CALCULATION OF SHIELD TUNNEL LINING'S CROSS-SECTIONAL FORCES USING JAPANESE CONVENTIONAL METHOD AND MUIR WOOD-CURTIS SOLUTION

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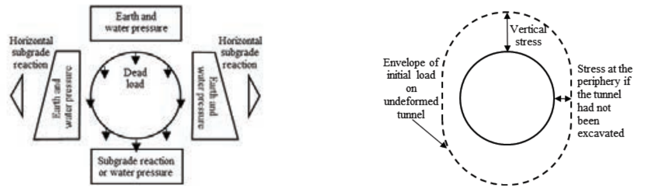
1. INTRODUCTION

In modern developed urban areas such as Tokyo and London, most of the underground tunnels are built using Mechanized Shield Tunneling Method due to its feasibility in restricted space. In terms of geological condition, major cities in Japan are situated on top of soft alluvial deposits, while in contrast, the soil in most of European Cities is comparatively expected to be sufficiently self-standing[1]. Thus, it is inferred that the tunnel lining design methods are fundamentally different. When these methods are used for tunnel lining design in other countries, the applicability are of concern. This paper presents the comparison of simplified methods used to design tunnel lining in Japan (i.e. conventional method) and Europe (i.e. Muir Wood-Curtis Solution) and their suitability to be applied under different ground conditions and tunnel sizes are discussed.

2. METHODOLOGY

This paper calculates the cross-sectional forces acting on the tunnel lining using 2 design methods that are similar in their structural model. Fig. 1 shows the loading condition of The Japanese Conventional Method and A.M. Muir Wood-Curtis Solution.



(1) Japanese Conventional Method (2) Muir Wood-Curtis Solution

Fig. 1 Loading condition

2.1 Japanese Conventional Method

Also known as the Elastic Equation Method, a simplistic approach which has been widely used in Japan. The Japanese Conventional Method assumes earth and water pressure as the combination of vertical uniform load and horizontally uniformly varying load. The horizontal subgrade reaction is evaluated as a triangularly varying load between 45°to 135°from the crown on both sides.[2]

2.2 A.M. Muir Wood-Curtis Solution

Commonly referred to as `closed-form` solution, the continuum analytical model proposed by A.M. Muir Wood (1975) assume plane stress, where the elastic circular tunnel lining deforms elliptically in a homogeneous elastic ground. [3] This solution was extended by Curtis (1976) by considering the effect of shear forces within the interaction between the lining and the ground.[4]

2.3 Case Study

In this paper, 16 cases derived from the combination of 4 design considerations are used in the calculation of cross-sectional forces as shown in Table 1. The properties of the tunnel lining and soil are shown in Table 2 and Table 3.

Table 1 Breakdown of Cases Considered in This Paper

Case		Alluvial Clay				Diluvium Clay				Alluvial Sand				Diluvium Sand			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Water Level	Max	○	○			○	○			○	○			○	○		
	Min			○	○			○	○			○	○			○	○
Tunnel Size	Small	○		○		○		○		○		○		○		○	
	Large		○		○		○		○		○		○		○		○

Here, max water level refers to groundwater at surface level, while min water level refers to groundwater below tunnel level.

Table 2 Properties of The Tunnel Lining

Tunnel Lining Specification	Small Diameter	Large Diameter
Tunnel outer diameter (m)	5.50	11.00
Tunnel inner diameter (m)	5.00	10.00
Segment type	RC Segment	
Segment width (m)	1.50	
Segment thickness (m)	0.25	0.50
Ec (kN/m2)	3.90 E+07	
ν_c	0.17	

Table 3 Properties of Soil

Soil Property	Alluvial Clay	Diluvium Clay	Alluvial Sand	Diluvium Sand
Overburden (m)	5.50	27.50	5.50	27.50
Es (kN/m2)	5600	56000	36400	140000
γ (kN/m2)	16.5	18	18	20
c (kN/m2	15	135	0	0
Φ (°)	0	0	30	40
N-value	2	20	13	50
ν	0.35			
λ or K	0.85/0.75	0.5/0.75	0.5/0.5	0.35/0.4

Here, λ/K both refers to the lateral earth pressure coefficient

3. RESULTS AND DISCUSSION

The calculated cross-sectional forces acting on the tunnel lining are shown in Table 4. Here, only the maximum bending moment (M) and axial forces (N) are shown.

3.1 Deep Tunnel

For deep tunnels in clay (Case 5-8), the adoption of loosening earth pressure by the Japanese Conventional Method resulted in a significant decrease of bending moment. However, this is only true for small tunnel in Diluvium sand (Case 13&15), as the coefficient of lateral earth pressure decreases, size of the tunnel shows detrimental effect in the bending moment (Case 14&16).

Keyword Shield Tunnel Lining, Calculation Method, A.M. Muir Wood, The Japanese Conventional Method
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Table 4 Calculation Results

Max Cross-sectional Forces			Alluvial Clay				Diluvium Clay				Alluvial Sand				Diluvium Sand			
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Japanese Conventional Method	M	kNm/m	-31.2	-354.1	-31.2	-354.1	31.7	242.1	98.8	638.4	-10.6	-324.5	62.1	200.1	49.7	343.7	107.3	665.2
	N	kN/m	365.1	1010.9	365.1	1010.9	981.8	2489.7	547.0	2190.7	355.3	979.5	313.4	683.3	1039.6	2719.8	606.5	2440.7
A.M. Muir Wood-Curtis Solution	M	kNm/m	24.4	125.0	57.4	306.8	93.0	357.0	185.9	816.8	31.9	164.5	66.5	349.1	62.4	271.5	122.8	534.9
	N	kN/m	400.7	1050.2	393.7	1020.3	1381.3	3262.2	1387.5	2990.8	426.2	1119.1	415.8	1091.2	1610.9	3510.2	1533.1	3340.5

3.2 Shallow Tunnel

3.2.1 Effect of Ground Condition and Groundwater

In Alluvial Clay, calculation result given by the Japanese Conventional Method bears the same value (Case 1&3; Case 2&4) regardless of groundwater condition due to the adoption of total stress method. In contrast, A.M. Muir Wood-Curtis Solution considers effective stress method, which inferred that its bending moment is to be correlated with groundwater effect. Fig. 2 shows the bending moment diagram of Case 1, while Case 2-4 follow the same pattern.

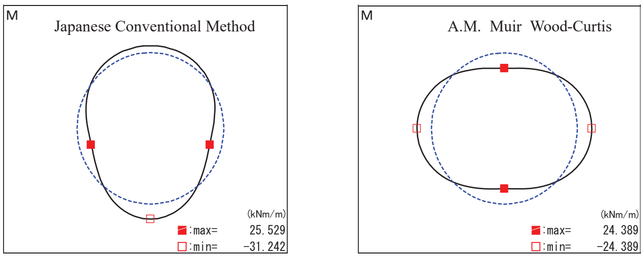

Fig. 2 Bending Moment Diagram (Case 1)

In Alluvial Sand (Case 9-12), all cases adopted the effective stress method. Fig. 3 shows changes in the bending moment diagram obtained using The Japanese Conventional Method from vertical (Case 9, with groundwater) to horizontal deformation (Case 11, without groundwater). Similarly, Case 10 and Case 12 follows the same trend. In contrast, the shape of the bending moment diagram produced by A.M. Muir Wood-Curtis remains unchanged, as previously shown in Fig. 2

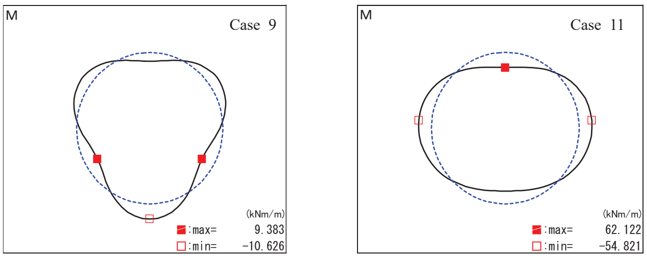

Fig. 3 Bending Moment Diagram (The Japanese Conventional Method)

Thus, referring to the loading condition shown in Fig. 1, The Japanese Conventional Method calculates its loading on both top and bottom of the tunnel with an additional consideration of horizontal subgrade reaction, making it largely dependent on the appropriate determination of coefficient of lateral earth pressure. Therefore, in shallow tunnel with limited overburden, the tunnel tends to deform vertically. On the contrary, A.M. Muir Wood-Curtis Solution calculates its loading at the tunnel axis level and assume that the active soil pressures on the lining to be equal to the stresses in an undisturbed ground, resulting in a constant horizontal deformation.

3.2.2 Additional Effect of Tunnel Size

The result of bending moment calculation using the A.M. Muir Wood-Curtis Solution shown in Case 2 and Case 10 suggested the necessity to additionally assess the effect of tunnel size in the design consideration. Here, for large tunnel in both clay and sand which is submerged under groundwater, the consideration of pore water pressure in the calculation of vertical stress, combined with exclusion of water pressure in the bending moment calculation resulted in an underestimation of the calculation result.

Therefore, special care should be taken when adopting A.M. Muir Wood-Curtis Solution for the design of large tunnel submerged under groundwater. The sensitivity of the sectional forces under different selection of groundwater levels should be carefully studied.

4. CONCLUSION

In this paper, the cross-sectional forces acting on the tunnel lining are calculated using 2 design methods to evaluate their differences. The two methods are The Japanese Conventional Method used in Japan and Continuum Analytical Solution proposed by A.M. Muir Wood (1975) and Curtis (1976) used outside of Japan. From the calculation result, it is observed that the 4 design considerations greatly affect the cross-sectional forces acting on the tunnel lining.

In deep tunnels, A.M. Muir Wood-Curtis Solution tends to be on the conservative side with the exceptions of large tunnel in sand. In shallow tunnel, the size of tunnel and groundwater level dictates whether one method is more conservative than the other. However, for large-submerged tunnel, result shows that The Japanese Conventional Method tends to be more conservative.

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