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Modeling of loads acting on shield

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SYNOPSIS: The model of acting load on shield, which satisfies the dynamic equilibrium conditions, was developed taking account of shield behavior. And the validity of this model was inspected by applying this model to in-situ data. As conclusions, acting load on shield is heavily influenced by shield behavior, and the physical properties of ground can be obtained from in-situ data by reverse analysis method.

1 INTRODUCTION

Closed shield driven method is widely used to construct the tunnel under ground water surface. Furthermore, shield has been controlled automatically by utilizing expert system and/or artificial intelligence recently. Accompanying the adoption of these systems, numerous data have been measured and stored. But these systems can not forecast the shield behavior and the acting load on shield in case of a shield with deformed cross section, such as multi-face shield etc.. To solve these problems, theoretical research is necessary.

In the previous study (Sugimoto et al. 1991), author showed the possibility of theoretical approach to acting load on shield by regarding a shield as a large load cell, and indicated that the consideration of shield behavior is necessary to satisfy the dynamic equilibrium conditions. Therefore, this paper aims to develop the model of acting load on shield taking account of shield behavior and to inspect the validity of this model by using in-situ data.

2 ANALYTICAL METHOD

2.1 Modeling of acting load on shield

In this modeling, followings were assumed:

1. Acting load on shield is composed of five forces, that is, F1: self weight, F2: buoyancy, F3: equipped jack force, F4: acting load on face, and F5: acting load on skin plate, as shown in Fig. 1. According to the conventional design concept, in case of sandy ground, F4 and F5 are divided into effective earth pressure and hydraulic pressure, while in case of clayey ground, total earth pressure is adopted as acting load. Therefore, in case of clayey ground, F2 and the hydraulic pressure of F4 are equal to zero.
2. F4: acting load on face is equal to the sum of earth pressure at rest and hydraulic pressure.
3. F5: acting load on skin plate is divided into three forces, that is, F51: ground reaction in normal direction on skin plate, F52: skin friction in tangential direction within vertical section, and F53: skin friction in tangential direction within cross section.

F51 shall be given as follows:

$$F51 = S \times \sigma_n \tag{1}$$

where S and σ_n represent the acting area of ground reaction and the earth pressure in normal direction on skin plate respectively. σ_n shall be given as follows, based on the concept of ground reaction:

$$\sigma_n = \sigma_{no} \times KR(U_n) \tag{2}$$

where σ_{no} represents σ_n at rest. KR, which is a non-dimensional parameter, can be obtained by the normal earth pressure on skin plate divided by that at rest, which shall be called 'earth pressure ratio'. On the other hands, U_n shows the normal relative displacement of ground on skin plate, which shall be given by the distance from the excavated area to the position of skin plate. The normal earth pressure on skin plate is considered to be a function of the relative displacement of ground. Therefore, logistic function, as shown below, is adopted as the function of the relation between U_n and KR, in order to take account of the ground in active state and in passive state around shield.

$$KR(U_n) = (SP-SA)/(1-\frac{1-SP}{1-SA}\exp(-A \cdot U_n))+SA \tag{3}$$

where:

$$SP = \sigma_{np}/\sigma_{no}$$
$$SA = \sigma_{na}/\sigma_{no}$$

Suffix p and a represent the passive state and the active state respectively. And A is the parameter related to the coefficient of ground reaction. Eq.(3) is shown in Fig. 2.

F52 and F53 shall be given as follows:

$$F52 = S(\mu \times \sigma_n + C) \tag{4}$$

$$F53 = \begin{cases} S(\mu \times \sigma_n + C) \times \mathrm{sgn}(-U_t) & \text{(clayey ground)} \\ 0 & \text{(sandy ground)} \end{cases} \tag{5}$$

where μ, C and U_t represent the coefficient of dynamic friction between skin plate and ground, the cohesion of ground and the tangential rela-

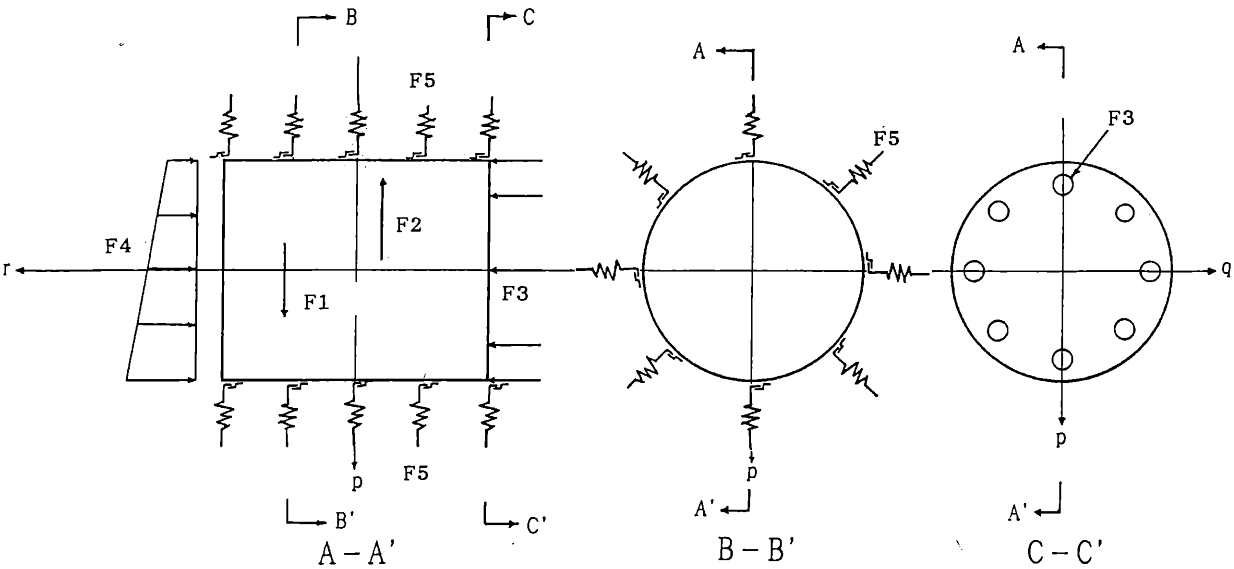

Fig. 1. Model of acting load on shield

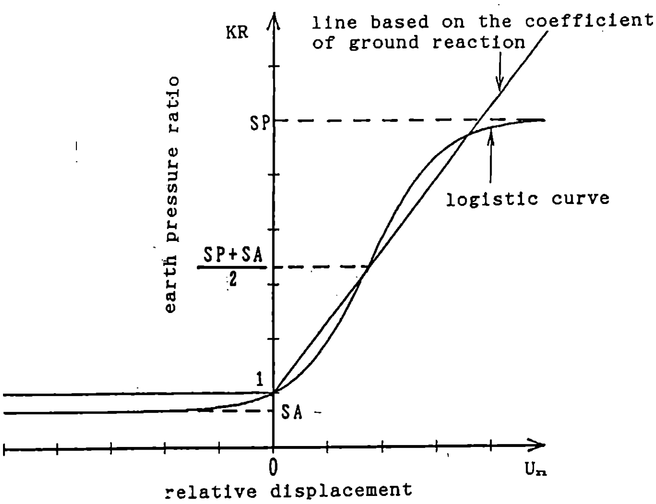

Fig. 2. Relation between U_n and KR

tive displacement of ground on skin plate.

2.2 Computational method

In calculation of acting load on shield, six dynamic components, that is, Fp, Fq, Fr, Mp, Mq and Mr generated due to the previous mentioned five forces, were considered to satisfy the dynamic equilibrium conditions. Here, F and M represent force and moment respectively, and suffix p,q and r represent the coordinate on the following machine rectangular coordinates:

1. The origin is taken at the center of the section on which jack thrust acts.
2. p-axis is taken in downward vertical direction under no rolling.
3. r-axis is taken in longitudinal direction of shield.

The procedures of calculating the acting load on shield are as follows:

1. Calculate the excavated area by using the position and the direction angle of shield.
2. Calculate the relative displacement of ground around shield.
3. Calculate the coefficient of skin friction and that of ground reaction, which are unknown parameters in Eqs.(3),(4) and (5), by applying non-linear least square method to the dynamic equilibrium conditions as to Fr, Mp and Mq at each segment ring. The dynamic equilibrium conditions as to Fp, Fq and Mr are not used here since Fp, Fq and Mr of F3 generate according to those components of other forces and then the dynamic equilibrium conditions of those components satisfy automatically. But those components at each jack can not be determined because the number of jack is more than 4 generally.
4. Calculate each dynamic component by using the obtained coefficient of skin friction and that of ground reaction.

3. APPLICATION

3.1 Used data

The data here in use are obtained from the single track railway tunnel, which was executed at the seaside along Tokyo bay by mud shield driven method. The dimensions of the tunnel and of the shield are shown in Table 1 and the geologic profile is shown in Fig. 3. And the

Table 1 Dimensions of tunnel and shield

tunnel	inner radius	3.350 m
	segment width	1.000 m
shield	radius	3.420 m
	length	6.665 m
	self weight	2.767 MN
	radius of excavation	3.425 m
	capacity of jack thrust	2 MN/jack
	number of jack	24
	radius of jack position	3.200 m

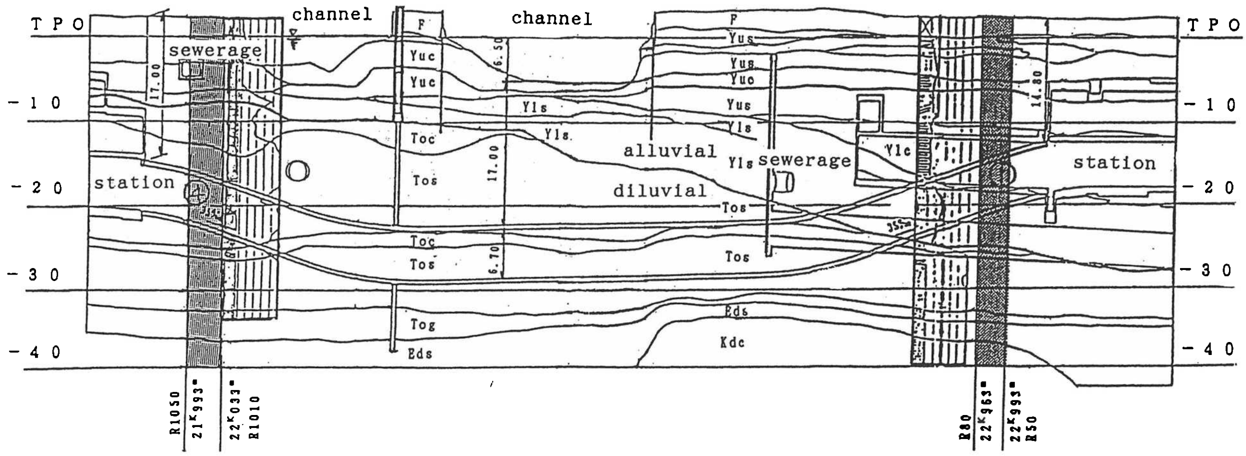

Fig. 3. Geologic profile at the used data

Table 2 Alignment of tunnel and physical properties of ground

Ring No.		70	1037
depth	(m)	17.0	18.8
ground water level	(m)	14.4	16.2
incline		-35/1000	+35/1000
alignment		R=1000m (clockwise)	straight
layer		alluvial sandy silt	diluvial sand
N-value		0-3	25-40
ϕ	(deg)	6.5	40.0
cohesion	(kPa)	43.8	0.0
unit weight	(kN/m^3)	16.6	20.0

ϕ :internal friction angle

alignment of the tunnel and the physical properties of the ground at the points for measurement are shown in Table 2.

3.2 Skin friction and ground reaction

The followings were assumed in calculation:

1. Shield is a rigid body.
2. The earth pressure at rest in vertical direction is equal to the overburden load, and that in horizontal direction is equal to the overburden load multiplied by the coefficient of earth pressure ar rest, which is given by Jaky's experimental formula.
3. F5:acting load on skin plate is calculated at each point which is generated by dividing the skin plate into 18 along circumferential direction and into 6 along longitudinal direction.

Table 3 shows the results of reverse analysis. From this table, the followings are made clear:

1. Both friction angles have a good agreement with the internal friction angles of ground. Furthermore, the obtained μ of sandy ground coincides with μ of previous study (Yoshida & Yamada 1992), but is larger than that used in design of shield. This model is required to be improved at this point since the actual acting earth pressure on face is considered to be larger than that at rest in excavation.
2. λ of alluvial sandy silt coincides with λ of previous study (JSCE 1986), while λ of diluvial sand is smaller than λ of previous study (JSCE 1986). Furthermore, both standard deviations of λ are large. These reasons are as follows: a)the ground around shield is almost at active state, because the radius of excavation is a little longer than that of shield; b)in case that the ground is at active state, the weight of loosened area based on Terzaghi's theory is loaded on skin plate as earth pressure, especially in hard sandy ground; c)then λ, which is obtained by using the assumption that the vertical earth pressure is represented by the overburden load, is smaller than actual λ.

Table 3 Results of reverse analysis

layer	alluvial sandy silt μ	alluvial sandy silt λ	diluvial sand μ	diluvial sand λ
n	13	13	16	16
x	0.112 (6.4°)	2.82	0.650 (33.0°)	4.23
σ	0.025	2.08	0.068	4.45

μ :coefficient of dynamic skin friction
λ :coefficient of ground reaction(MN/m^3)
n:number of data x:average σ :standard deviation

3.3 Acting load on shield

The relative position between the excavated area and the shield position and F51:ground reaction in normal direction on skin plate are shown in Fig. 4 for example. The followings are made clear in these figures:

1. Even if the alignment is almost straight, the shield is not located at the center of the excavated area due to the control of meanders.
2. The normal stress on skin plate depends on the relative displacement of ground. Therefore, it is necessary to take account of the relative position between the excavated area and the shield position in calculation of acting load on skin plate.

Table 4 and 5 show the acting load on shield for example. The followings are made clear in these tables:

1. F5:acting load on skin plate can not be ig-

nored in order to satisfy the dynamic equilibrium conditions.

2. The residual is within a few % of the maximum absolute value at each force component except for Mp at Ring No. 1037. This fact indicates the validity of this modeling.

3. Fp, Fq and Mr of F3 to satisfy the equilibrium conditions is within 9 % of jack thrust(Fr of F3). This reason is that F53 is calculated by Eq.(2), which is assumed to give F53 a maximum value as to clayey ground, and to give F53 a minimum value as to sandy ground. F53 is considered to take the value within both actually.

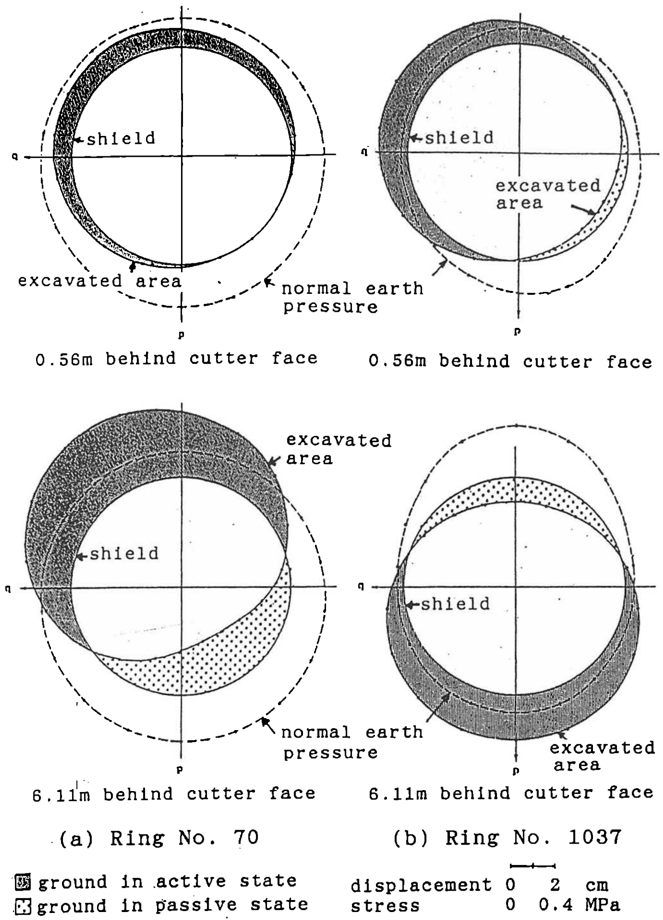

Fig. 4. Relative position between the excavated area and the shield position and normal ground reaction

Table 4 Acting load on shield at Ring No. 70 (unit:MN, MN-m)

force	Fp	Fq	Fr	Mp	Mq	Mr
F1	2.77	0	0.08	0	0.03	0
F2	0	0	0	0	0	0
F3	1.93	0.13	21.43	-3.57	-14.29	-0.14
F4	0	0	-11.06	0	1.59	0.80
F5	-4.70	-0.13	-10.45	3.47	12.72	-0.66
sum	0	0	0	-0.10	0.05	0

Table 5 Acting load on shield at Ring No. 1037 (unit:MN, MN-m)

force	Fp	Fq	Fr	Mp	Mq	Mr
F1	2.77	0	-0.08	0	0.02	0
F2	-2.08	0	0.06	0	3.92	0
F3	0.89	-1.20	27.92	-3.85	0.51	-0.70
F4	0	0	-10.52	0	1.47	0.70
F5	-1.58	1.20	-17.49	3.27	-6.00	0
sum	0	0	-0.11	-0.58	-0.08	0

4 CONCLUSIONS

Conclusions are as follows:

1. The model of acting load on shield was developed taking account of the relative position between the excavated area and the shield position. Furthermore, the validity of this model was inspected by applying the developed model to in-situ data.

2. Acting load on skin plate can not be neglected to satisfy the dynamic equilibrium conditions. Furthermore, in calculation of acting load on skin plate, it is necessary to take account of the ground displacement due to the meanders of shield.

3. Considering a shield as a large load cell, the physical properties of ground can be obtained from in-situ data by reverse analysis.

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