnel to reduce the upward infiltration pressure resulting from excessive groundwater.
- An XRD analysis revealed the occurrence of smectite, chlorite, illite, and hematite, which were formed from the hydrothermal alteration of tuff. In particular, smectite is a highly expandable mineral; when it comes in contact with water, the strength of the ground is greatly reduced.
- The swelling test of soil samples and rock samples indicated that samples containing clay minerals had a larger capacity of expansion (2.4 times soil, 3.3 times rock) than general soil samples. Under these conditions and considering the long-term behavior of the tunnel, a countermeasure against deformation of the tunnel bottom should be implemented.

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