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Study on shield behaviour by 3-D shield simulator

M. Sugimoto, N. Yoshiho & A. Sramoon
Nagaoka University of Technology, Niigata, Japan

ABSTRACT: Automatic shield control systems have been developed based on empirical relationships during the past decade. But they do not have a precise theoretical background. Therefore, it is difficult to predict the shield behaviour. A model of loads acting on a shield has been developed to address this problem. The model was extended to study the effect of using a copy cutter attached on the cutter face, which can adjust in length and position to increase the competence of the excavation. The copy cutter effect was evaluated by adding the excavation area of the copy cutter to that of the cutter face. The shield behaviour was obtained by considering of equilibrium conditions. The results show reasonable simulations of shield position and shield behaviour.

1 INTRODUCTION

The closed shield tunnelling method has emerged as a popular tunnelling method in soft ground during the past decade. Some automatic shield control systems were developed recently. But these systems are based on empirical relationships and they do not have a precise theoretical background. That is, the present automatic shield control systems control the shield after snakelike motions to move it back on the planned alignment, instead of decreasing the snakelike motion. And they can not evaluate the copy cutter effect quantitatively. Therefore, it is difficult to control the shield in complicated geological formation and to evaluate the required capacity of a shield. To solve these problems, a theoretical approach is necessary.

A theoretical model of loads acting on a shield, taking account of the ground displacement around the skin plate was presented by Sugimoto & Luong 1996. By extending this model, a three dimensional shield simulator, which can evaluate the copy cutter effect quantitatively, was developed.

In this model, the load acting on the shield is composed of five forces namely: force due to self weight of machine; force due to buoyancy; force due to jack thrust; force acting at face; and force acting on skin plate of shield. The force acting at the face is given by a function of the shield velocity and the rotation speed of the cutter face, and the force acting on the skin plate is given by a function of the ground displacement around the skin plate. The copy cutter effect is evaluated by adding the excavation area of the copy cutter to that of cutter face. The shield behaviour, such as, shield position, shield rotating angle and the mobilized ratio of friction in the circumferential direction of the skin plate, was obtained under equilibrium conditions. Consequently, the obtained shield behaviour has a good agreement with the empirical law.

This paper shows some examples of the shield behaviour by the newly developed 3-D shield simulator and discusses the performance of it.

2 MODELING OF LOADS ACTING ON SHIELD

The load acting on a shield is composed of five forces: force due to self weight of machine, f_1; force due to buoyancy, f_2; force due to jack thrust, f_3; force acting at face, f_4; force acting on skin plate, f_5; as shown in Figure 1.

Here, the following coordinate systems were used to model each force. The global coordinate system, C^T, is selected so that the x-axis is vertically down-

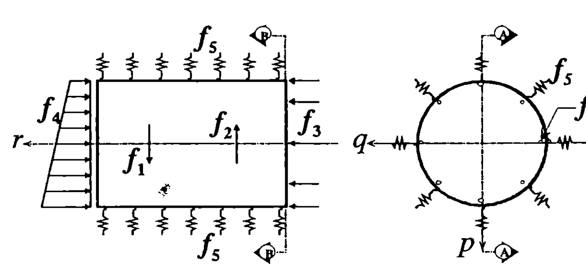

Figure 1. Model of loads acting on shield.

wards and the y-axis and z-axis are on a horizontal plane. A machine coordinate system, C^M, is selected so that the p-axis is vertically downward under no-rotating conditions and the r-axis is in the direction of the machine axis. The origin of the machine coordinate system is selected at the centre of the section on which the jack thrust acts. In addition to the above two systems, a coordinate system generated by rotating C^M about the r-axis is also considered as C^{MR} and axes are named as p_R, q_R and r_R. Here, the super suffix T, M and MR show the coordinate system used. The calculation procedures of forces can be explained as follows:

2.1 *Self-weight of the shield*

The self-weight of the shield, $\boldsymbol{F}_1$, is acting vertically downwards in the direction of the x-axis at the centre of gravity as follows:

$$\boldsymbol{F}_1^T = \begin{bmatrix} W_s \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

where W_s is the self weight of the shield.

2.2 *Buoyancy of the shield*

The buoyancy, $\boldsymbol{F}_2$, is considered only in the case of the shield in cohesionless soil. This force is acting vertically upward at the centroid of the volume of the shield, and can be written as

$$\boldsymbol{F}_2^T = \begin{bmatrix} -V_s\gamma_w \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

where V_s is the volume of shield and γ_w is the unit weight of water.

2.3 *Jack force*

The jack thrust acts in the r-axis direction on the plane where the jacks are mounted. The force due to the jack thrust, $\boldsymbol{F}_3$, can be obtained by summation of each jack thrust, that is

$$\boldsymbol{F}_{3i}^M = \begin{bmatrix} 0 \\ 0 \\ A_J P_J S_i \end{bmatrix} \quad (3)$$

where A_J is the cross section area of a hydraulic jack, P_J is the applied hydraulic pressure, S_i is the status of the ith jack ($S_i = 1$ for active jack and 0 for inactive jack).

2.4 *Earth pressure at face*

The force due to earth pressure acting at the face can be divided into three categories, that is, force due to earth pressure normal to cutter face, f_{41}, force due to earth pressure acting on periphery of cutter face, f_{42}, and force due to weight of slurry or mud in chamber, f_{43}. And the followings were assumed.

1. The normal earth pressure distribution at the face, σ_n, is linearly proportional to the normal earth pressure at rest, σ_{no}.

$$\sigma_n = \left(a\frac{v_s}{fr} + b\right)\sigma_{no} \quad (4)$$

where a and b are constants, v_s is the velocity of the shield, f is the rotating speed of the cutter face and r is the radius at calculation point on cutter face.

2. The normal earth pressure distribution along the outer circumference of the cutter face, σ_s, is equal to the normal earth pressure at rest.

$$\sigma_s = \sigma_{no} \quad (5)$$

3. The weight of slurry or mud is loaded on the shield at the centroid of the mud in the chamber.

The force due to f_{41}, $\boldsymbol{F}_{41}$, can be obtained by the summation of the following force acting on ijth element of cutter face.

$$\boldsymbol{F}_{41ij}^{MR}[k] = A_{41ij}\begin{bmatrix} 0 \\ -\left(\mu_{ms}\,\sigma_{CFij}[k] + \tau_{mudij}[k]\right)sign(CT) \\ \sigma_{CFij}[k] + \sigma_{mudij}[k] \end{bmatrix} \quad (6)$$

where $\tau_{mudij[k]}$ is the shear resistance on the cutter face due to mud pressure which can be defined as

$$\tau_{mudij[k]} = 2\begin{Bmatrix} (1-\alpha_o)(\mu_{ms}\,\sigma_{mudij}[k] - c_{ms}) \\ +\,\alpha_o\,(\mu_m\,\sigma_{mudij}[k] - c_m) \end{Bmatrix} \quad (7)$$

and $\sigma_{CFij[k]}$ is the normal pressure acting on ijth calculation point of cutter face at step $[k]$, $\sigma_{mudij[k]}$ is the slurry or mud pressure in the chamber acting normal to the cutter face, A_{41ij} is the area of the ijth calculation point on the cutter face, α_o is the open ratio of cutter face, c_{ms} and μ_{ms} are the mobilized cohesion and the coefficient of mobilized friction between the skin plate of the shield and ground respectively, c_m and μ_m are the mobilized cohesion and the coefficient of mobilized friction of slurry or mud. CT is the cutter torque with the positive sign for the clockwise rotation of cutter face. Then $sign(CT)$ is equal to 1 for CT>0.

The force due to f_{42}, F_{42}, can be obtained by the summation of the following force at jth element along the outer circumference of cutter face.

$$F^{MR}_{42j[k]} = A_{42j} \begin{bmatrix} \sigma_{noj[k]} \\ -\left(\mu_{ms}\,\sigma_{noj[k]} - c_{ms}\right) sign(CT) \\ 0 \end{bmatrix} \tag{8}$$

where $\sigma_{noj[k]}$ is the normal earth pressure at the jth calculation point along the outer circumference of cutter face and A_{42j} is the area of the jth calculation point on cutter face periphery.

The weight of slurry or mud in the chamber f_{43}, F_{43}, can be found from

$$F^{T}_{43[k]} = \begin{bmatrix} W_{mud} \\ 0 \\ 0 \end{bmatrix} \tag{9}$$

where W_{mud} is the weight of slurry or mud in the chamber.

2.5 *Earth pressure acting on shield periphery*

In estimating the earth pressure loading on skin plate, the following assumptions were made:

1. The shield is regarded as a rigid body.
2. The relationship of the coefficient of earth pressure in the vertical and horizontal directions, K_v and K_h, and the normal ground displacement around the shield in the normal direction, U_n, can be given by the following functions, as shown in Figure 2.

$$K_i = \frac{K_{i\max} - K_{i\min}}{1 - \left(\dfrac{K_{io} - K_{i\max}}{K_{io} - K_{i\min}}\right)\exp(-a_i U_n)} + K_{i\min} \tag{10}$$

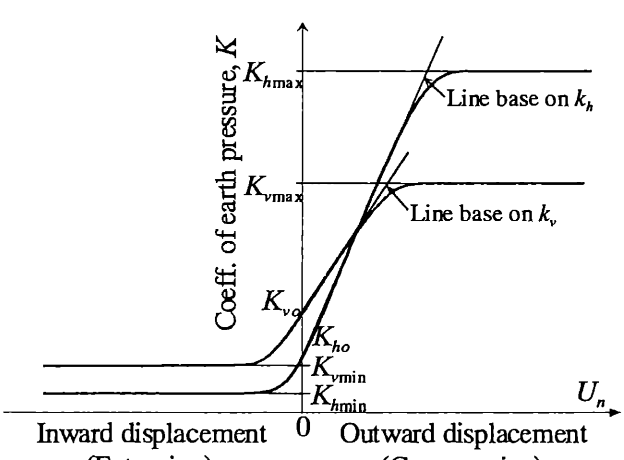

Figure 2. Ground reaction curve for K_h and K_v.

where i is v or h, and a_v, a_h are constants defining the slope of curve. The coefficient of earth pressure in any direction, K_θ, can be interpolated as

$$K_{\theta ij} = K_v \cos^2\theta_{ij} + K_h \sin^2\theta_{ij} \tag{11}$$

where θ_{ij} is the angle measured from the vertical direction to the ijth normal displacement vector.

The summation of the following force at ijth element is considered as the total force acting on skin plate, F_5.

$$F^{MR}_{5ij} = A_{5ij} \begin{bmatrix} \sigma_{ppij} \\ \alpha\left(\mu_{ms}\,\sigma_{ppij} - c_{ms}\right) sign(CT) \\ \mu_{ms}\,\sigma_{ppij} - c_{ms} \end{bmatrix} \tag{12}$$

where A_{5ij} is the area of ijth calculation point on the shield periphery, α is the factor of shearing resistance which depends on the cutter torque and has a range between 0 to 1, and the normal earth pressure acting on the periphery of the shield, σ_{ppij}, can be calculated as follows:

$$\sigma_{ppij} = K_{\theta ij}\,\sigma_{voij} \tag{13}$$

where σ_{voij} is the initial vertical earth pressure at the ijth calculation point on the shield periphery.

3 SIMULATION PROCEDURES

The shield behaviour during excavation plays an important role in the calculation of ground displacement around a shield, and this is directly related to the earth pressure acting on the shield periphery. The shield behaviour is meant deviation of the shield in x, y and z directions (Δx, Δy and Δz), yawing and pitching angles (ϕ_y and ϕ_p), and factor of shearing resistance due to cutter torque (α). The definitions of yawing, pitching and rolling angles are illustrated in Figure 3. These parameters of shield behaviour can be obtained by applying the equilibrium equations of forces and moments to the shield model, that is,

$$\begin{bmatrix} \sum_{i=1}^{5} F_i^M \\ \sum_{i=1}^{5} M_i^M \end{bmatrix} = 0 \tag{14}$$

The copy cutter is used to increase the competence of the excavation and the alignment control of shield tunnelling. The copy cutter can adjust in length and position to increase the radius of excavation. Therefore, the radius of excavation, R_E, can be defined as

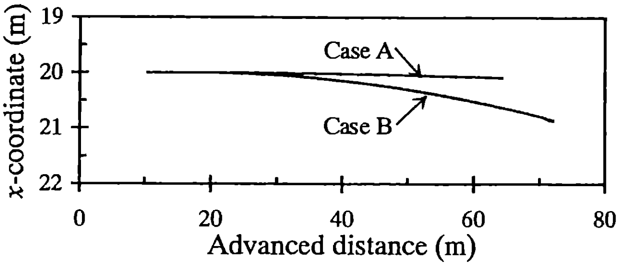

Figure 4(a). Trace of shield in vertical plane.

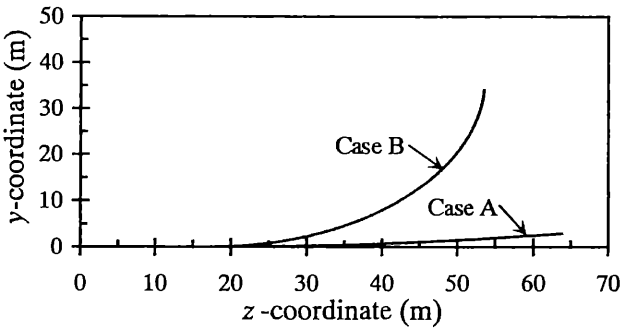

Figure 4(b). Trace of shield in horizontal plane.

cutter. As a result, the advancing distance in Case B is longer than that in Case A.

4. While θ_{xT} is close to 0 on the straight line, θ_{xT} is less than 0 on the curved line and θ_{xT} becomes smaller according to the decrease of radius of curvature. This means that the shield axis rotates more from the tunnel horizontal alignment to the inward curve according to the decrease of radius of curvature, that is, the shield excavates the ground while sliding in the transverse horizontal direction. This fact coincides with the practical work.

5. While θ_{yT} is less than 0 on the straight line, θ_{yT} is more than 0 on the curve and θ_{yT} becomes larger according to the decrease of radius of curvature. This means that the shield axis on the straight line is upward from the tunnel vertical alignment and the shield axis on the curve rotates more downward from the tunnel vertical alignment according to the decrease of radius of curvature, that is, the shield excavates the ground while sliding in the vertical direction. This fact results from the balance of forces acting on the shield under the conditions that: 1) the centre of gravity is near the head of the shield at the centre of the plane on which the jack is mounted; 2) the tunnel vertical alignment is a little bit downward due to the constant jack moment around the q-axis for all cases.

6. α decreases according the order of Case B, straight line and Case A. This fact results from the change of the normal earth pressure on the skin plate and that of the shield velocity as described above. When α is larger than 1, the shield is supposed to rotate around the r-axis since the dynamic friction between the skin plate and ground is smaller than the required friction to resist the cutter torque.

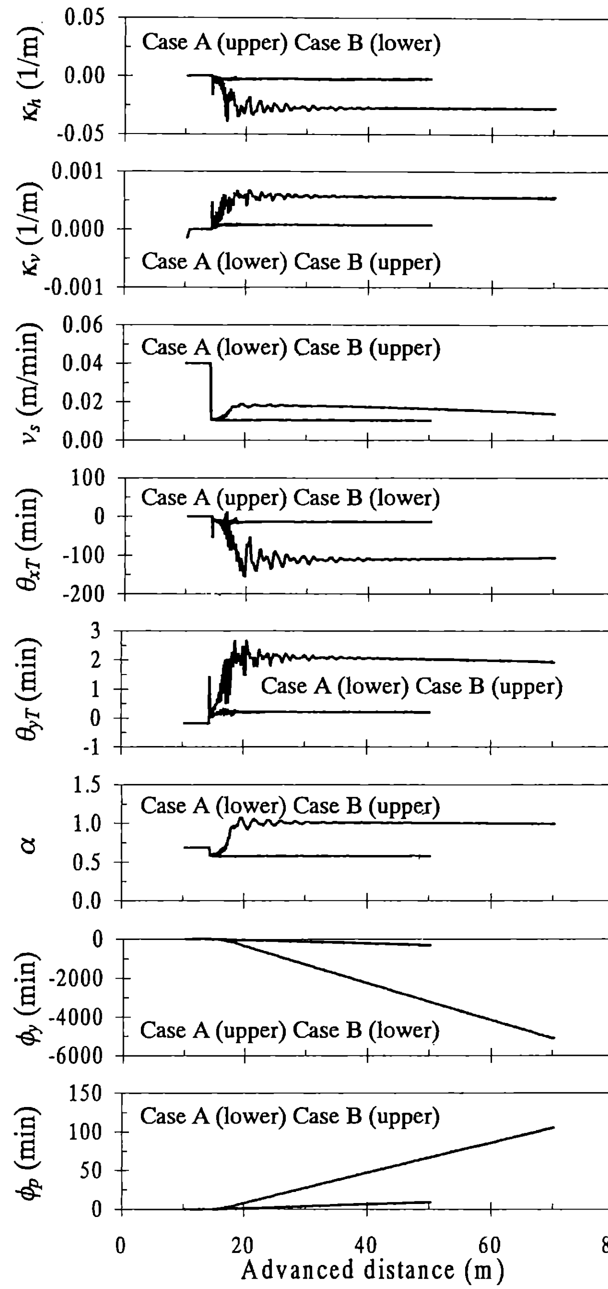

Figure 5. Parameters during shield behaviour simulation.

Figures 6-7 show respectively distribution of the normal displacement and the normal earth pressure around the skin plate at step 100, at which the shield behaviour is considered to reach the steady state. Tables 3(a)-3(b) show the force acting on the shield at step 100. From these figures and tables, the following were found:

1. From Figure 6, the ground around the spring line inside of the curve and from the cutter face by 1.5 m is in a passive state and the ground at the opposite side is in an active state. And Case B using the copy cutter has a larger active state area compared with Case A. These facts are reasonable from the viewpoint of the geometry.

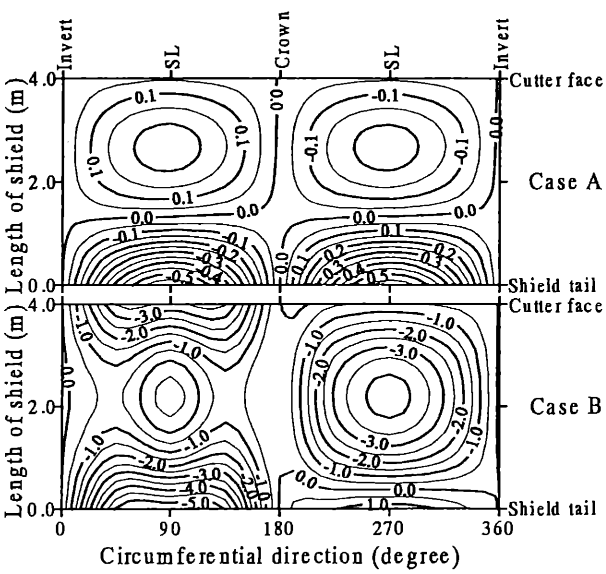

Figure 6. Normal ground displacement around the shield (cm).

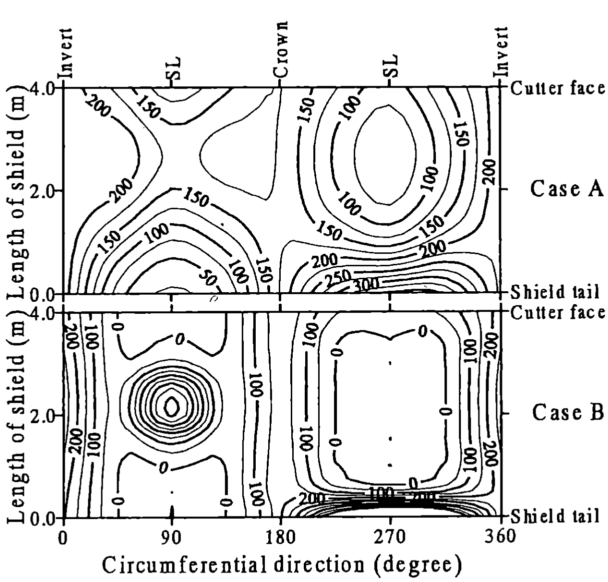

Figure 7. Effective normal earth pressure around the shield (kN/m^2).

2. From Figure 7, in Case B, the area around the spring line inside of the curve at the centre of the shield has a large normal earth pressure and the normal earth pressure in the other part is smaller than that in Case A, while the normal earth pressure distribution is complicated. These facts result from the normal displacement distribution around the skin plate and the ground reaction curve in Equations (10)-(12). Here, it is noted that Figures 6-7 have different contour intervals and Case A and B show a different radius of curvature.

Table 3(a). Force and moment components for case A (MN, MN-m).

	F_p	F_q	F_r	M_p	M_q	M_r
F_1	1.00	0.00	0.00	0.00	0.00	0.00
F_2	-0.50	0.00	0.00	0.00	0.40	0.00
F_3	0.00	0.00	5.00	-1.59	-1.25	0.00
F_4	0.04	0.03	-4.20	-0.03	0.20	0.92
F_5	-0.54	-0.03	-0.80	1.62	0.65	-0.92
ΣF	0.00	0.00	0.00	0.00	0.00	0.00

Table 3(b). Force and moment components for case B (MN, MN-m).

	F_p	F_q	F_r	M_p	M_q	M_r
F_1	1.00	0.00	0.02	0.00	0.00	0.00
F_2	-0.50	0.00	-0.01	0.00	0.40	0.00
F_3	0.00	0.00	5.00	-1.59	-1.25	0.00
F_4	0.04	0.03	-4.53	-0.02	0.21	0.95
F_5	-0.54	-0.03	-0.48	1.61	0.64	-0.95
ΣF	0.00	0.00	0.00	0.00	0.00	0.00

5 CONCLUSIONS

The model of loads acting on a shield taking account of the copy cutter effect was proposed and a 3-D simulator was developed. And the simulation results were demonstrated in this paper. As a result, the following points were made:

1. The developed model can demonstrate the shield behaviour on a curved alignment and can show the effect of a copy cutter.

2. The earth pressure acting on a shield caused by the ground displacement is the major factor affecting shield behaviour, since the copy cutter has an effect on the tunnel alignment.

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