Simulation on small diameter shield for pre-support method by numerical analysis

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ABSTRACT

When the road shield tunnels are constructed in urban area, the construction of branch tunnels from a main road tunnel by non-open cut method is required. Therefore, a pre-support method using several small diameter shield tunnels above and below the main shield tunnel was proposed for soft ground under groundwater level. But the small diameter shield tunnel with three dimensional sharp curve has never been constructed before, since it is difficult to control the shield along the planned alignment. Therefore, the shield operation parameters were estimated theoretically and the shield behaviors were simulated to examine the possibility of the shield tunnels using a small diameter shield with 3D sharp curve. As a result, it was confirmed that the calculated shield behavior has a good agreement with the planned one, by adjusting the shield operational parameters.

Keywords: shield tunneling method; control; simulation; pre-support method

1 INTRODUCTION

Recently, a pre-support method for underground space enlargement, as shown in Fig. 1, was proposed to connect two existing shield tunnels by non-open cut method. Its construction procedure is shown in Fig. 2. The pre-support method was planned to be constructed using several small diameter shield tunnels with a sharp curve (JSCE 1996) in three-dimensional space, which launch from the main tunnel and ramp tunnel, as shown in Fig. 3 (Miki et al. 2016). But the small diameter shield tunnels with 3 dimensional sharp curve has never been constructed before, since it is difficult to control the shield along the planned alignment. To realize this method, it is necessary to examine the shield operation method preliminarily by estimating shield operation parameters and simulating shield behavior using its operation data.

Shield direction is controlled by shield jack, copy cutter, and articulation mechanism in practice. But since these three functions have a high co-linearity to shield behavior, it is difficult to obtain a unique solution at once. To solve this problem, the authors have developed a shield steering method (Huynh 2015). On the other hand, the authors have proposed the kinematic shield model, taking into account shield tunnel engineering practices, namely, the excavated area, the tail clearance, the rotation direction of the cutter disc, sliding of the shield, ground loosening at the shield crown, and the dynamic equilibrium condition (Sugimoto & Sramoon, 2002). Based on this model, the simulations on shield behavior were carried out, using the recorded shield operation data at several sites (Sramoon et al. 2002; Sugimoto et al. 2007; Chen et al. 2008).

In this research, to examine the possibility of the small diameter shield tunnelling for the pre-support method at underground space enlargement, the simulation on shield behavior was carried out, using

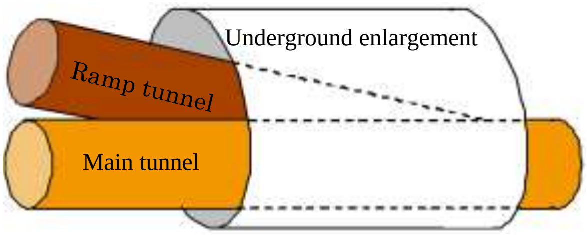

Fig. 1. Underground enlargement around a main road tunnel and a ramp tunnel.

Construct the main & ramp tunnels.
↓
Construct shield roof by the small diameter shields.
↓
Fill RC in the small diameter tunnels.
↓
Apply freezing method around the shield roof.
↓
Excavate the ground inside the frozen area, and install the special segments at the crown & invert of its inside.
↓
Break some segments of the main & ramp tunnels, and reform the lining for the enlarged underground space.

Fig. 2. Construction procedure of pre-support method for underground space enlargement.

the shield operational parameters estimated under the setting analysis conditions. This paper shows the estimated shield operation parameters and the simulated shield behavior, and finally examines the possibility of the pre-support method at underground space enlargement quantitatively, comparing the calculated shield behavior with the planned tunnel alignment.

2 METHODOLOGY

In this research, the following procedures were adopted (Sugimoto et al. 2018):

1. The operation parameters, such as, copy cutter articulated direction, are calculated theoretically, based on the geometric relation of planned alignment and shield dimension;

2. The operation parameters, which are jack force and jack moment, are computed as an unbalanced acting force on the shield by the kinematic shield model (Sugimoto and Sramoon, 2002);

3. The simulations of the shield behavior are carried out by the kinematic shield model using the above obtained shield operation parameters; and

4. The possibility of its realization is discussed, comparing the calculated shield behavior with the planned one.

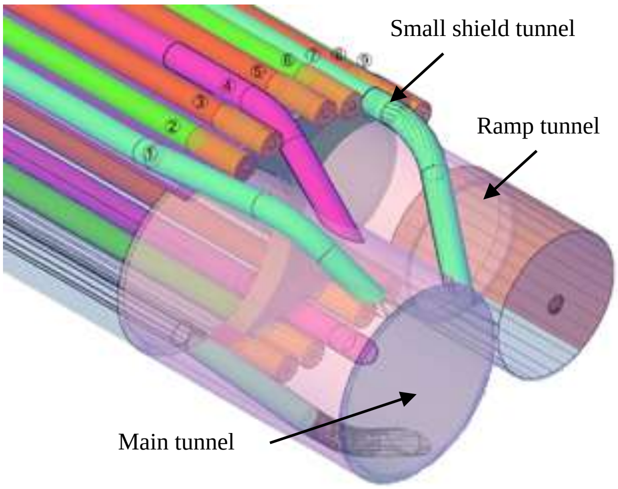

Fig. 3. Small shield tunnels for pre-support method.

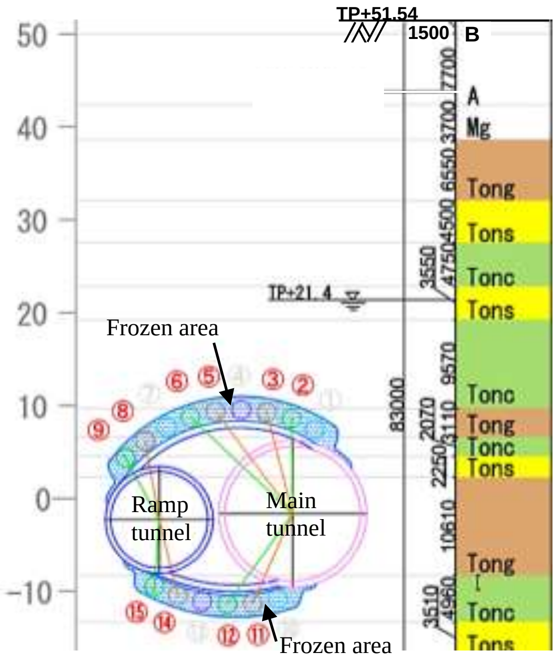

Fig. 4. The position of small diameter shields on the cross section of the underground space enlargement and the geological profile.

3 APPLICATION

3.1 Site description

To construct the pre-support for underground space enlargement, 15 small diameter shield tunnels, which launch from the main tunnel and the ramp one, were planned as shown in Fig. 4. The overburden depth is

Table 1. Ground properties.

Ground layer	Tong	Tonc	Tons
Unit weight (kN/m^3)	21	18	20
Cohesion (kN/m^2)	0	710	0
Internal friction angle (deg)	42	0	41
K_{ha} (= K_{hmin})	0	0	0
K_{ho}	0.331	1	0.344
K_{hp} (= K_{hmax})	5	5	5
K_{va} (= K_{vmin})	0	0	0
K_{vo}	1	1	1
K_{vp} (= K_{vmax})	5	5	5
k_h (MN/m^3)	60.0	51.2	55.0
k_v (MN/m^3)	60.0	51.2	55.0
Coeff. of friction	0.1	0.1	0.1

Table 2. Dimensions of shield and tunnel.

Item	Component	Value
Shield	Outer radius (m)	1.070
	Total length (m)	4.575
	Length of front body (m)	2.235
	Length of rear body (m)	2.340
	Length between crease center & segment front end (m)	1.260
	Self-weight (kN)	232
Shield jack	Number of jacks	8
	Radius of jack (m)	0.810
Segment	Outer radius (m)	1.00
	Width (m)	0.75, 0.30
Tunnel	Horizontal curve radius (m)	10.00
	Slope (ascend)	0.577
Ground	Ground water level (m)	GL-30.14
	Overburden depth (m)	53.20

approximately 53.2 m, and the groundwater level is GL-30.14 m. Here, the tunnel passes in Toneri gravel layer (Tong), Toneri clay layer (Tonc), and Toneri sandy layer (Tons), of which the properties are shown in Table 1. This means that the tunnel is located in the stiff soil. In this paper, No. 6 shield tunnel is taken as an example, since No. 6 shield tunnel has the largest launching angle from the main tunnel axis among 15 shield tunnels. No. 6 shield tunnel launches to the leftward direction with the yawing angle of about 60 degrees and the upward direction with the pitching angle of about 32 degrees from the main tunnel, and passes a curve with a radius of 10 m from 12.7 m distance to 23.8 m distance. The analysis length is approximately 31.9 m. The dimensions of the shield and the tunnel are shown in Table 2, that is, the shield is an articulated shield with 2.14 m in outer diameter and 4.575 m in total length.

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3.2 Shield operation

The input data used for the simulation were estimated as shown in Fig. 5. The tunneling operations are jack thrust F_{3r}, horizontal jack moment M_{3p} (+: right turn), vertical jack moment M_{3q}(+: downward), cutter face (*CF*) rotation direction (1: counterclockwise direction, viewed from the shield tail), copy cutter length *CCL*, area of applied copy cutter *CC* range (0: at the bottom of the shield, +: clockwise direction, viewed from the shield tail), articulation angle in horizontal direction θ_{CH} (+: leftward), and articulation angle in vertical direction θ_{CV} (+: upward), which are employed to control the shield position and the shield rotation during excavation. The shield rotation is defined as yawing angle ϕ_y (+:right turn) and pitching angle ϕ_p (+: downward). The excavation conditions are shield velocity v_s, slurry pressure σ_m, and slurry density γ_m in the chamber, which is usually controlled to stabilize the tunnel face.

F_{3r} is applied to the shield to drive the shield forward against the earth pressure at the face and the friction on the shield skin plate, as it advances. M_{3p} is applied to negotiate the horizontal moment due to the shear resistance on the cutter disk and the normal earth pressure around the skin plate. M_{3q} is applied against the vertical moment due to the normal earth pressure

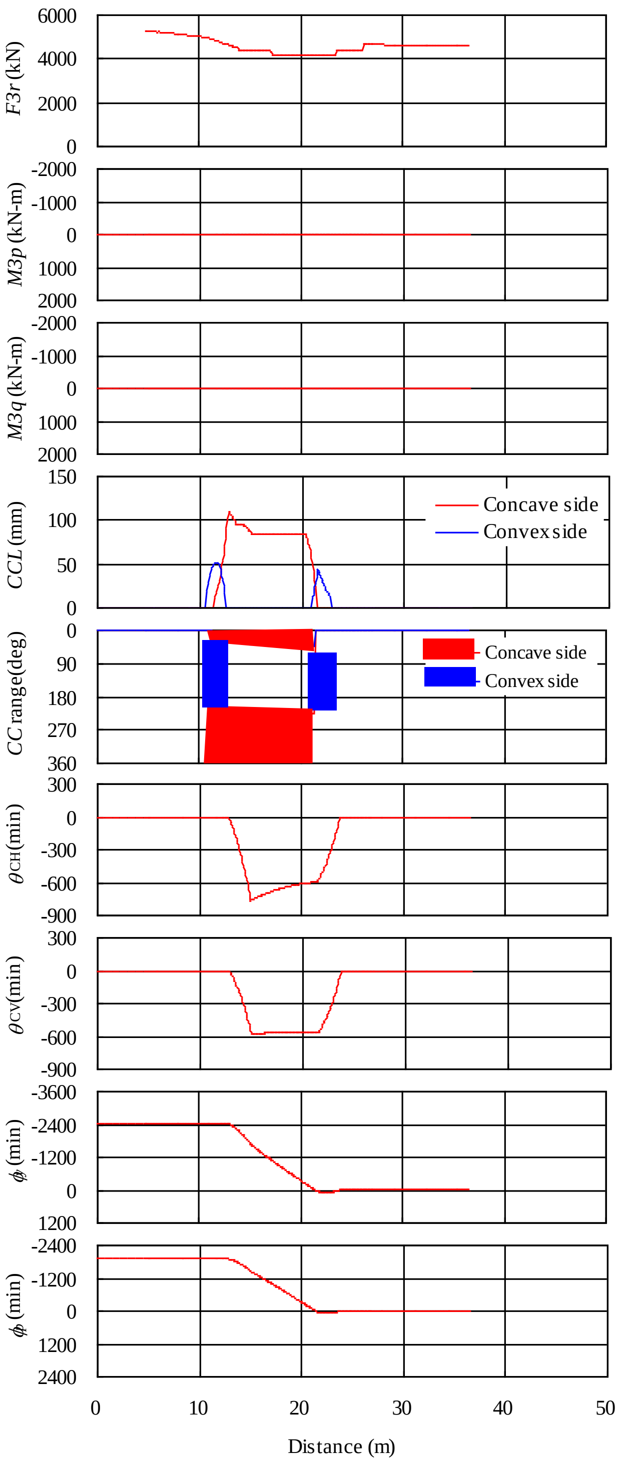

Fig. 5. Shield operation data (No. 6 tunnel).

around the skin plate, the earth pressure on the cutter disc and the self-weight of the shield. Here, F_{3r} of approximately 4 ~ 5 MN was obtained by the sequential analysis using the kinematic shield model without jack force (F_{3r}, M_{3p}, and M_{3q} are zero). On the other hand, M_{3p} and M_{3q} were assumed to be zero as the initial values, since the sequential analysis, which does not consider the equilibrium conditions, provides eccentric values of M_{3p} and M_{3q}, especially at a sharp curve.

CCL and *CC* range were set, based on the required overcut. The copy cutter is used to increase the excavated area around the cutter disc. θ_{CH} and θ_{CV} are about -10 degrees, which correspond to the curve radius of the tunnel alignment against the shield length. The use of articulation of shield is to fit the skin plate to the area excavated by cutter disk and copy cutter. The copy cutter and the shield articulation can reduce the ground reaction force acting on the skin plate and makes a shield easily translate or rotate.

ϕ_y and ϕ_p show that the rotation of the front body follows the planned tunnel alignment.

Shield velocity v_s of 0.025 m/min and muck density γ_m of 13.5 kN/m^3 were set, based on the experience. To stabilize the face, chamber pressure σ_m approximately 230 kPa is applied based on the lateral earth pressure at the tunnel face.

3.3 Shield behavior

The shield behavior was simulated from 4.7 m distance to 36.6 m distance, based on the shield operational data in Fig. 5. In this figure, the shield steering data on shield jack and copy cutter were modified so that the calculated shield behavior has a good agreement with the planned one.

Fig. 6 shows the planned alignment and the calculated traces of the shield on vertical and horizontal planes. The calculated and planned time-dependent parameters ϕ_y, ϕ_p, and v_s are shown in Fig. 7. From Fig. 6, it was found that the shield traces on vertical and horizontal planes have a good agreement with the planned one. From Fig. 7, the following were found: 1) the ϕ_y and ϕ_p of the front body have a good agreement with the planned one; and 2) the v_s is close to the planned one, but the v_s fluctuates within 5 mm/min at the sharp curve.

4 CONCLUSION

To examine the possibility of the small diameter shield tunnelling for the pre-support method at underground space enlargement, the simulation on the articulated shield behavior was carried out by the kinematic shield model, using the estimated shield operational parameters. As a result, the followings can be concluded:

1. The calculated steering conditions, that is, the copy cutter length and range, and the articulation angle and direction, are reasonable from the viewpoint of theory and site experience.

2. When the setting shield operation data including the shield steering parameters are in use, the calculated shield behavior has a good agreement with the planned tunnel alignment.

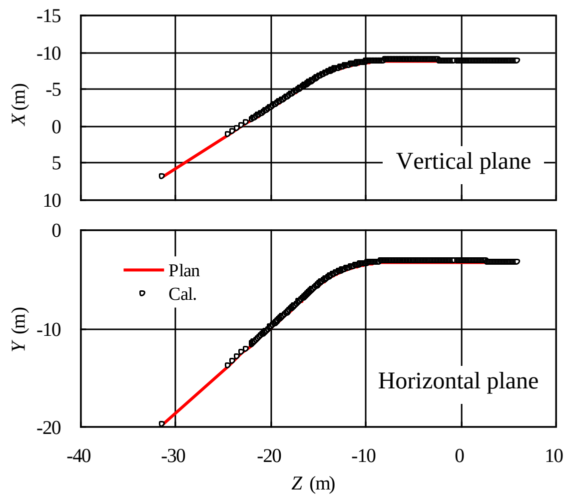

Fig. 6. Calculated and planned shield traces (No. 6 tunnel).

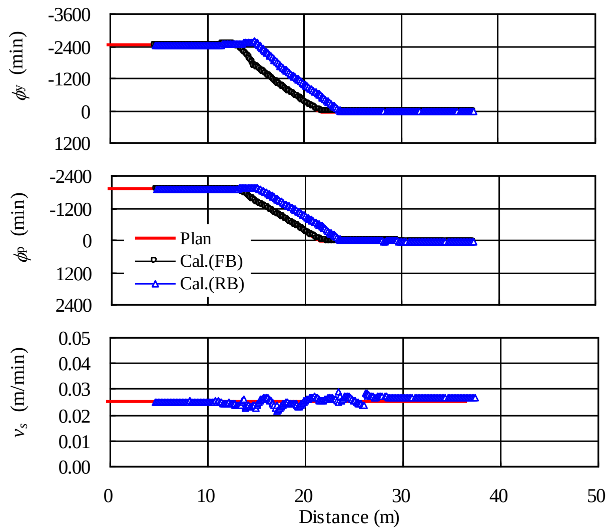

Fig. 7. Calculated and planned shield behavior (No. 6 tunnel).

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