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Theoretical analysis and seismic investigation for TBM jamming in squeezing fissile slate

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ABSTRACT

The S tunnel is a 4.2 km-long headrace tunnel. In the tunnelling project, the ground was assumed to be hard slate and suitable for TBM excavation based on the primary site investigation. However, TBM jamming frequently occurred with the increase of the tunnel cover, and the TBM excavation was cancelled. In order to investigate the TBM jamming, theoretical analyses and seismic investigations were conducted. It was found that analytical model proposed in this paper well explained the influence of the cover on the possibility of TBM jamming. It was also found that the depth of the loosened zone was expanded 6–8 m at the location where TBM jamming occurred.

1. Introduction

The S tunnel is a 4.2 km-long headrace tunnel. A 3.4 km-long part of the tunnel was planned to be excavated by a tunnel boring machine (TBM), the diameter of which was 2.8 m. With the increase of the tunnel cover, however, the ground began to show squeezing behaviours, which brought larger convergences than expected. As a result, TBM jamming due to the friction between the TBM body and the ground occurred several times. The TBM excavation was eventually cancelled after it excavated 2.95 km, and the rest part of the tunnel was excavated by a road header. In order to investigate the reason for which the TBM jamming had occurred, theoretical analyses as well as seismic investigations were conducted. In this paper, the results of the analyses and investigations will be presented.

2. Geological settings and TBM specifications

The geology of the S tunnel was mainly slate formed in the Cretaceous Period of the Mesozoic Era. Based on the result of site investigations conducted in advance of the tunnel construction, it was assumed that the strength of the slate was relatively high and was suitable for TBM excavation. Photo 1 shows the tunnel face observed when the ground around the TBM was widened after a TBM jamming occurred. As shown in Photo 1, the ground was composed of a number of thin layers that could be clearly seen. From the photo, it could be said that the location where the TBM jamming occurred was not a fractured zone but fissile slate disturbed by the influence of fold. Photo 2, which is zooming up Photo 1, shows the alternation of thin layers composed by dark-grey slate and white sandstone. Site investigations conducted in advance of the tunnel construction indicated that the uni-axial strength of the slate was approximately 20 MN/m^2, which implied that the competence factor would be more than 2. However, the slate observed near the tunnel face could be crushed easily by a hammer. The uni-axial strength estimated by needle penetration test was about 2–5 MN/m^2. No water inflow occurred during the tunnel construction.

The used TBM was a double-shield type TBM, the diameter of which was 2.8 m. 23 disc cutters were deployed on the cutter head. The overcut of the TBM was widened as much as possible by adjusting the location of the outer cutter, and it became 30 mm after the 2nd TBM jamming occurred.

3. Theoretical analysis for assessing earth pressure on TBM body

The TBM was frequently jammed when the tunnel cover became more than 300 m. Therefore, it was thought that the increase of the tunnel cover, that is to say the increase of the initial stress, should be an important parameter which significantly influenced the possibility of the TBM jamming. Thus, the relationship between earth pressure and the displacement of tunnel wall using an analytical elasto-plastic solution of stresses by Kastner (1971)

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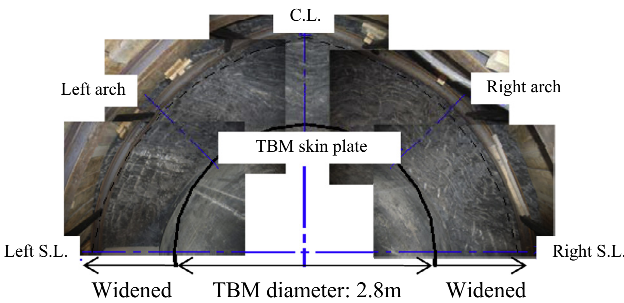

Photo 1. Fissile slate observed at tunnel face.

Photo 2. Alternation of thin layers of slate and sandstone.

was studied, changing the tunnel cover as well as geotechnical properties of the ground. As an example of the analysed results, Fig. 1 shows the relationship between earth pressure and the displacement of tunnel wall in case that the cover is 400 m. Table 1 shows the assumed geotechnical properties used to calculate the relationship. The Young's modulus was obtained from borehole load tests at the site. The cohesion and the friction angle were assumed based on the Young's modulus. As shown in the figure, since the amount of the TBM overcut was 30 mm as mentioned in Section 2, the earth pressure which the TBM received in this case was thought to be 0.61 MN/m^2.

As a next step, it was thought that the possibility of TBM jamming could be analysed by a simple mechanical model shown in Fig. 2. In the figure, frictional forces caused by the earth pressure as well as the weight of the TBM rear body and the maximum thrust (7212 kN) to draw the TBM rear body toward the gripper

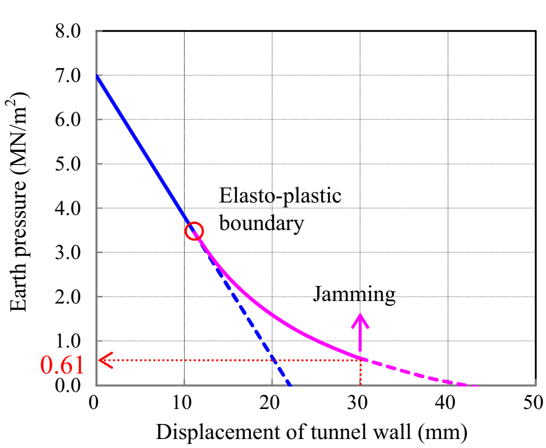

Fig. 1. Relationship between earth pressure and displacement of tunnel wall.

Table 1
Assumed geotechnical properties.

Property	Unit	Value
Stress relaxation rate	%	30
Young's modulus	MN/m^2	600
Cohesion	MN/m^2	1.0
Friction angle	degree	35

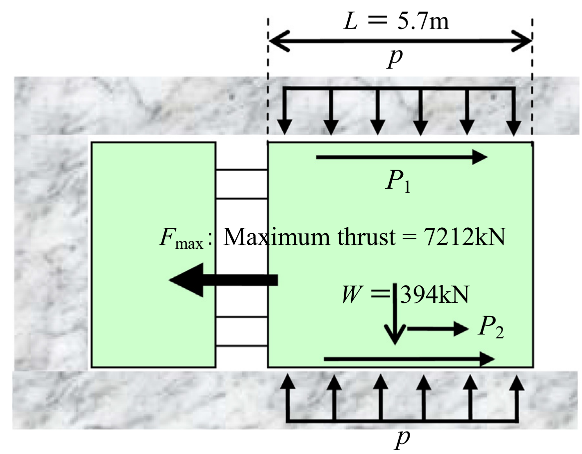

Fig. 2. Simple mechanical model of friction between TBM and ground.

were compared. It was assumed that as the sum of the frictional forces is larger than the maximum thrust, the TBM would be likely to be jammed. Following the mechanical model, the relationship between the possibility of jamming and the tunnel cover was summarized in Table 2. For this calculation, the friction coefficient between the ground and the TBM shown in Fig. 2 was assumed to be 0.5.

Table 2 implies that the ground would begin to pressurize the TBM at the cover of 330 m, and that the TBM would be likely to be jammed at the cover of 360 m, under the assumed geotechnical properties. This result corresponds well to the fact actually observed at the S tunnel. It was confirmed that the tunnel cover was an important parameter to determine the possibility of TBM jamming, and the methods proposed in this section would be useful to estimate the risk of TBM jamming.

4. SEISMIC investigation for measuring loosened zone

As mentioned in Section 2, the excavated ground was squeezing fissile slate composed of a number of thin layers of slate and sandstone. Therefore, the reason why the ground squeezed much more than expected was thought that the cleavages between the layers opened due to the tunnel excavation, which would result in forming loosened zone around the tunnel. Thus, in order to investigate

Table 2
Tunnel cover and possibility of TBM jamming.

Cover (m)	Earth pressure, p (MN/m^2)	Required thrust to avoid TBM jamming, $P_1 + P_2$ (kN)	Comparison with Max. thrust, *Fmax*	Possibility of TBM jamming
250	0	197	<*Fmax*	None
300	0	197	<*Fmax*	None
330	*0.03*	*949*	*<Fmax*	*Small*
350	0.19	4960	<*Fmax*	Medium
360	*0.31*	*7969*	*>Fmax*	*High*
400	0.61	15,490	>*Fmax*	High

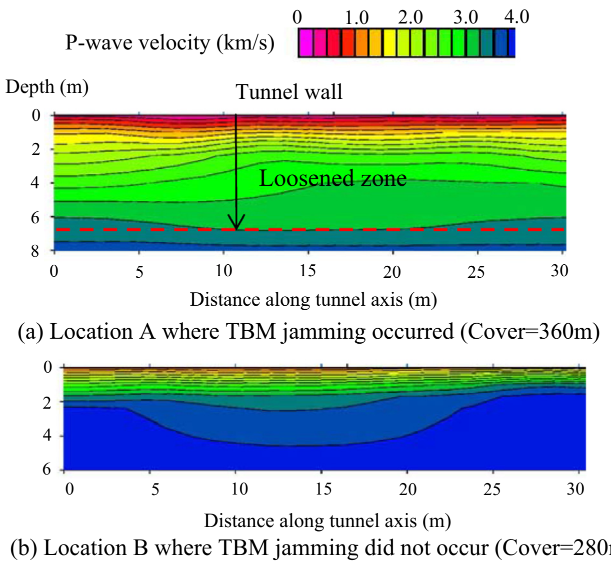

Fig. 3. P-wave contour maps at two locations.

the degree of the loosening, seismic refraction investigations were conducted at two locations where TBM jamming had occurred and had not, respectively. Fig. 3 shows the contours of P-wave velocity obtained at the two locations. Assuming the P-wave velocity of the intact slate which had not been loosened yet would be 3.25–3.50 km/s or more, it was found that the depth of the loosened zone where TBM jamming had not occurred was approximately 2.0–2.5 m. On the other hand, the depth of the loosened zone where TBM jamming had occurred was approximately 6.0–8.0 m. Considering the diameter of the TBM was no more than 2.8 m, it can be said that the loosened zone was expanded much deeper than expected at the location where TBM jamming had occurred.

In conclusion, in addition to its high stress due to the tunnel cover, cleavages between thin layers of slate and sandstone were developed by the influence of fold more significantly at the location where the TBM jamming had occurred. Furthermore, as the orientation of cleavage planes was typically parallel to the tunnel axis at the site, it was thought that the location around the tunnel could be loosened easily.

5. Conclusions

In order to investigate the TBM jamming that had occurred at the S tunnel, theoretical analyses and seismic investigations were conducted. As a result, it was found that the possibility of TBM jamming would be higher with the increase of the tunnel cover, and that the TBM would be likely to be jammed if the tunnel cover was more than 360 m. It was also found that the loosened zone expanded to no less than 6.0–8.0 m where the TBM jamming had occurred.

In this tunnelling project, based on the uni-axial strength and seismic velocity obtained from primary site investigations conducted in advance, the ground was thought to be relatively hard slate formed in the Cretaceous Period of the Mesozoic Era, and therefore suitable for TBM excavation. Nevertheless, the ground was loosened due to the tunnel excavation and squeezed more than expected. More attentions will have to be paid for selecting excavation methods and the type of TBM, especially in case of excavating fissile ground.

Reference

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