Analysis Of Ground Movements Induced By Mrt Construction: A Case Study Of Bangkok Mrt Blue Line Project

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ANALYSIS OF GROUND MOVEMENTS INDUCED BY MRT CONSTRUCTION: A CASE STUDY OF BANGKOK MRT BLUE LINE PROJECT

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Bangkok metropolitan located on thick river soft clay deposit has recently construction project on mass rapid transit underground railway (MRT). This paper presents a simplified two-dimensional finite element studies on deep excavation and tunnelling in soft ground. The Finite Element Code PLAXIS is selected as a numerical tool and the Bangkok MRT underground construction project is chosen as a case study. This study will focus on the effects of mesh generation, initial input of ground condition and the constitutive soil models. The geotechnical conditions were carried out based on soil investigation report. The parameters of constitutive models were determined and calibrated against the laboratory testing results. Finally, all finite element analysis results are compared with the real field investigations.

Keywords: Excavation, Tunnelling, Finite element method, MRT, Bangkok clay.

1. INTRODUCTION

Tunnelling and underground construction in soft ground are usually associated with substantial difficulties. Since this type of soils are sensitive to deformations and possesses small shear strength, they may lead to structural damages during the constriction as well as throughout the life of the projects. It is well-known that Bangkok metropolitan is located on a thick soft to very soft clay layer on the top deposit. There have been several construction projects to improve the quality of infrastructures in the past fifty years. One of the most recent important construction projects in Bangkok is the Mass Rapid Transit (MRT) underground railway. This project involves significant geotechnical works especially foundations and excavations. Presently, some commercial finite element codes especially written for geotechnical problem have become increasingly popular and powerful analytical tool. Various constitutive soil models, from simple elastic model to mathematically complex

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non-linear elasto-plastic models have been developed to explain the strength and deformation behaviour of soft soils. However, there is still problem in prediction of movements in and around an excavation with the numerical method. The results of numerical analysis may be influenced by many factors such as simplified geometry and boundary conditions, mesh generation, initial input of ground conditions and significantly the constitutive relationship chosen to model the behaviour of soils.

This paper aims to present a simplified two-dimensional finite element studies on underground excavation and tunnelling in soft clays. The Finite Element Code PLAXIS is selected as a numerical tool and the Bangkok MRT underground construction project is chosen as a case study. This study will focus on the effects of mesh generation, initial input of ground condition as well as the constitutive soil models. Finally, all finite element analysis results are compared with the real field investigations.

1.1. *Bangkok MRT Project*

The first phase of the Bangkok Mass Rapid Transit (MRT) Underground Railway named the Chaloem Ratchamongkhon (or Blue Line) was operated in 2004. It comprises approximately 20 km of tunnels, constructed using tunnel boring machines (TBM). The project was constructed along highly congested roads in the heart of Bangkok city. The tunnel alignment, which is 22 km in length, included 18 underground cut-and-cover underground stations. The typical underground stations are up to 230 m long and approximately 25 m wide, and are excavated up to a depth of 25 m to 30 m below the ground surface. The station perimeter was constructed of diaphragm walls, 1.0–1.2 m thick and up to 30–35 m deep. The tunnel lining is of twin bored single-track tunnels. Each tube has an outer diameter of 6.3 m, with an inner diameter of 5.7 m of concrete segmental lining. A total of 18 underground stations were constructed using the Top-Down construction technique, together with diaphragm walls and concrete slabs as excavation supports. A total tunnel length of 20 km was constructed using eight Earth Pressure Balance (EPB) shields. More detail on the construction methods for tunnelling and underground stations of the existing MRT Blue Line project can be found in Suwansawat (2002).

1.2. *Geological Condition of Bangkok Subsoils*

The Bangkok subsoil forms a part of the larger Chao Phraya Plain and consists of a broad basin filled with sedimentary soil deposits. These deposits form alternate layers of sand and clay. Field exploration and laboratory tests from both the MRT Blue Line project show that the subsoils, down to a maximum drilling depth of approximately 60 to 65 m, can be roughly divided into: (1) Made ground (MG), (2) Bangkok Soft Clay (BSC), (3) Medium Clay (MC), (4) First Stiff Clay (1^{st}SC), (5) Clayey Sand (CS), (6) Second Stiff Clay (2ndSC) and then following by (7) Hard Clay (HC) see Figures 1–3. The aquifer system beneath the city area is very complex and the deep well pumping from the aquifers, over the last fifty

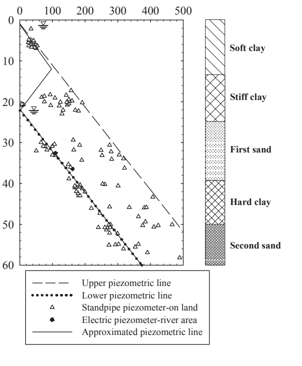

Figure 1. Typical soil profile and piezometric pressure in Bangkok subsoils.

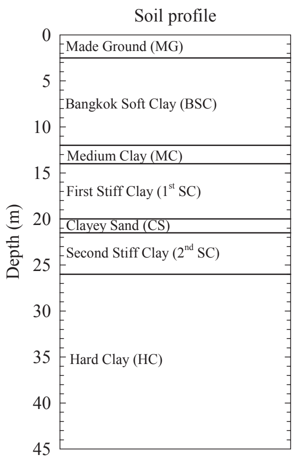

Figure 2. Soil profile at the Sukhumvit station.

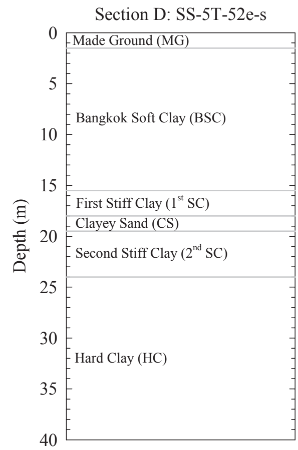

Figure 3. Soil profile of Khlong Toei to Queen Sirikit section.

years, has caused substantial piezometric drawdown in the upper soft and highly compressible clay layer as presented in Figure 1.

2. CONSTITUTIVE MODELLING AND SOIL PARAMETERS FOR BANGKOK SUBSOILS

The numerical studies of deep excavation and tunnelling in Bangkok subsoil are often conducted using finite element software with the Mohr-Coulomb model. Many researchers (e.g., Teparaksa, *et al.*, 1999; Phienwej & Gan, 2003; Phienwej, 2008) concentrated their work on back calculating the ratio of undrained elastic modulus and undrained shear strength (E_u/s_u). This study has extended the previous research incorporated with the advanced soil model to simulate the ground response due to the MRT construction in Bangkok subsoil.

2.1. *Hardening Soil Model*

The Hardening Soil model (HSM) has developed under the framework of the theory of plasticity. The total strains are calculated using a stress-dependent stiffness, in which the stiffness is different in loading and unloading/reloading parts. The strain hardening is assumed to be isotropic, depending on the plastic shear and volumetric strains. A non-associated flow rule is adopted when related to frictional hardening and an associated flow rule is assumed for the cap hardening. Schanz *et al.* (1999) explained in detail the formulation and verification of the HSM.

2.2. *Calibrations of Soil Parameters*

The stiffness and strength parameters for the HSM of soft and stiff Bangkok clays have been numerically studied using PLAXIS finite element software (Surarak, 2010). The numerical study was based on a comprehensive set of experimental data on Bangkok subsoils from

Table 1. Parameters for Hardening Soil Model (HSM) analysis.

Layer	Soil type	γ_b (kN/m^3)	c′ (kpa)	ϕ' (°)	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	v_{ur}	m	$K_{\circ}^{nc}$	R_f	Analysis Type
1	MG	18	1	25	45.6	45.6	136.8	0.2	1	0.58	0.9	Drained
2	BSC	16.5	1	23	0.8	0.85	8.0	0.2	1	0.7	0.9	Undrained
3	MC	17.5	10	25	1.65	1.65	5.4	0.2	1	0.6	0.9	Undrained
4	1stSC	19.5	25	26	8.5	9.0	30.0	0.2	1	0.5	0.9	Undrained
5	CS	19	1	27	38.0	38.0	115.0	0.2	0.5	0.55	0.9	Drained
6	2ndSC	20	25	26	8.5	9.0	30.0	0.2	1	0.5	0.9	Undrained
7	HC	20	40	24	30.0	30.0	120.0	0.2	1	0.5	0.9	Undrained

oedometer and triaxial tests carried out at Asian Institute of Technology. The HSM parameters determined are the Mohr-Coulomb effective stress strength parameters together with the stiffness parameters; tangent stiffness for primary oedometer loading, secant stiffness in undrained and drained triaxial tests, unloading/reloading stiffness and the power for stress level dependency of stiffness. The total input parameters required in the HSM for all soil layers are presented in Table 1. This can be seen more detail in Surarak, *et al*. (2012).

3. MODELLING OF BANGKOK MRT UNDERGROUND STATION

The 2D plane strain finite analysis approach, using Plaxis v.9 software, was adopted in this study. The Sukhumvit station located underneath Asok Road, next to the Sukhumvit – Asok intersection was selected in this study. The geometry of the Sukhumvit station is illustrated in Figure 4. As the ratio of the length (L) to width (B) of Sukhumvit Station box was high ($L/B = 8.7$), the 3D effect along the long sides of the station was small, thus the 2D plane strain approach was considered appropriate. Only the right half of the station box was modelled because the station configuration was symmetric. A seven-layer soil profile as shown in Figure 2 was adopted. Importantly, the Hardening Soil Model (HSM) was used to evaluate their performances in deep excavation modelling. All soil layers were modelled

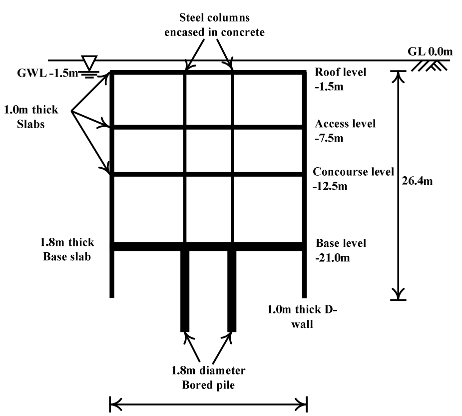

Figure 4. Geometry of Sukhumvit station.

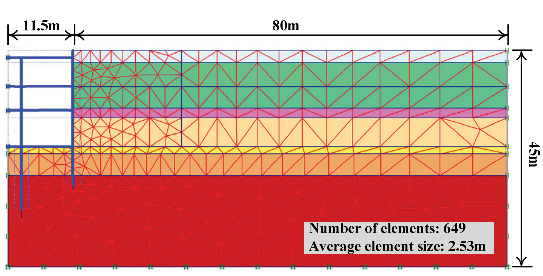

Figure 5. Finite element modelling of MRT station.

Table 2. Input parameters for structure components.

Parameters	Diaphragm wall (1 m thick)	Platform slab (1 m thick)	Base slab (1.8 m thick)	Column (0.8 m dia. @ 11.4 spacing)	Pile (0.8 m dia. @ 11.4 m spacing)
Axial stiffness, EA (MN/m)	28000	28000	50400	1712	3852
Flexural rigidity, EI (MN/m^2/m)	2333	2333	13608	91.3	1040
Weight, w (kN/m^2)	16.5	25	45	25	25
Poisson ratio, v'	0.15	0.15	0.15	0.15	0.15

using the 15-noded triangular elements. For the structural components (i.e., diaphragm wall, platform and base slab, column and pile), the non-volume plate elements were used. The stiffness of the concrete was reduced by 20% to take into account the possibility of cracking. Table 2 presents the input parameters for the structural components. The finite element models and their mesh generation are shown in Figure 5. The model has an average element size of 2.53 m and a total element number of 649. The drawdown pore water pressure (Figure 1) was adopted for the studied model.

3.1. *Finite Element Analysis Results and Discussions*

The strength and stiffness parameters from the study by Surarak *et al.* (2012) were used as inputs for the HSM analysis. The input parameters listed in Table 1 are the results of the parametric studies and the undrained triaxial test series back-calculations. More specifically, the following procedure is adopted.

(a) The E_{50}^{ref} used in the analyses of drained materials (MG and CS) is estimated from SPT N values of adjacent boreholes. The ratios of $E_{oed}^{ref} = E_{50}^{ref}$ and $E_{ur}^{ref} = 3\ E_{50}^{ref}$ were suggested by Brinkgreve (2002).
(b) For BSC, MC, 1st SC, 2nd SC and HC, the procedure of triaxial and oedometer modelling are adopted. The triaxial and oedometer tests results from the samples taken from adjacent boreholes were used in stiffness moduli back-calculation.
(c) The parameters v_{ur}, m and R_f were kept as 0.2, 1 and 0.9, respectively. These values were suggested in Surarak *et al*. (2012).

Figure 6 compares the measured lateral wall movement and the ground surface settlement with those predicted by the HSM. The predicted lateral wall movements at all excavation stages within the BSC layer (2.5 to 12 m depth) were slightly higher than the field measurements. This overestimation extends further into the deeper layers for the excavation stages 1 to 3. The maximum lateral movement in the last excavation stage (located in 1st and 2nd SC layers) agrees well with the measured values. In the case of the ground surface settlement comparison, the HSM predicted better settlement envelopes compared to those predicted by the MCM and SSM. However, the settlements within the influence zone were still slightly larger than the predictions using the Hsieh & Ou (1998) method.

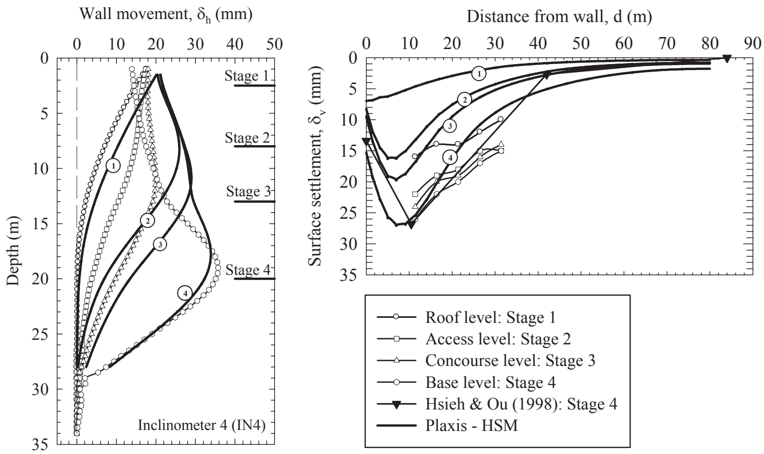

Figure 6. Measured and predicted lateral wall movement and surface settlement from HSM analysis.

4. MODELLING OF BANGKOK MRT TUNNEL

The 2D finite element method with the contraction method was used to model the shield tunnelling of the Bangkok MRT Blue Line project. A section from Khlong Toei to Queen Sirikit section, selected for the case study, was twin tunnels with a side-by-side pattern. The twin tunnels of this section are located partially in the stiff clay and partially in the hard clay layers. A high face pressure of 170 kN/m^2 was applied to both the SB and NB tunnels, along with a penetration rate of 25 mm/min, a high grout pressure of 250 to 400 kN/m^2, and a high percentage of grout filling of 150%. The maximum surface settlement after both shields had passed was about 25 mm. The soil profile is illustrated in Figure 3.

The soil constitutive model adopted herein was the Hardening Soil Model (HSM). The input parameters of the HSM finite element analysis study as presented in Table 1 were retained. The tunnel lining was modelled using the plate element with $EA = 8000$ MN/m and $EI = 56$ MNm^2/m. Figure 7 depicts the finite element mesh generation of the section. The number of elements is 1670 with an average element size of 1.55 m. The drawdown pore water pressure as shown in Figure 1 was adopted for this model.

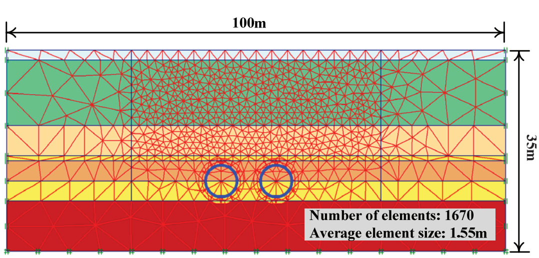

Figure 7. Finite element modelling of Twin tunnel at the Khlong Toei to Queen Sirikit section.

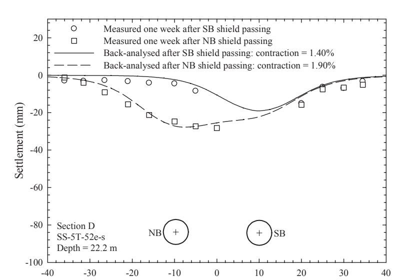

Figure 8. Finite element analysis results from contraction method back-analysis.

Table 3. Volume loss from superposition technique and FEM back-analysis.

Section	V_L(%) from superposition technique		Contraction (%) from FEM back-analysis		i (m)		$\delta_{v,\max}$(mm)	
	SB	NB	SB	NB	SB	NB	SB	NB
Khlong Toei to Queen Sirikit section	1.69	1.99	1.40	1.90	13	13	17.0	20.0

5. RESULTS AND DISCUSSIONS FROM THE CONTRACTION METHOD

The contraction method was used in the first set of the analysis. The calculation steps involved the two-phase calculation (see Vermeer & Brinkgreve, 1993). The values of prescribed contraction ratio were chosen so that the predicted maximum settlement matched with the measured one. The results of the contraction method back-analysis are highlighted in Figure 8. In general, the soil profiles, estimated from the contraction method along with the Hardening Soil Model, agree well with the measured profiles. The back-calculated percentage of the contraction for each tunnel is also shown in Figure 8, and listed in Table 3. The percentage of the contraction required to match the measured settlement profiles range from the values of 1.4 to 1.9. As one would expect, the larger percentage of the contraction was needed in the case of the higher maximum surface settlement.

Another comparison was made between the back-analysed percentage of volume loss (V_L) and the percentage of the contraction. By using the Gaussian curve (Peck, 1969) to match the measured settlement, the trough width parameter (i) and the maximum surface settlement ($\delta_{v,\max}$) were obtained. For the second tunnel in the side-by-side pattern, the superposition technique (Suwansawat & Einstein, 2007) was used for i and $\delta_{v,\max}$ estimation. The back-analysed i and $\delta_{v,\max}$ are also listed in Table 3. The percentage of the volume loss, listed in Table 3, was calculated. The back-analysed percentage of the volume loss and contraction are in good agreement. However, in the finite element calculations, the material of all the dominant clay layers was set as undrained. This means that the area enclosed by the computed surface settlement profiles and the contracted area of the tunnel lining are the same (i.e., no volume loss). Thus, the percentage of the volume loss and the contraction are comparable.

6. CONCLUSIONS

The results from the analytical and numerical studies on ground movements associated with the MRT underground and tunnel excavations are presented in this paper. The finite element analysis result employed the Hardening Soil Model with soil parameters interpreted from laboratory and in-situ tests (Surarak, *et al.*, 2012), provided good agreement with lateral wall movement and surface settlement field observations in both cases. As a consequence of this study, it can be stated that the numerical method could necessarily give a good prediction of ground movements if the relevant parameters are selected. In the case of the finite element method, a suitable simulation process should also be adopted in the analysis.

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