SHIELD TUNNELING ADVANCEMENT SIMULATION USING 3D FEM CONSIDERING DISTANCE FACTOR AND ITS VALIDATION

Alireaza Afshani[1,a], Hiroshi Dobashi[2], Shinji Konishi[3], Kazuhito Komiya[4], Hirokazu Akagi[1,b] and Kaho Orihara[1,c]

[1] *Department of Civil and Environmental Engineering, Waseda University, Japan. E-mail: [a] aafshani@moegi.waseda.jp, [b] akagi@waseda.jp, [c] kaho@toki.waseda.jp*

[2] *Metropolitan Expressway Company Limited, Japan. E-mail: h.dobashi118@shutoko.jp*

[3] *Tokyo Metro Company Limited, Japan. E-mail: s.konishi.r4r@tokyometro.jp*

[4] *Chiba Institute of Technology, Japan. E-mail: komiya.kazuhito@it-chiba.ac.jp*

A new approach of shield tunnel advancement for soil deformation calculation is presented using 3D finite element method. Applying step by step tunneling loads in this method, total soil deformation is calculated by summation of induced displacement from the first loading step to the current step deformation. In this approach, shield machine face distance from monitoring locations is taken as a factor which affects way of calculating soil displacement. If TBM machine face distance from the monitoring location is assumed to be less than a specific distance say "D", drained condition is used to calculate soil deformation; on the other hand, if the machine face distance from monitoring location is more than "D", undrained condition is used for soil deformation calculation. Additionally field data of an EPB shield tunneling site were gathered and used to investigate the validity of proposed approach.

1. INTRODUCTION

Both field study and numerical investigation have shown that tunneling is a three dimensional procedure. Shield machine advancement and tunneling construction sequences using 3D analysis have been investigated by previous researchers (see e.g. [3], [4], and [5]).

In order to simulate earth pressure balance tunneling, authors already proposed a way of 3D analysis of tunnel advancement and loading sequences [1]. In that work drained or undrained behavior of soil during tunneling was decided by the soil type and the boundary condition. Later on, it was found that using FEM and summation of loading step displacements required to takes into account another factor. In this way, effect of distance (length of drainage path) is also considered for soil displacement calculation. Meanwhile, field data of twin EPB shield tunneling were gathered and used to validate FEA results. Additionally, high permeability of a specific soil type which was observed in field was

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applied to analysis procedure when making comparison between field results and FEA outputs.

2. ADVANCEMENT APPROACH OF SHIELD TUNNELING BASED ON DISTANCE OF MACHINE FACE FROM MONITORING LOCATIONS

2.1. *General*

In this work, FEA is performed using a program that was already developed by Komiya *et al.* [3].

Tunnel advancement procedure using 3D mesh is carried out by applying step by step tunneling loads. In each step, face pressure at the front of tunnel is calculated by increasing linearly from top to bottom of shield machine face. Tail void grouting is also applied perpendicular to tunnel perimeter through the entire length of one ring exactly at the back of shield machine. Initial vertical stress applied in 3D models is obtained by considering overburden load and ground water table. Then, difference between face pressure and initial earth pressure is applied to elements in front of the tunnel face; similarly difference between grouting pressure and initial earth pressure is also applied at the back of shield machine as an acting force in each loading step.

Applying these forces, nodes of elements are displaced, and stress and strain are developed throughout the mesh. Developed stresses in elements at each step are used as an initial stress for the next loading step.

In each step, undeformed mesh is used for applying forces and obtaining stress, strain, and deformation. Then final displacement of any node at any step (any advancement step of tunnels) is obtained by adding of deformation of all previous steps plus deformation of current step. Above mentioned procedure has been already described by these authors in details [1]; due to necessity, here, its summary is presented:

In front of shield TBM machine, difference between face pressure and earth pressure is applied as follows:

$$\begin{aligned} \text{Loading step 1: } P_1 &= (FP_1 - EP_1) \\ \text{Loading step 2: } P_2 &= FP_2 - (EP_2 + St_1) \\ \text{Loading step } n\text{: } P_n &= FP_n - (EP_n + St_{n-1}) \end{aligned} \tag{1}$$

At the back of TBM machine, difference between grouting pressure and earth pressure is applied as follow:

$$\begin{aligned} \text{Loading step 1: } G_1 &= (GP_1 - EP_1) \\ \text{Loading step 2: } G_2 &= GP_2 - (EP_2 + St_1) \\ \text{Loading step } n\text{: } G_n &= GP_n - (EP_n + St_{n-1}) \end{aligned} \tag{2}$$

in which P_n and G_n are applied stress as an input loading to the elements in front and back of shield machine in loading step "n", respectively; FP_n is the face pressure values at loading step "n" obtained from field data; GP_n is the grouting pressure values in loading step "n" obtained from field data; St_{n-1} is induced stress in elements at loading step "$n-1$"; EP_n is the earth pressure values at loading step "n" obtains using $\mathbf{EP}_n = \frac{1}{3}(\sigma_v + 2\sigma_h)$ in which σ_v and σ_h are vertical and horizontal stresses of soil.

2.2. *Procedures of Presented Approach*

In the previous paper done by these authors, drained or undrained behavior of soil was determined mainly based on soil type [1]. Using summation of displacement in all of the loading steps in 3D analyses in this approach requires to takes into account another factor. In this paper, effect of distance (length of drainage path) has taken into consideration. If shield machine face distance from monitoring location is assumed to be less than a specific distance say "*D*" same as shown in Figure 1, drained condition is used to calculate soil deformation; on the other hand, if shield machine face distance from monitoring location is more than "*D*", undrained condition is used. Considering relationship between drainage path and degree of consolidation, this relationship can be presented using the following equation:

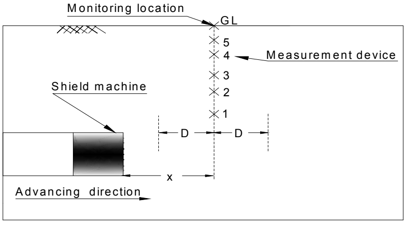

Figure 1. Drained or undrained condition for soil displacement calculation based on shield machine face distance from monitoring location, "*D*".

$$T = \frac{c_v.t}{x^2} \tag{3}$$

In which T_v is time factor, c_v is consolidation coefficient, t is construction time, and x is drainage path. By approaching of tunnel face to a monitoring location, when tunnel face distance from monitoring locations is decreasing, say less than D, and by assuming relatively small amount of construction time, t, and constant consolidation coefficient, time factor, T_v, is increasing, which leads to the higher degree of consolidation. For high degree of consolidation, drained analysis is preferable as it also suggested by others like Vermeer and Meier for deep excavation [6]. On the other hand, if the distance from monitoring locations is more than D value, undrained analysis is used. In the next part, D value is defined for a specific case study. It should be mentioned that during drained condition, earth pressure is calculated using effective stress of soil, while during undrained condition total stress of soil is used for earth pressure calculation.

3. SHILED TUNNELING CASE STUDY

3.1. *General Description*

The site is located in Yokohama, Japan, and intended to be a motorway of total length about 8.2 km. About 5.9 km of this route is a side by side twin tunnel with diameter of about 12.5 m.

Main part of this route is excavated using Earth Pressure Balanced Shield tunneling method. Length of each lining is 2 meter which is equal to each advancement length. Soil layers and their material parameters have been shown in Table 1.

In this site, two lines are named as Outbound, and Inbound, each of which has two monitoring locations (MLs). MLs at each line were located of about 15 m (ring No. 8) and 50 m (ring No. 25) from the launching shaft at starting point. In each of these MLs, vertical displacement of the soil is measured at various depths before, during, and after passing of shield machines. Number of measurement devises at each ML has been shown in Table 2. Orientation of measurement devices schematically are depicted in Figure 1. Excavation

Table 1. Soil layers description and their property.

Soil Type	Description	γ (kN/m^3)	c (kN/m^2)	φ (degree)	E (Mpa)	ν	K_0
B	Fill material	14.0	30	0	1.2	0.45	0.80[1]
Ac	Cohesive soil	15.5	35	3	3.3	0.45	0.80[1]
Ks	Sand and sandstone	19.5	60	42	289	0.3	0.33[2]
Kms	Sandy mudstone	19.0	1840	10	492	0.35	0.16[3]
Km	Mudstone	18.5	2020	7	430	0.35	0.16[3]

[1]Based on Standard Specifications for Tunneling, Shield tunnel, Japan Society of Civil Engineers, 2006.
[2]Based on Jaky's formula.
[3]A value of experience obtained during operation of shield machine.

Table 2. Number of measurement devices at each monitoring location.

Line	Monitoring location 1 (ML1)	Monitoring location 2 (ML2)
Outbound	5	6
Inbound	6	7

construction in each lines is being done separately in a way that shield machine head in outbound is approximately 30 meter ahead of inbound line.

3.2. *Simulation of EPB Tunnel Advancement Using Presented Approach*

3.2.1. *Mesh Generation*

Using longitudinal profile of the Yokohama site, a 3D mesh of the twin lines for about 120 m long was prepared. Diameter of each tunnel (outbound and inbound) is 12.3 meter; length, width, and height of the whole mesh are 120, 127.5, and 54 meter, respectively. Figure 2 shows the whole 3D FE mesh, twin tunnels, and launching shafts, as well as monitoring locations. All of the elements in mesh are 8 nodded cubic. Due to the large scale of 3D mesh, and in order to reduce the time of calculation, soil constitutive model is assumed to be linear elastic.

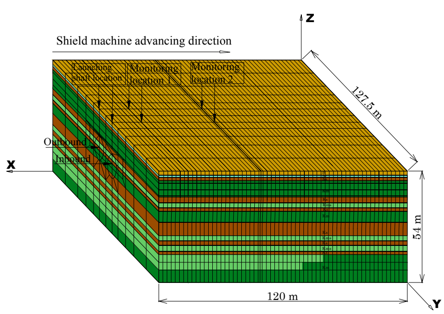

Figure 2. Generated 3D mesh.

3.2.2. *Estimation of "D" Distance for Soil Deformation Calculation Based on Drained or Undrained Condition*

During tunnel advancement, shield machine face mainly passes through sandstone, mudstone, and sandy mudstone. Mudstone is usually taken as a low permeable soil type. Field survey in this site showed that after applying of machine face pressure, generated excess

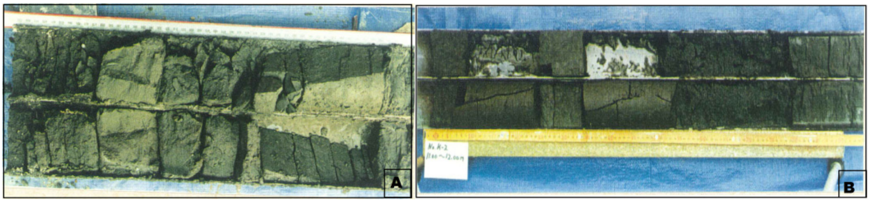

Figure 3. An example of mudstone at Yokohama area. A: Horizontal cracks without any bond between them; B: Long vertical fissures as well as horizontal cracks.

pore water pressure is dropping to its initial value after of about 1 or 2 days. Furthermore, taken pictures of the mudstone samples from similar project at Yokohama area manifested that mudstone at this area has some horizontal sand lenses as well as numerous horizontal and long vertical fissures which act as a drainage path. Figure 3 presents an example of mudstone in this area. So, knowing high permeability characteristic of mudstone at this site, it was decided to use machine face distance from monitoring locations, shown "D" distance in Figure 1, to determine drained or undrained condition for calculation of soil deformation. According to Figure 1, estimation of "*D*" distance depends on the shield machine advancement rate and soil type. In this site, average daily advancement of machine is around 3 rings length per day, as the length of each ring is 2 meter, so, "*D*" is assumed to be 6 meter in this case.

4. COMPARISON OF FIELD DATA WITH PREDICTED RESULTS

Presented approach validation is presented in this part by comparing of FEA results with measurement data of Yokohama site. Figures 4 to 7 show vertical displacement of soil at the location of measurement devices based on the distance from monitoring locations (MLs). TBM machine face distance from the ML determines drained or undrained condition for soil deformation calculation. As it was mentioned before, during drained condition, earth pressure is calculated using effective stress of soil while during undrained condition, total stress of the soil is used.

Vertical displacements calculated by FEA in the graphs are consistent with measured field data.

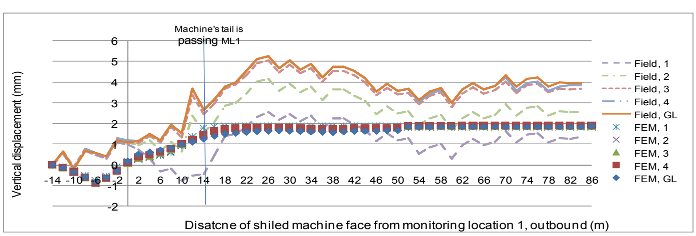

Figure 4. Comparison of vertical displacement of soil at monitoring location 1 outbound measured in field with output of Finite Element Analysis.

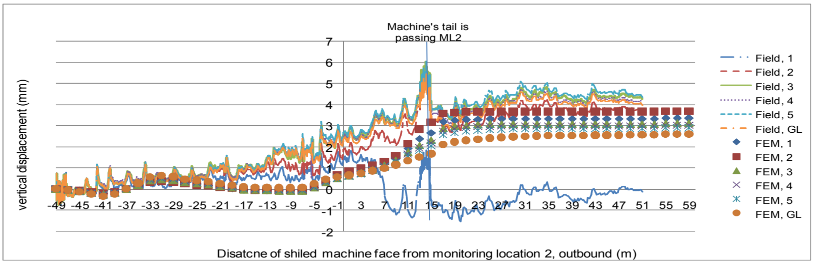

Figure 5. Comparison of vertical displacement of soil at monitoring location 2, outbound measured in field with output of Finite Element Analysis.

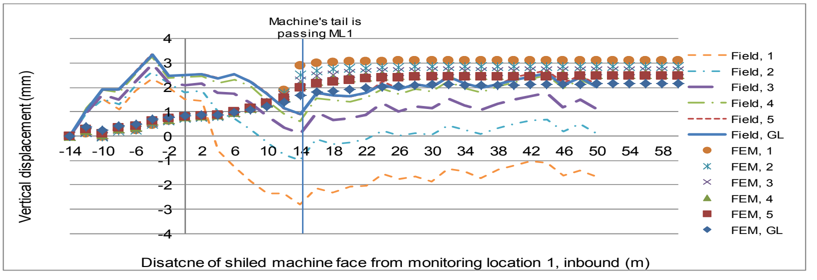

Figure 6. Comparison of vertical displacement of soil at monitoring location 1, inbound measured in field with output of Finite Element Analysis.

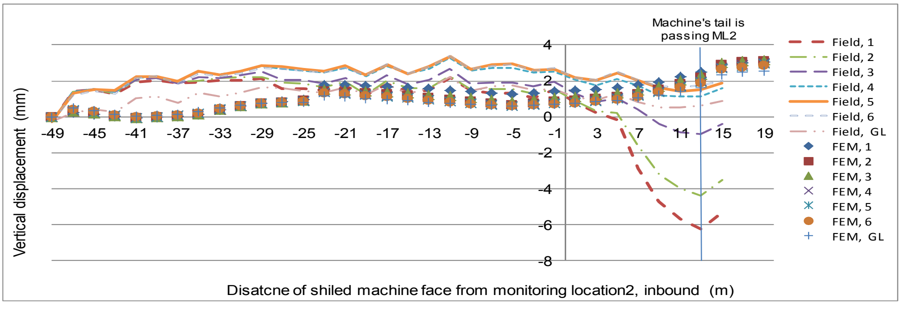

Figure 7. Comparison of vertical displacement of soil at monitoring location 2, inbound measured in field with output of Finite Element Analysis.

In both of field data and calculated results by FEA, graphs show a slight jump in two cases, one when machine face is approaching the ML, and the other one is the time when machine tail is passing monitoring section during applying tail void grouting.

According to the results of FEA in graphs of 4 to 7, first part of these graphs show a slight settlement. This happens because during the time when shield machine face distance from monitoring location is more than "*D*" value, undrained condition is used for soil deformation calculation. As in undrained condition, earth pressure is calculated by supposing total stress of soil; therefore, earth pressure value is becomes equal or slightly more than face pressure, and consequently difference between earth pressure and face pressure becomes negative which leads to soil settlement. However, final predicted heaves are in good harmony with measurement results.

5. CONCLUSION

New approach of 3D shield tunneling advancement was presented for soil displacement calculation. In this approach, shield machine face distance from monitoring locations is taken as a factor which affects way of calculating soil displacement. If shield machine face distance from monitoring location is become less than a specific distance say "D", drained condition is used to calculate soil deformation; on the other hand, if shield machine face distance from monitoring location becomes more than "D", undrained condition is used. In the case of undrained condition, total stress and in the case of drained condition, effective stress is used to calculate earth pressure. Comparing of FEA results using presented approach showed good harmony with field measurement. Because of the presented method's simplicity and its good accuracy, it is a useful tool for 3D soil deformation prediction. Additionally using this method, soil deformation due to the neighbor tunneling construction is also well-predicted.

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