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Soil properties based on in-situ data of the shield driven method

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ABSTRACT: The clayey ground properties under the closed type shield driven method were obtained by applying the model of acting loads on shield to the in-situ data. This model was developed, paying more attention to the earth pressure at face and that acting on skin plate. Furthermore, the validity of the model was studied comparing the obtained ground properties with the empirical values.

1 INTRODUCTION

Closed shield tunneling method had emerged as a popular tunnelling method in soft ground during the past decade. Furthermore, some automatic shield control systems were developed recently. But these systems are based on empirical relationships and they do not have precise theoretical background. Therefore, it is difficult to control the shield in complicated geological structure and the required capacity of shield cannot be predicted. A theoretical approach is necessary to solve the above mentioned problems. So far only a limited number of theoretical studies on shield behavior have been carried out.

Author showed the possibility of theoretical approach to acting loads on shield and pointed out that the displacement of ground around skin plate should be taken into account in order to satisfy the equilibrium conditions (Sugimoto 1995). The aim of the present study is to obtain the ground properties, such as coefficient of earth pressure at rest, coefficients of ground reaction in vertical and horizontal direction, earth pressure ratio at face during excavation, mobilized ratio of friction in circumferential direction of skin plate and coefficient of skin friction/adhesion under dynamic condition, by applying the modified model to in-situ data, regarding the shield as a large load cell. The model of acting load on shield was modified from previous one, paying more attention to the earth pressure acting at face, and that acting on skin plate. And the modified Marquart method (Kowalik & Osborne 1968) was in use to obtain the ground properties. Furthermore, the validity of the modified model was discussed by comparing the analyzed ground properties with the empirical values.

2 MODELING OF LOADS ACTING ON SHIELD

The load acting on 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 Fig. 1. Here, the following coordinate systems were used to model each force. The global coordinate system, C^T, is selected so that x-axis is vertically downwards and y-axis and z-axis are in transverse horizontal and longitudinal horizontal directions respectively at the initial point. A coordinate system called machine coordinate system, C^M, is selected so that p-axis is vertically downward under no rotating condition and r-axis is in the direction of machine axis. The origin of machine coordinate system is selected at the center of the section on which jack thrust acts. In addition to above two systems, a coordinate system generated by rotating C^M about r-axis is also considered and it is called as C^{MR} and axes are named as p_R, q_R and r_R.

The followings show each component of force. A force vector can be converted to any coordinates expression by the transformation matrix. And a moment vector can be obtained by taking cross product of the position vector and the force vector.

2.1 *Force due to self weight of shield*

The self weight of shield, F^T_1, is acting vertically downwards at the center of gravity of shield.

$$F_1^T = \begin{bmatrix} W \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

where W is the self weight of shield.

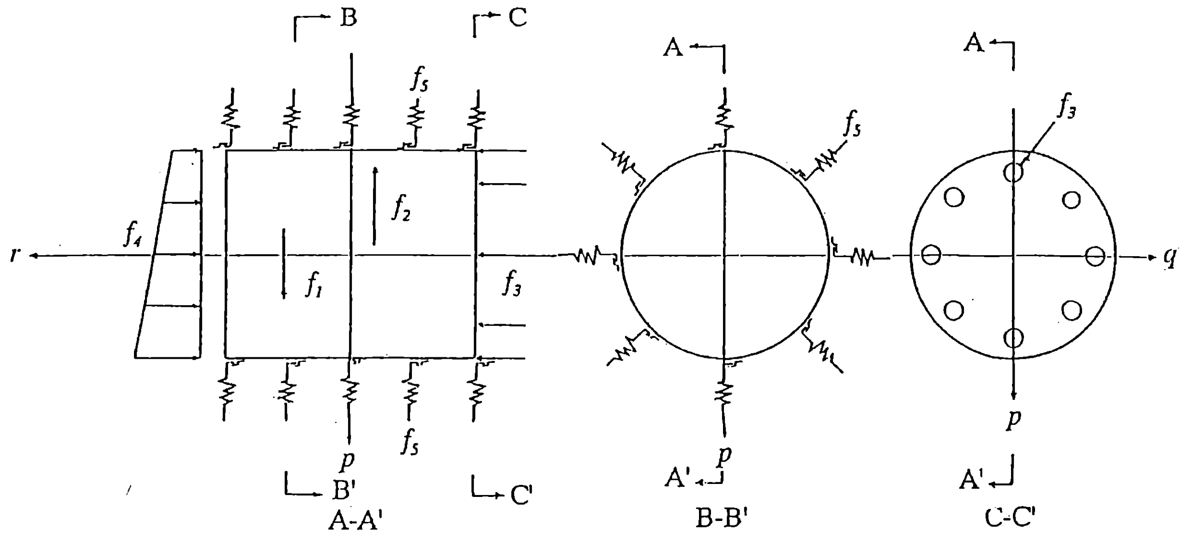

Fig. 1. Model of acting load on shield

2.2 *Force due to buoyancy*

The buoyancy force, $F^T{}_2$, is acting vertically upwards at the center of buoyancy of shield.

$$F_2^T = \begin{bmatrix} -\gamma_W V \\ 0 \\ 0 \end{bmatrix} \qquad (2)$$

where γ_w and V are the water density and the volume of shield respectively. But in case of clayey soil, $F^T{}_2$ is not necessary to consider since the total earth pressure is considered.

2.3 *Force due to jack thrust*

The force due to jack thrust, $F^T{}_3$, can be obtained by the summation of the following each jack thrust.

$$F_{3i}^M = \begin{bmatrix} 0 \\ 0 \\ APS_i \end{bmatrix} \qquad (3)$$

where *A, P* and *Si* are the cross section area of jack, the oil pressure and the status of *i*th jack respectively.

2.4 *Force acting at face*

In modeling the force due to earth pressure at face, $F^T{}_4$, f_4 was divided into three forces, that is, f_{41} : force due to earth pressure normal to cutter face, f_{42} : force due to normal earth pressure acting along the circumference of cutter face and f_{43} : force due to the weight of slurry or mud in chamber. And the following assumptions were made.

1. Normal earth pressure distribution at face, σ_n is linear to the normal earth pressure distribution at rest, σ_{n0}.

$$\sigma_n = (a\frac{V}{f\,r} + b)\sigma_{n0} \qquad (4)$$

where,

- a, b : constant
- V : velocity of shield
- f : rotating speed of cutter face
- r : radius.

2. Normal earth pressure distribution along the outer circumference of cutter face, σ_S , is equal to the normal earth pressure at rest, σ_{n0}.

$$\sigma_s = \sigma_{n0} \qquad (5)$$

3. Weight of slurry or mud is loaded on the shield at the centroid of the mud chamber.

The force due to f_{41}, $F^M{}_{41}$, can be obtained by the summation of the following force acting on *ij*th element of cutter face.

$$F_{41ij}^{MR} = A_{ij}\begin{bmatrix} 0 \\ -\left[\mu_{ms}\sigma_{CFij} + 2\left\{\left(1-\alpha_0\right)\left(\mu_{ms}\sigma_{mij} - c_{ms}\right) + \alpha_0\left(\mu_m\sigma_{mij} - c_m\right)\right\}\right]Sign\left(M_{CT}\right) \\ \sigma_{nij} \end{bmatrix} \qquad (6)$$

where σ_{CFij} and σ_{mij} are the earth pressure loaded on cutter face and the slurry or mud pressure at *ij*th element respectively. Here, the first term of q_R component in eq.6 is the dynamic friction due to σ_{CFij} at the front of cutter face, and the second term of that is the dynamic friction due to σ_{mij} at the both side of cutter face. The r_R component in eq.6 represents the exerted earth pressure normal to cutter face, σ_{nij}, which is equal to σ_{CFij} and σ_{mij}.

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

$$F^{MR}_{42j} = A_j \begin{bmatrix} \sigma_{sj} \\ -\left(\mu_{ms}\sigma_{sj} - c_{ms}\right)Sign\left(M_{CT}\right) \\ 0 \end{bmatrix} \quad (7)$$

Here, the p_R and q_R component in eq.7 are the normal earth pressure at the outer circumferential surface of cutter face and the dynamic friction respectively.

The weight of mud or slurry, $F^M{}_{43}$, is acting vertically downwards at the centroid of mud chamber.

$$F^T_{43} = \begin{bmatrix} \gamma_{mud} V_C \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

where γ_{mud} and V_C are the slurry density and the volume of chamber respectively.

2.5 *Force acting on skin plate*

In estimating the earth pressure loaded on skin plate, the following assumptions were in use.

1. Shield is regarded as rigid body.
2. The relationship of the coefficients of earth pressure, K_V, K_H, and the displacements of ground around shield in both directions, U_V, U_H, can be given by the following logistic functions, as shown in Fig. 2.

$$K_V(U_V) = \frac{K_{V\max} - K_{V\min}}{1 - \left(\frac{K_{V0} - K_{V\max}}{K_{V0} - K_{V\min}}\right)\exp\left(-a_V U_V\right)} + K_{V\min}$$

$$K_H(U_H) = \frac{K_{H\max} - K_{H\min}}{1 - \left(\frac{K_{H0} - K_{H\max}}{K_{H0} - K_{H\min}}\right)\exp\left(-a_H U_H\right)} + K_{H\min} \quad (9)$$

where a_V, a_H are defined as the constants showing the slope of the logistic curve and the other symbols are defined in Fig. 2. It is clear from Fig. 2 that the line based on the coefficient of ground reaction is the first order approximation of this curve.

3. The relationship of the coefficient of earth pressure at ijth element, K_{ij}, is obtained by the interpolation between K_V and K_H, as follows;

$$K_{ij} = K_V(U_{nij})\cos^2\theta_{ij} + K_H(U_{nij})\sin^2\theta_{ij} \quad (10)$$

where θ_{ij} is the angle between p_R-axis and the vertical direction, U_{nij} is the normal displacement from the skin plate to the excavated area where the cutter face passed during excavation, as shown in Fig. 3.

The summation of the following force at ijth element is considered as the total force acting on skin plate, $F^M{}_5$.

$$F^{MR}_{5ij} = A_{ij} \begin{bmatrix} \sigma_{nspij} \\ \alpha\left(\mu_{ms}\sigma_{nspij} - c_{ms}\right)Sign\left(M_{CT}\right) \\ \mu_{ms}\sigma_{nspij} - c_{ms} \end{bmatrix} \quad (11)$$

$$\sigma_{nspij} = K_{ij}\sigma_{V0ij} \quad (12)$$

where σ_{V0} and α are the overburden load and the mobilized ratio of friction in circumferential direction of skin plate respectively. Here, the effective earth pressure and the total earth pressure are used in case of sandy ground and clayey ground respectively. Furthermore, p_R, q_R and r_R component in eq. 11 are the normal earth pressure on skin plate, the resistance force against cutter torque and the dynamic friction between skin plate and ground respectively.

3 ANALYSIS

3.1 *Reverse analysis*

Ground properties, such as coefficient of total earth pressure, K_{H0}, adhesion under dynamic condition, C_{ms},

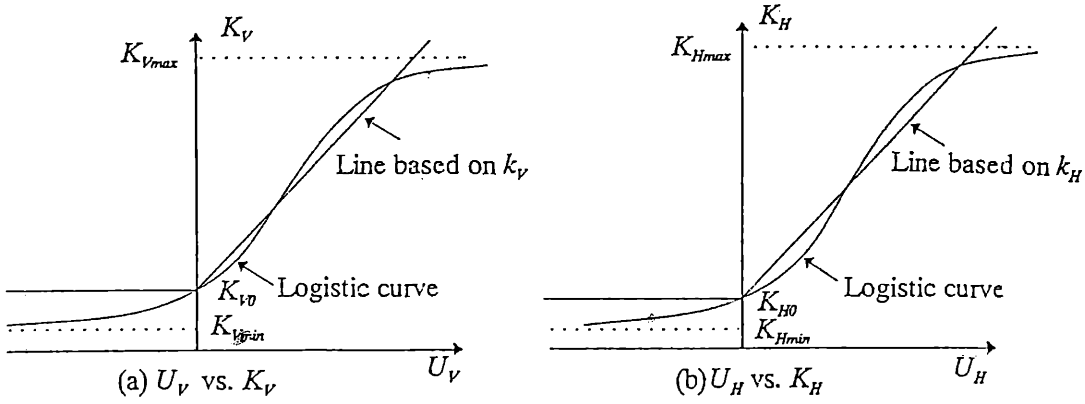

Fig. 2. Displacement vs. coefficient of earth pressure

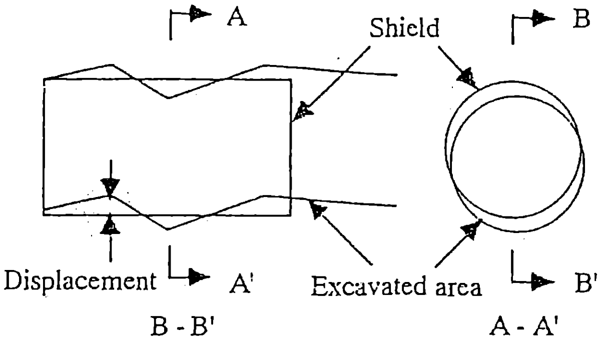

Fig. 3. Displacement and excavated area

coefficients of ground reaction in vertical direction and horizontal direction, k_H, k_V, and other construction parameters, b and α, are obtained by applying modified Marquart method to the following objective function, S.

$$v = -\begin{bmatrix} \sum_{i=1}^{5} F_i^M \\ \sum_{i=1}^{5} M_i^M \\ M_{4(r)}^M - M_{CT} \end{bmatrix}, \quad S = v^T v \qquad (13)$$

Other ground properties in eq. 13 were assumed as follows;

1. μ_{ms} and μ_m are equal to 0, because of clayey ground.

2. C_m can be ignored, compared with C_{ms}.

3. K_{Hmax} and K_{Hmin} is equal to K_a and K_p of Rankin-Resal equation. K_{Vmax}, K_{V0} and K_{Vmin} are equal to 5, 1 and 0 respectively.

4. a is equal to 0 because of the less fluctuation of V/f in the measured data.

3.2 *Data used in the analysis*

The data obtained from the single track railway tunnel, which was excavated in alluvial sandy silt layer at the seaside along the Tokyo bay by slurry shield driven method, were used. The dimensions of the shield and the ground properties are shown in Table 1. And the geological profile and the measured data are shown in Fig. 4 and 5 respectively. The accuracy of the input data was assumed in Table 2.

3.3 *Ground properties and construction parameters*

The reverse analysis results by using the measured data at 61 - 63 Ring are as follows;

1. The obtained value 0.56 for K_{H0} is close to the previous research values, i.e., between 0.6 and 1.6 for clay having OCR between 1 and 10 (Clough & Schmidt 1981), and between 0.55 and 0.75 for clay having N-value less than 4 (JSCE 1986).

2. The analyzed value 6.2 kN/m^2 for C_{ms} is considerably small compared with the cohesion under static condition. According to the empirical values C_{ms} lies between 4 and 10 kN/m^2 for pipe jacking

Table 1. Dimension of tunnel, shield and soil

Item	Value
Tunnel	
Alignment	R=1000 m to the right
Profile	-35/1000
Outer radius of segment	3.350 m
Width of segment	1.000 m
Machine	
Shield	
Radius	3.420 m
Length	6.665 m
Weight	2.767 MN
Center of gravity	(-0.045, 0.000, 0.010) m
Center of erector	(0.000, 0.000, -2.915) m
Cutter face	
Radius	3.425 m
Rotating speed	0.7 rpm
Open ratio	0.12
Thickness	0.300 m
Jack	
Capacity	2 MN/jack
No.	24
Radius	3.200 m
Position	4.715 m from tail
Ground	
Depth of overburden	about 17.0 m
Depth of Ground water	about 14.4 m
Properties	
N-value	0-3
Cohesion	43.8 kN/m^2
Internal friction angle	6.5 deg.
Density	16.6 kN/m^3

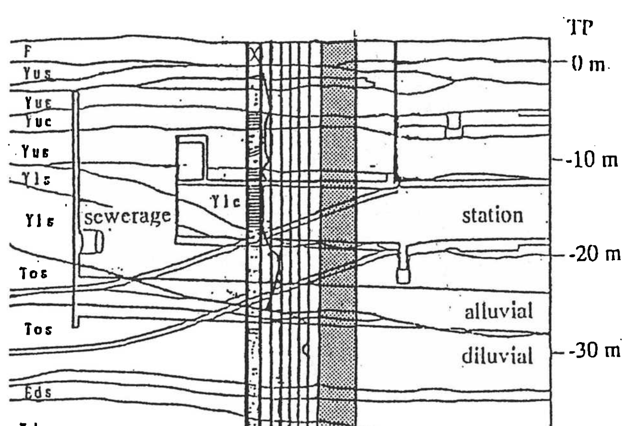

Fig. 4. Geological profile

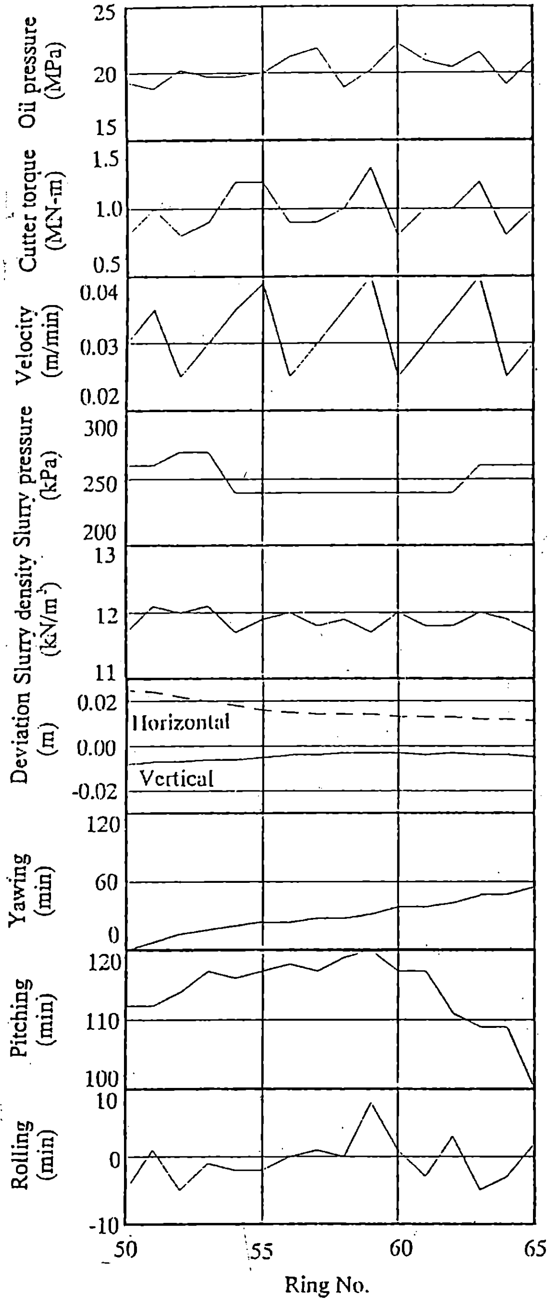

Fig. 5. Measured data (50 - 65 Ring)

method with N-value less than 4 (Nanno 1981), between 34 and 49 kN/m^2 for pile driving method with cohesion between 37 - 73 kN/m^2 (Japanese Port Harbor Assoc. 1979), and between 0 and 70 kN/m^2 for shield driven method with N-value less than 3 (Yoshida 1992). Hence the obtained value for C_{ms} is within the range of empirical value for pipe jacking method.

3. The obtained value 1.03 MN/m^3 for k_H is close to the empirical value. k_H lies between 0 and 5 MN/m^3 for clay where N-value is less than 4 (JSCE 1986), and between 2 and 10 MN/m^3 for the horizontal resistance of pile (Japanese Port Harbor Assoc. 1979).

4. The other parameters k_V, b and α are 53 MN/m^3,

Table 2. Accuracy of input data

Item	Value
Shield	
Self-weight	1 %
Center of gravity	(0.100, 0.100, 0.100) m
Buoyancy	1 %
Center of buoyancy	(0.100, 0.100, 0.100) m
Measured data	
Oil pressure of jack	10 %
Velocity of excavation	10 %
Slurry pressure	10 %
Slurry density	10 %
Position of shield	0.010 m
Rotation angle of shield	7.5 min
Cutter torque	10 %

2.97 and 0.35 respectively. But these parameters could not be compared with the empirical values because very few studies have been done on those parameters. Hence the physical meaning of b and α is discussed here. First, the value 2.97 obtained for b shows that the earth pressure loaded on shield at face during excavation is more than that at rest. Next the value 0.35 obtained for α shows that the adhesion in circumferential direction is mobilized by 35% to resist mainly the cutter torque. According to the above discussion, the obtained values for each property based on the developed model could be considered as reasonable.

Figure 6 shows the distribution of displacement of ground in normal direction and the distribution of normal earth pressure on skin plate, based on the above reverse analysis results. In this figure, 0, 360 deg. and 180 deg. are the bottom of shield and the

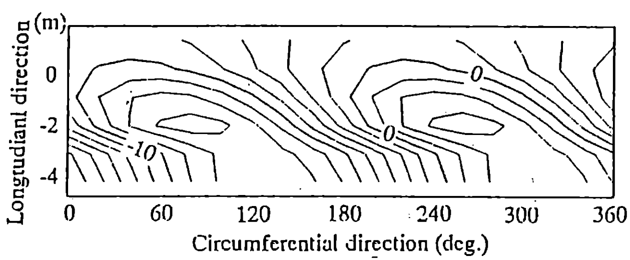

Fig. 6. (a) Distribution of normal displacement of ground (mm)

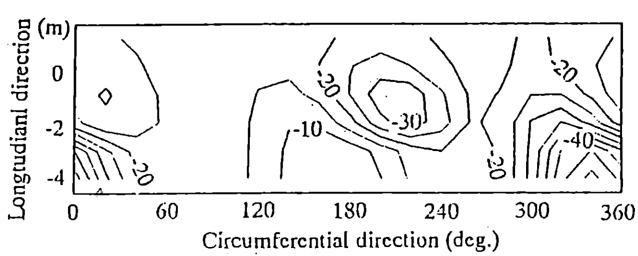

Fig. 6. (b) Distribution of normal earth pressure (10 kPa)

Table 3. Estimate force and estimate standard deviation, σ (62 Ring)

Force	F^M_p	F^M_q	F^M_r	M^M_p	M^M_q	M^M_r	CT
f_1	2.76	0	0.09	0	0.03	0	0
f_2	0	0	0	0	0	0	0
f_3	0	0	21.03	-4.19	-17.03	0	0
f_4	0.14	0	-20.62	0	3.04	1.05	1.05
f_5	-2.50	3.38	-0.89	6.96	13.68	-1.05	-1.00
Total	0.40	3.38	-0.39	2.77	-0.28	0.00	0.05
σ	0.20	1.03	0.41	2.03	1.38	0.05	0.02

Notation: -1.00 at f_5 and CT is the measured cutter torque.
Units: MN, MN-m

top of shield respectively. And the upper direction is the advanced direction of shield. It is made clear from this figure that the ground at the spring part of the inside of curve is pushed by shield and the ground at the opposite side is moved toward shield. Furthermore, the normal earth pressure on skin plate distribute complicatedly due to the influence of the change of the coefficient of earth pressure in normal direction and the above mentioned displacement of the ground.

Table 3 shows each component of the acting load on shield and the standard deviation for the estimate acting loads based on the assumed accuracy of input data in Table 2 and the reverse analysis results. The assumed accuracy in Table 2 is supposed to be a little bit smaller, because the estimate error of F_q component becomes three times of the standard deviation.

4 CONCLUSIONS

Conclusions are as follows;

1. The model of acting load on shield was developed, paying more attention to the earth pressure acting at face and that on skin plate. Furthermore, the validity of the developed model was inspected by comparing the analyzed ground properties with the empirical values.

2. The ground properties, such as coefficient of earth pressure at rest, coefficients of ground reaction in vertical and horizontal direction, earth pressure ratio at face during excavation, mobilized ratio of friction in circumferential direction of skin plate and adhesion under dynamic condition, were obtained from the in-situ data, regarding the shield as a large load cell.

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NOTATIONS

f	: component of force
F	: force vector
M	: moment vector
M_{CT}	: cutter torque (+ : clockwise direction)
A	: area of element
α_0	: open ratio of cutter face
μ_{ms}	: coefficient of dynamic friction between steel and mud
μ_m	: coefficient of dynamic friction of mud
C_{ms}	: adhesion between steel and mud
C_m:	: cohesion of mud
suffix	
T	: total coordinate system
M	: machine coordinate system
MR	: rotating machine coordinate system
1	: force due to self weight of shield
2	: force due to buoyancy of shield
3	: force due to jack thrust
4	: force at face
5	: force on skin plate
i,j	: no. of calculation point
V	: vertical direction
H	: horizontal direction