

TUNNELING SIMULATION IN SOFT GROUND USING SHELL ELEMENTS AND GROUTING LAYER

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ABSTRACT: With the advancement of computer sciences and researches on tunneling simulation in the past, the 3D finite element analysis of tunnel excavation by Tunnel Boring Machines (TBMs) has been extensively used over the last decade. Due to that the complicated construction sequences and relevant loads can be taken into account, complex interaction problems can then be performed. Many simulation techniques have been proposed depending on the assumptions used in the modeling. For modeling the tunnel lining, solid elements are commonly used due to the ratio between the width and thickness of the lining is not large. In addition, most studies focused on the ground deformation, not the lining forces. In the circumstance that the lining forces are essentially observed, the structural elements that directly provide the values are preferred. Therefore, this research attempts to propose the shell elements as tunnel lining together with the grouting layer in the analysis. The analysis results from the proposed method and the conventional one are compared and discussed in terms of ground deformation and lining forces together with the field measurement data. The results reveal that the simulation by the proposed method is sufficient and can reasonably reproduce the soil and lining responses.

Keywords: 3D FEM, Tunnel boring machines, Tunnel lining, Shell element, Lining force

1. INTRODUCTION

The construction of tunnels in urban areas can induce ground movements, which have harmful effects on existing structures. To limit soil disturbance and resultant surface settlement, Tunnel Boring Machines (TBMs) combined with the earth pressure balance shield (EPBS) method are popularly employed in tunnel construction projects as shown in Fig. 1.

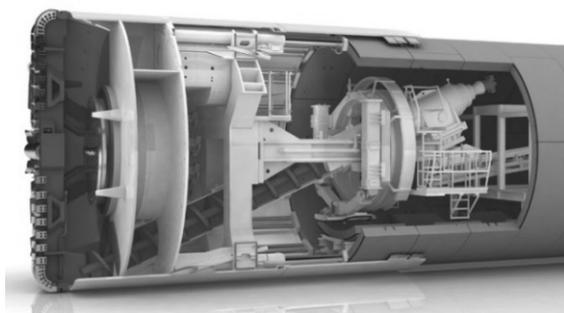


Fig.1 Schematic section of a Herrenknecht TBM-EPB machine (<http://www.herrenknecht.com>) [1]

Analyses on ground movement due to tunneling by TBM or induced structural forces in the lining are necessary during the design stage. Among various analysis methods, Finite Element Method (FEM) is one of the most widely used tool

for tunneling works. At the beginning, the simulations of tunneling using TBMs were analyzed in 2D finite element (FE) models [2]- [5]. In these models, the different stages of the TBMs advancement are considered by stress-relief method. The 3D FE models for TBMs tunneling were first applied in the early 1990s. Various simulation methods considering different factors and simplifications have been developed [6]- [10]. Among different factors considered in the analysis by each researcher, the shield element and the tail void grout process have not been considered yet. These two parameters were measured and emphasized by Abu-Krishna [11] and Swoboda and Abu-Krishna [12]. The complicated simulations of 3D EPBS tunneling models using several parameters e.g., face pressure, shield element or shield weight, tunnel lining element, tail void grout process, hydraulic jack, steering control, and backup trailer loads were gradually introduced [13], [14]. The 3D FE models using face pressure, shield element, tunnel lining element, and grouting process as the parameters are used in studies [15], [16]. As the studies mentioned above, only four main parameters (face pressure, shield element, grouting process and lining element) are generally used to model the 3D EPBS tunneling. Thus, these parameters are also used to simulate the 3D EPBS tunneling in the present work.

Various methods to model the grouting process have been proposed in the simulation of the excavation by EPBS in the past. For example, the method which uses a distributed pressure to represent the grouting process was introduced by Broere and Brinkgreve [17] and Plaxis [18]. In the grouting process in engineering practice, the grouting will change from the liquid state to solid. To realistically model this characteristic, solid elements having different stiffness are represented to simulate the grouting process [12], [15] and [19]. However, an actual behavior of initial grout is in a fluid state with no stiffness. In practice, it is then difficult to specify the modulus of grouting during liquid state. The pressure boundary may thus be more appropriate than the solid elements.

In simulation of ground movement due to tunneling, the solid elements or the brick elements are generally adopted to represent the tunnel lining [13], [14] and [17]. The lining which has a certain width and the actual excavated periphery of the soil can then properly be modeled. By using the solid elements, the structural forces (i.e., bending moment, normal force and shear force) cannot directly be obtained. In the circumstances that the structural forces are needed to be investigated, the modeling by the solid elements becomes inconvenient. In this situation, shell elements which offer the direct quantification of lining structural forces are preferable. The shell elements have been also used in the past researches, e.g., the influence of ground stratification on lining force and settlement due to tunneling [19], the effects of tunneling on adjacent building and existing tunnel respectively [15], [16] and [20]. However, using the shell elements to model the tunnel lining causes a problem due to that the shell elements have no thickness in the process of meshing. It is reasonable to model the shell element (as line on cross sectional plane) at the mid plane. Consequently, the treatment on the gap between the excavated soil periphery and mid plane during meshing is essential.

This study introduces the grouting layer as solid element in the gap to represent the solid-state grouting while using pressure boundary to represent the liquid-state grouting. The comparison of three tunneling simulation methods using 3D FE models are made and discussed. The first method follows one suggested in PLAXIS 3D 2013.1 manual [18]. The second method is similar to the first method but the solid elements as tunnel lining are replaced by the shell elements assuming the excavated boundary at the mid plane. In the last method which is proposed by the authors, the shell elements are used to represent the tunnel lining together with the adapted grouting process mentioned above. Moreover, the thickness of grouting layer is also varied to represent the effect

of pitching and yawing of the TBM during advancement. The results are discussed in terms of surface settlement profiles and the structural forces in tunnel lining.

2. SITE DESCRIPTION

The geotechnical conditions of the Mass Rapid Transit Authority (MRTA) Blue Line Project is used for modeling in this study. The geotechnical conditions along the MRTA project can be separated into the North Tunnel section and the South Tunnel section. The soil profile is very uniform with soft clay underlain by stiff clay along the tunnel alignment in the North section. In this section, tunneling with horizontal-twin tunnel is conducted mostly within the stiff clay layer. For the South section, most of the tunnel alignment is also located within a stiff clay layer [21]. The section CS-8B of the South section is chosen to simulate in this study as shown in Fig. 2.

Geological conditions can be described as follows. The uppermost first layer consists of weathered crust or fill material. The second layer is the very soft clay layer overlaying on the first stiff clay. A thin seam of clayey sand is found below the first stiff clay as the fourth layer. The second stiff clay is found below the upper sand. Tunnel with inner and outer diameter of 5.7 m and 6.3 m, respectively, is located into the stiff clay layers at the depth of about 19 m from ground surface. A typical pore water pressure profile in Bangkok is a piezometric drawdown as shown in Fig. 2. The pore water at the depth of about 20 m is almost zero and restored condition to hydrostatic pressure at the depth about lower than 20 m.

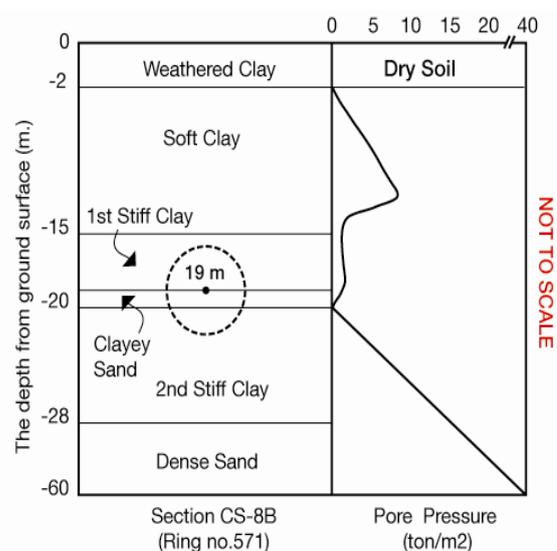


Fig. 2 Soil profile and pore pressure of case study in MRTA Blue Line Project

3. FINITE ELEMENT ANALYSIS

3.1 Numerical Model

The 3D FE mesh presenting the sample case of the proposed method (the final method) is depicted in Fig.3. The soil layers were discretized into the six-node bricks or the solid elements with a suitable aspect ratio. The simulation of tunnel components consisted of three layers, EPB shield layer, grouting layer and tunnel lining layer. The four-node shell elements were used to model the tunnel lining and EPB shield. The hardened grouting layer was simulated by the solid elements. Their information will be detailed in next section.

Previous study on three-dimensional analysis of TBM tunneling [22] indicated that a lateral distance of $4D_T$ from the tunnel axis and the advancement of $4D_T$ ahead and behind the tunnel excavation face are sufficient for 3D FE mesh of tunneling problem. Thus, the distance of $5D_T$ ahead and behind the monitoring section, and of $6D_T$ in lateral direction from the tunnel axis, are enough to fully simulate the tunneling problem in this study. The dimension of model is 80 m ($\approx 12.5D_T$) in the transverse direction, 60 m ($\approx 9.5D_T$) in the longitudinal and vertical directions. D_T is the outer diameter of a tunnel lining. At center of longitudinal direction is the monitoring section. The PLAXIS 3D 2013.1 software was implemented for mesh generation and analysis.

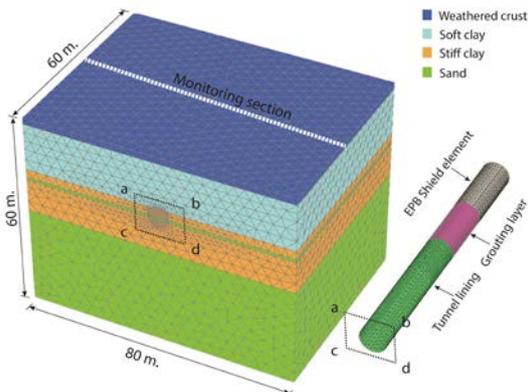


Fig. 3 The mesh in FE model (the proposed method)

3.2 Analysis Condition

The initial distribution of vertical effective stress and horizontal effective stress are controlled by the given soil unit weight, the coefficient of earth pressure at rest, K_0 , for all strata. The pore water pressure was generated in the whole geometry domain as piezometric drawdown. The undrained analysis was considered.

The displacement boundary was adopted in this

study. The sides of the mesh including the front side and rear side are restrained against lateral movements but free to move vertically. Therefore, no movement perpendicular to their side of meshes is allowed. The bottom of the mesh is fixed (no vertical and horizontal movements). These conditions were used for all finite element meshes throughout this study.

3.3 Earth Pressure Balance Shield (EPBS) Advancement and Simulation Procedures

The tunneling process of EPBS was simulated using a step-by-step approach. Each excavation step corresponded to an advancement of the tunnel face of 1.2 m which is equal to the width of the tunnel lining. A simplified geometry of EPBS as cylindrical shape is assumed in stead of modeling the original cone shape. The schematic of simulated process with EPBS was shown in Fig. 4. The simulation process can be described as follows.

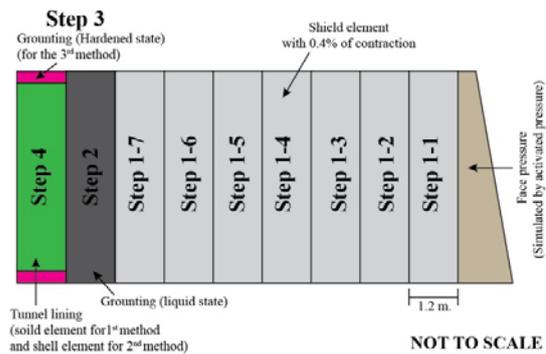


Fig. 4 The tunneling simulation process

Step 1, the soil elements in the targeted excavation zone were deactivated. When over cutting is not considered, the dimension in radial direction equals to the outer radius of lining (6.30/2 m in this study) for case of using solid elements and shell elements with grouting layer. This can be larger when the shield driving quality (over cutting and pitching-yawing) is taken into consideration. The support of excavation face was modeled by applying a pressure distribution with linear increase of pressure with depth. The face pressure in this study is about 150 to 200 kPa at crown and invert of tunnel, respectively [21]. The shell elements were activated to represent the EPB shield with contraction ratio of 0.4%, which was calibrated from the previous FE analysis of tunneling projects in Bangkok subsoil. These procedures were repeated until the advancement of shield was completed with seventh rings for the length of about 8.4 m in longitudinal direction. Step 2, the simulation of tail void grouting in a first phase, the grout has not yet fully hardened, the liquid state of grouting was simulated by

applying a radial pressure with 200 kPa [21] acting on soil around tunnel. The simulation of tunneling process in steps 1 and 2 follows ones recommended by manual of PLAXIS 2013.1 [18]. Step 3, the tail void grouting in a second phase is considered to be hardened, the grouting layer was simulated by the solid elements. Step 4, the shell or solid elements representing the tunnel lining were activated in the same grouting layer section. These steps, 3 and 4, are differed for the simulation by each method in this study. The details are described in next section.

3.4 Patterns of Simulation Method

Three simulation methods of EPBS tunneling with different modeling techniques are carried out in this study. The main differences are the techniques to simulate the tunnel lining and grouting layer section as schematically shown in Fig. 5.

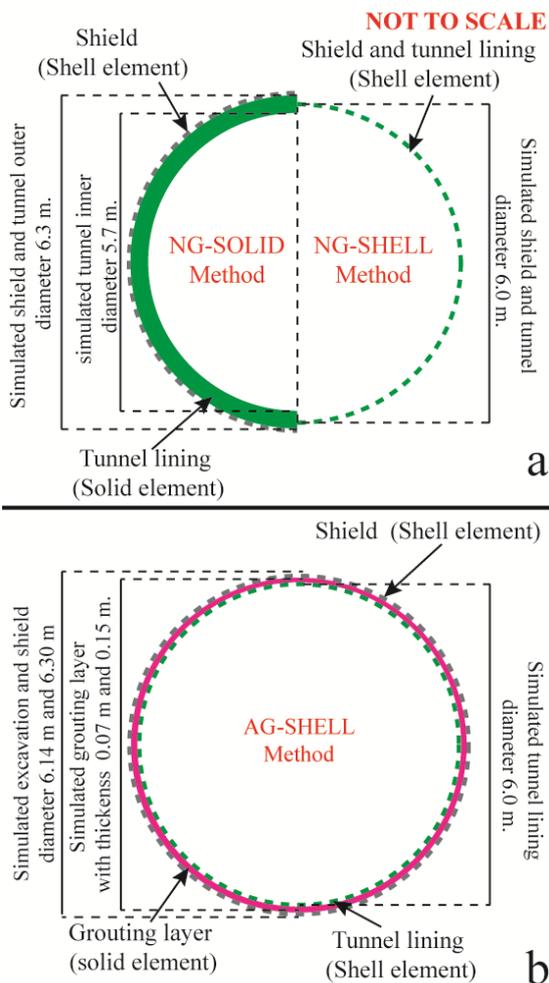


Fig. 5 The cross sections of simulation patterns

In the first method that is called “NG-SOLID method”, the tunnel linings are modeled by the

solid elements with thickness of 0.30 m. The step 3 of simulation procedures is not considered in this method. The second method, that is called “NG-SHELL method”, is similar to the first method. The shell elements are represented to simulate the tunnel lining and the geometry of simulation is thus different. The difference between using the solid or shell elements is that the geometry of thin shell element is modeled as zero-thick line at mid plane. Thus, the diameter of excavated soil periphery in this modeling is 6.0 m which is the same as shield diameter. The details of two simulation methods are depicted in Fig 5a.

For the method proposed in this study, the shell elements were used to represent the tunnel lining together with introduction of the grouting layer, that is called “AG-SHELL method”. The thicknesses of grouting layer considered in this study are 0.07 m and 0.15 m to represent ideal TBM driving and effect from over cutting together with pitching-and-yawing, respectively. The diameter of excavated soil periphery in each model is thus as 6.14 m and 6.30 m respectively. The grouting layer of 0.07 m which is equal to the thickness of EPBS in the case that the pitching angle of excavation process and over cutting of EPBS are not considered. In other words, the thickness of grouting layer is a theoretical tail-void gap. To take the effect of over cutting and pitching angle into consideration, grouting layer of 0.15 m, which is average value of tail void gap during shield excavation as reported by Babendererde [23], is chosen. The schematic cross section of AG-SHELL method is depicted in Fig. 5b.

3.5 Material Properties

Table 1 Soil parameters for modeling [24]

Soil layer	Wea. crust	Soft clay	Stiff clay	Sand
Material model	MC	Hardening Soils (HS) model		MC
$E' \text{ (kPa)}$	6,000	-	-	80,000
$E_{oed}^{ref} \text{ (kPa)}$	-	5,000	60,000	-
$E_{50}^{ref} \text{ (kPa)}$	-	5,000	60,000	-
$E_{ur}^{ref} \text{ (kPa)}$	-	15,000	180,000	-
$\gamma_{sat} \text{ (kN/m}^3\text{)}$	17	16	18	20
$\nu' \text{ (-)}$	0.32	0.33	0.33	0.3
$\phi' \text{ (}^\circ\text{)}$	22	22	22	36
$c \text{ (kPa)}$	8	5	18	0
$m \text{ (-)}$	-	1	1	-
$p_{ref} \text{ (kPa)}$	-	100	95	-

The properties of soils are determined from the MRTA projects [24]. The soil layers, stiff and soft clays, were assumed by hardening soil model (HS) [25]. The Mohr-Coulomb model (MC) was assumed to represent the weathered clay and sand layer. The soil properties in this study are calibrated from field testing data [26] and testing data of previous studies as shown in Table 1. Table 2 shows the properties of the components of EPBS tunneling simulation. The EPB shield, tunnel lining and grouting layer were assumed to be linear elastic. The properties of grouting layer at 28 days of curing are obtained from Kasper and Meschke [13] and Kasper and Meschke [14] while those of EPBS are acquired from Katebi et al. [19].

Table 2 Material properties of EPB shield, tunnel lining and grouting layer.

EPB Elements	Young modulus [E] (kN/m ²)	Poisson's ratio [ν] (-)	Unit weight [γ] (kN/m ³)
Tunnel lining	31 x 10 ⁶	0.20	24
EPB shield	21 x 10 ⁷	0.28	78
Grouting layer	1 x 10 ⁶	0.30	21

4. ANALYSIS RESULT

The results in terms of surface settlement and lining forces from the three simulation methods are compared and discussed together with the measurement data if available. The observations of FE analysis results are carried out after the process of tunneling simulation is completed.

4.1 Surface Settlement

Figure 6 shows the surface settlement profiles compared between FE analyses and MRTA monitoring data in section CS-8B. The surface settlement profiles analyzed by FEM are similar in shape but quantitatively different. The surface settlement profile of the NG-SOLID method is noticeably deeper than that obtained from the NG-SHELL method. It is clear that the selection of simulation method significantly affects the nature of the computed surface settlements. The difference of the surface settlement profiles may be presumed to be associated with properties of the elements or the excavated cavity of tunneling.

Although the excavated cavity of NG-SOLID is larger than that of the AG-SHELL method with grouting thickness of 0.07m (the AG_{0.07}-SHELL method), the surface settlement profile of the AG_{0.07}-SHELL method is close to that of the NG-SOLID and the MRTA monitoring data. Moreover, when increasing the grouting thickness to 0.15m

(the AG_{0.15}-SHELL method), the surface settlement becomes larger than that of the NG-SOLID. This implies that the quality of TBM shield control during excavation (due to over cutting and pitching-and-yawing of TBM) can be reflected by varying the thickness of the grouting layer.

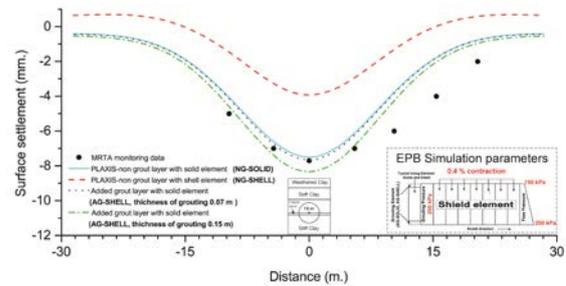


Fig. 6 Comparing transverse settlement profile from MRTA section CS-8B with FEM analyses

4.2 Lining Forces

The comparison of the computed structural forces in the tunnel lining for three simulation methods is presented hereafter. The structural forces are plotted from the reference lining ring located at the mid-section of the model.

4.2.1 Bending moment

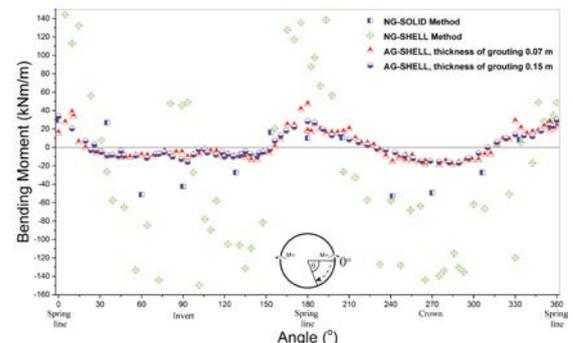


Fig. 7 The computed bending moment in linings for three different methods

Figure 7 shows the computed bending moments resulted by the three simulation methods. From this figure, the significant differences of the computed bending moments are revealed. Especially, the distribution of the computed bending moments by the NG-SHELL method is drastically different with those by the others. The computed bending moment of tunneling simulation located in soft clay ($K_0 < 1.0$) is positive values at the spring line and negative values at crown and invert. This behavior is obtained by NG-SOLID and AG-SHELL methods. Although the trends of the computed bending moments for NG-SOLID

and AG-SHELL methods are similar, the magnitudes are different. However, the ranges of magnitude of computed bending moment obtained from the NG-SOLID and AG-SHELL methods are close to those reported in the previous studies [27], [28]. For the AG-SHELL method, although the excavated cavity of the AG_{0.15}-SHELL method is larger than the AG_{0.07}-SHELL method, their computed bending moments are close.

4.2.2 Axial force

Figure 8 depicts the computed axial forces resulted by three simulation methods. The tendency of the computed axial forces is similar to the computed bending moments. The computed axial forces of the NG-SOLID method and both of AG-SHELL methods are in the same range. This range agrees well with the previous researches [27], [28], which should be in the range of 0 to 1000 kN/m. In contrast, the distribution of the computed axial forces by the NG-SHELL method becomes differed and the magnitudes are much higher.

For the AG-SHELL methods, although the excavated cavity of AG_{0.15}-SHELL method is larger than AG_{0.07}-SHELL method, their computed bending moments and axial forces are close. This indicates that the grouting layer with greater thickness can absorb more stress transmitted from the soil. Consequently, the induced structural forces become smaller.

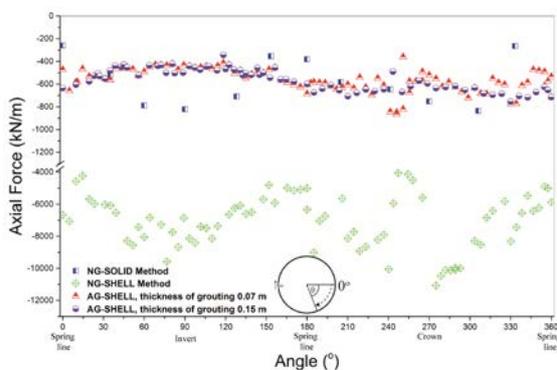


Fig. 8 The computed axial force in linings for three different methods

5. DISCUSSION

The above described results of using the shell elements alone to model the tunnel lining in tunneling simulation cannot provide satisfaction in terms of both the surface settlement and the structural forces. This drawback can be solved by introduction of grouting layer proposed in this study. Although the simulated thickness of grouting layer obtained from real construction may provide more accurate results, the ideal thickness of grouting layer which is equal to the thickness of TBM can be satisfactorily used in the simulation.

6. CONCLUSION

In this study, the modeling of tunnel lining with the shell elements together with the grouting layer in tunneling analysis by TBM in soft ground was proposed. The grouting is modeled as pressure boundary and solid elements in liquid and solid states, respectively. By the proposed method, grouting process and actual excavated boundary of the soil can then be realistically modeled. Analysis of tunnel excavation using the proposed method in conjunction to 4 main factors (face pressure, shield element, grouting process and lining element), provides good agreement with results from the conventional method and field measurement data. Besides, the structural forces obtained from the current method are in ranges of history records.

7. ACKNOWLEDGEMENT

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