Influence of copy cutter length on H&V shield behaviour

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ABSTRACT

Shield tunnelling technology has been widely applied in various ground conditions to minimize the change and possible damage of an area in which a tunnel is intended to be constructed. Subsequently, Horizontal and Vertical shield (H&V shield) machine technology has been developed from common shield tunnelling method by connecting two ordinary articulated shields between left and right body. The H&V shield machine can rotate multi-circular tunnel shape continuously from horizontal direction to vertical one or vice versa under simultaneous construction of multiple tunnels. Consequently, H&V shield machine technology is precious for saving cost, reducing time and increasing construction performance at tunnelling. Simulation algorithms based on the shield kinematic model were utilized to simulate the shield tunnelling behaviour. This paper examines the influence of copy cutter length (CCL) on H&V shield behaviour by a sensitivity analysis. As a result, it was found that the copy cutter length has more effect to the shield behaviour, especially in velocity and pitching angle, because the increase of copy cutter length (CCL) reduces ground reaction force.

Keywords: H&V shield, copy cutter length, shield kinematic model

1 INTRODUCTION

Tunnel Boring Machine (TBM) is a method whereby a solid cylinder or shield excavates ground for tunnelling under a variety of soil and rock layer. The tunnel lining is constructed inside the shield to prevent the ground from collapsing. Nowadays, tunnel boring machine is continuously developed from one circular shape to multi-circular shape due to excavation efficiency. Horizontal and Vertical shield (H&V shield) is a tunnelling machine which combines two ordinary articulated shields as shown in Fig.1, so that its cross section can be changed continuously from horizontal to vertical multi-circular shape or vice versa under simultaneous construction of multiple tunnels. Moreover, H&V shield have the significantly advantages in term of reducing cost, saving time, decreasing the ground

disturbance and increasing excavation efficiency. The Horizontal and Vertical shield were studied by many researchers (eg. Sonoda, 1992; Yamada, 1999; Kayukawa, 2001) for understanding the behaviour of shield tunnelling.

Shield tunneling methods have been investigated together with the computer aided approach to improve the understanding of the shield behaviour. This research carried out the sensitivity analysis in term of effective rate of copy cutter length (CCL) in case of H&V shield based on the shield kinematic model (Sugimoto, 2002) to examine the influence of a tunnel boring machine operation on its behaviour.

2 SIMULATION OF SHIELD BEHAVIOUR

During tunnel construction, there are many control factors to influence shield behaviour, such as 1) Excavation area, which involves copy cutter range, length, and articulation angle; 2) Forces (including thrust, horizontal and vertical moments), which are determined by jack pattern and shield jack pressure; and 3) Stability of excavation face, which involves face pressure, advancing speed and mucking rate.

2.1 Kinematic shield model

The kinematic shield model was proposed by Sugimoto and Sramoon (2002) in order to simulate the

Fig. 1. H&V shield (Shield Tunneling Association, 2013).

shield behaviour during excavations taking into account the excavated area, the tail clearance, the rotation direction of cutter face, the shield slide, the dynamic equilibrium condition and the ground displacement around the shield.

For mathematics purposes, the five forces, that is, force due to the self weight of machine, f_1 ; force on the shield tail, f_2 ; force due to the jack thrust, f_3 ; force acting at the face, f_4 ; and force acting on the shield periphery, f_5 ; are considered. And their physical representation can be appreciated in Fig. 2. The shield behaviour are obtained from the equilibrium of the forces acting on the shield, that is

$$\begin{bmatrix} \sum_{i=1}^5 \mathbf{F}_i^M \\ \sum_{i=1}^5 \mathbf{M}_i^M \end{bmatrix} = 0 \quad (1)$$

where $\mathbf{F}$ and $\mathbf{M}$ are the force and moment vectors respectively. The moment vector is generated by the cross product of the position and the force vectors. Here, note that superscript M indicates machine coordinate system, and subscript i represents the cause of the force acting on shield.

2.2 Ground reaction

During tunnel construction, the displacement of the surrounding ground around H&V shield machine is occurred because the earth pressure acting on shield machine is changed as shown in Fig. 3. When the ground around the shield machine deforms inwardly inside the tunnel periphery, the ground becomes an active state of earth pressure. The void between the excavated area and the outer skin plate of shield is generated by over-excavation of the cutter face or the copy cutter. In contrast, when some parts of the shield skin plates push forwards to the ground, the passive state of earth pressure is occurred. The earth pressures acting on the shield periphery is counted by the kinematic shield model (Sugimoto and Sramoon, 2002). Moreover, the shield movement is considered like the snake motion.

The ground reaction curve in Fig. 4 was proposed to present the interaction between ground and tunnel lining, which is expressed as follows

Fig. 2. Model of loads acting on shield.

For $U_n \leq 0$

$$K_h(U_n) = (K_{h0} - K_{h\min}) \tanh\left(\frac{a_h U_n}{K_{h0} - K_{h\min}}\right) + K_{h0} \quad (2)$$

$$K_v(U_n) = (K_{v0} - K_{v\min}) \tanh\left(\frac{a_v U_n}{K_{v0} - K_{v\min}}\right) + K_{v0} \quad (3)$$

For $U_n \geq 0$

$$K_h(U_n) = (K_{h0} - K_{h\max}) \tanh\left(\frac{a_h U_n}{K_{h0} - K_{h\max}}\right) + K_h \quad (4)$$

$$K_v(U_n) = (K_{v0} - K_{v\max}) \tanh\left(\frac{a_v U_n}{K_{v0} - K_{v\max}}\right) + K_v \quad (5)$$

where K_h and K_v are the coefficient of earth pressure in the horizontal and vertical direction, respectively; U_n is the distance from the initial tunnel surface to the tunnel lining (+: outward of tunnel); K_{h0} is the coefficient of earth pressure at rest; K_{v0} is the initial coefficient of vertical earth pressure normally equal to 1; subscripts max and min indicate the upper and lower limit of the coefficient of earth pressure respectively; and a_h and a_v are the gradient slope of function K_h and K_v at $U_n = 0$, respectively. Moreover, the coefficient of earth pressure in any direction, K_n , can be interpolated as

$$K_n(U_n, \theta) = K_v(U_n) \cos^2 \theta + K_h(U_n) \sin^2 \theta \quad (6)$$

where θ = angle measured from downward vertical direction to U_n .

Therefore, the normal earth pressure acting on the tunnel lining σ_n is obtained from

$$\sigma_n = \sigma_{no} + \Delta\sigma_n \quad (7)$$

where σ_{no} is the initial normal earth pressure acting on the tunnel lining and $\Delta\sigma_n$ is the change of earth pressure. σ_{no} can be defined as

$$\sigma_{no} = \sigma_{vo} \cos^2 \theta + \sigma_{ho} \sin^2 \theta \quad (8)$$

where σ_{vo} is the overburden pressure, σ_{ho} is the earth pressure at rest which can be defined as $\sigma_{ho} = K_{ho} \sigma_{vo}$, and K_{ho} is the coefficient of earth pressure at rest. $\Delta\sigma_n$ relies on U_n as

$$\Delta\sigma_n = (K_n(U_n, \theta) - K_n(0, \theta)) \sigma_{vo}, \quad (9)$$

Fig. 3. Definition of ground displacement.

Fig. 4. Ground reaction curve.

Fig. 5. The dimensions of H&V shield.

Table. 1 Shield operation and ground condition for simulation.

Component	Value
Shield	
Diameter of machine	5.85m(left and right)
Length of machine	8.25m (left) and 7.80m (right)
Shield operation	
Excavation velocity	2cm/min
Articulated angle	0degree (left) and 4degree (right) during spiral
Ground	
Tunnel center	GL-28.9m
Ground water level	GL-3.9m
SPT-N value	30
Earth pressure	Effective earth pressure method

2.3 Analysis condition

The H&V shield machine is divided into left and right body. The alignments in the left body are straight for the horizontal movement and horizontal for the vertical movement, while the right body presents a rotation around the left body. The dimensions of H&V shield in this study are illustrated in Fig. 5. The operations and the ground conditions were assumed as Table 1.

Table. 2 Sensitivity parameters for simulation.

Case No.	Effective rate	Copy cutter length (mm)
1	1.00	400
2	0.75	300
3	0.50	200
4	0.25	100

Fig. 6. Planed and calculated H&V shield behaviours. (Right rear body)

2.4 Sensitivity analysis

The copy cutter and the articulated angle are applied to increase the excavation efficacy and to control the alignment during excavation by ground reaction force.

The simulation was carried out to investigate the influence of the copy cutter length (CCL) that affects H&V shield behavior. In this study, the four effective rates of copy cutter length were adopted as illustrated in Table 2.

3 RESULTS AND DISCUSIONS

3.1 H&V shield behaviour

The simulation results are shown in Fig. 6. Distance of shield movement is presented in horizontal directions. Besides, yawing angle ϕ_y , pitching angle ϕ_p , rolling angle ϕ_r , and the shield velocity during excavation v_s , are plotted for comparison among all cases.

The graph tendencies in Case 1 and Case 2 are similar on the shield behaviour. On the other hand, the advanced distance and the velocity v_s of the shield decrease when effective rate reduces, especially in Case 4 where the advanced distance is less than 10 m. That means the shield advance becomes more difficult when the effective rate decreases because of larger frictional force around the skin plate due to ground reaction force.

Fig. 7. Contour map of U_n .

Moreover, when the effective rate decreases, the pitching angle ϕ_p substantially increases. This relates to the velocity v_s . This means that the shield changes the direction to go upward. This is because the shield rotates to upward to fit for the excavated space as the copy cutter length decreases.

3.2 Force acting on shield

The contour map of the gap between the initial excavation surface and the skin plate of the right body, U_n is illustrated in Fig. 7 to compare between case 1 and case 3. The shield periphery is unfolded as a flat plate, i.e., a vertical axis represents length of the shield and a horizontal axis shows circumference of the shield. 0° and 180° represent the invert and the crown of the shield respectively, whereas 90° and 270° represent the left and the right spring lines of the shield viewed from the tail respectively. When U_n is negative, the earth pressure acting on shield σ_n is an active state. Therefore, this figures show that σ_n is almost active state on both front and rear section in all cases.

U_n on the section through spring lines of the shield can be simply illustrated as shown in Fig. 8. From this figure, it is clear that negative U_n , i.e., the gap between the shield skin plate and the ground, at the spring lines are mostly generated and positive U_n , i.e., the shield pushing the ground, appears only at the middle length of the shield at the left spring line.

From Fig.7, it was found that U_n in Case 3 increases at the lower part of the front body and the top of the rear end of the rear body, compared with Case 1.

This indicates that the increase of the skin friction due to decreasing U_n causes the decrease of the velocity v_s . Furthermore, the pitching angle ϕ_p upward as decreasing U_n comes from the followings:

Fig. 8. Illustration of gap around shield during excavation

- 1) The articulated angle is kept as 4 degrees even U_n decreases; and
- 2) The whole body satisfies the equilibrium conditions.

4 CONCLUSIONS

This paper describes the simulations of the H&V shield behaviour that were carried out to validate the performance of copy cutter length (CCL). As a result, the conclusions can be made as follows:

1. In case of H&V shield, the copy cutter length gives much influence to the shield behaviour, especially in velocity v_s and pitching angle ϕ_p .
2. The increase of copy cutter length (CCL) reduces ground reaction force.

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