Long-term behaviour prediction of the Bangkok MRT tunnels using simplified finite-element modelling

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ABSTRACT

The existing Bangkok MRT Blue Line has been operating almost 10 years and its extension is now under construction. It is the first highlight underground construction project in Bangkok involving many excavations and tunnelling works. The long-term tunnel behaviour is identified by many influential factors such as the magnitude and distribution of excess pore pressure generated during construction, compressibility and permeability of soil as well as relative soil-lining permeability. This paper focuses on the long-term behaviour of the underground tunnels based on the finite element analysis. The work deals with the deformation analyses of the Bangkok MRT tunnels. The soil constitutive models adopted herein were the hardening soil model for soft and stiff clays and the Mohr-Coulomb for sand. The parameters selected were calibrated against the laboratory testing results. The short-term analysis results were calibrated and compared with the field measuring data during the construction phase. For long-term analysis, a coupled consolidation analysis based on Biot's theory was adopted. The long-term behaviours of the Bangkok MRT tunnels from the finite-element simulation were reported.

Keywords: consolidation, finite-element modelling, settlement, tunnels

1 INTRODUCTION

Tunnelling and underground construction in soft ground are usually associated with difficulties of low shear strength of soil. It may lead to structural damages during the construction as well as throughout the life of the structures. It is well-known that the Bangkok metropolitan area is located on a thick soft to very soft clay layer on the top deposit. One of the most recent important infrastructure improvement projects in Bangkok is a construction of the Mass Rapid Transit (MRT) underground railway. Now, the MRT tunnels have been used for almost 10 years. Therefore, it may need to think of intermediate and long term maintenances or rehabilitation.

Finite Element Method (FEM) has become increasingly popular and powerful analytical tool to model the construction works. Various finite element modelling methods from simple 2D linear elastic to complex 3D non-linear elasto-plastic analyses have been developed to explain the behaviour of tunnels in soft grounds. However, there is still a problem with prediction of ground response induced by tunnelling with the use of FEM. 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 constitutive relationships chosen to model the behaviour of soils. A series of numerical studies on building response to tunnelling for London underground construction projects have been carried out by two research groups at Imperial College (Addenbrooke et al., 1997, Addenbrooke and Potts, 2001 and Potts, 2003) and at Cambridge University (Burland, et al., 2001, Wongsaroj et al., 2006 and Mair, 2008). The studies have mainly focused on using in-house development of FEM codes with advanced constitutive models for predicting the tunnelling-induced ground movements including long-term behaviour.

This paper presents a long-term behaviour prediction of tunnels using simplified finite element method based on the Blue Line Bangkok MRT project. This paper aims to continue finite element analysis of tunnelling in soft Bangkok Clay based on the previous studies of Likitlersuang et al. (2014). The finite element code PLAXIS is selected as a numerical tool and the Bangkok MRT tunnel construction is chosen as a case study. This study focuses on the use of modified grout pressure method to back-analyse ground settlement due to tunnelling works. All the back-analysis results are compared with the monitoring data during construction in order to assess the validity of the finite-element models. For long-term analysis, a coupled consolidation

analysis based on Biot's theory was adopted. Finally, the long-term behaviours of the Bangkok MRT tunnels from the finite-element simulation were reported.

2 SIMPLIFIED FINITE ELEMENT METHOD FOR SHIELD TUNNELLING

Simplified the tunnel excavation techniques involve 3D phenomena. Simulating tunnel excavation in the 2D plane-strain finite element analysis requires a number of assumptions to govern the missing dimension. Three well-known simplified methods of the 2D finite element analysis are contraction, stress reduction and modified grout methods. All three methods provided a sensible degree of matching for the predicted surface settlement profiles. However, all three methods have their limitations in geotechnical practice. For instance, the contraction method provides unrealistic shape of structure forces in the tunnel lining. The results cannot be used for structural lining design. The calculated pore water pressure from the stress reduction method is misread. Thus, it is not suitable for long term analysis. In modified grout pressure method, the shield loss component is ignored. It should be restricted to limited tunnelling cases.

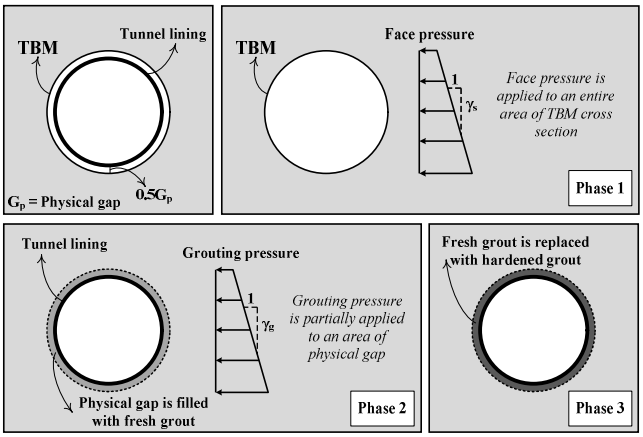


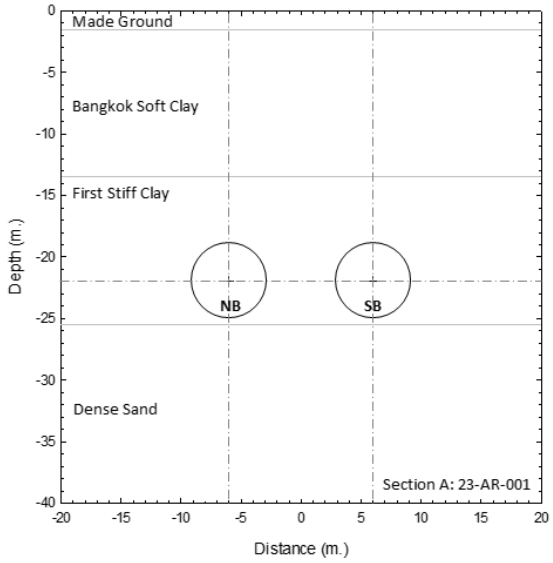
Fig. 1. Calculation phases in modified grout pressure method (After Likitlersuang et al., 2014)

In this study, the modified grout method is selected. This method used three calculation phases (see Fig. 1). In the first phase, the soil cluster inside the Tunnel Boring Machine (TBM) was deactivated. Simultaneously, the face pressure was applied to an entire area of the TBM cross section. This pressure represents the slurry pressure inside the TBM chamber, which increases linearly with depth at a gradient equal to the unit weight of the slurry (γ_s). The tunnel lining, as modelled by the plate element, was activated in the second calculation phase. The area surrounding the tunnel lining representing the physical gap was then filled with fresh grout, and the grout pressure was applied to the physical gap area. The grout pressure was selected in accordance with the applied grout pressure at the tail of the TBM. The unit weight of grout (γ_g) can be used as a gradient of the grout pressure along the depth. Importantly, the continuum element was used to model the grout material. Further, the cluster inside tunnel lining was set as a dry cluster. In the last phase, the grout pressure was removed, with the physical gap area being replaced by the hardened grout material. More details can be found in Likitlersuang et al. (2014).

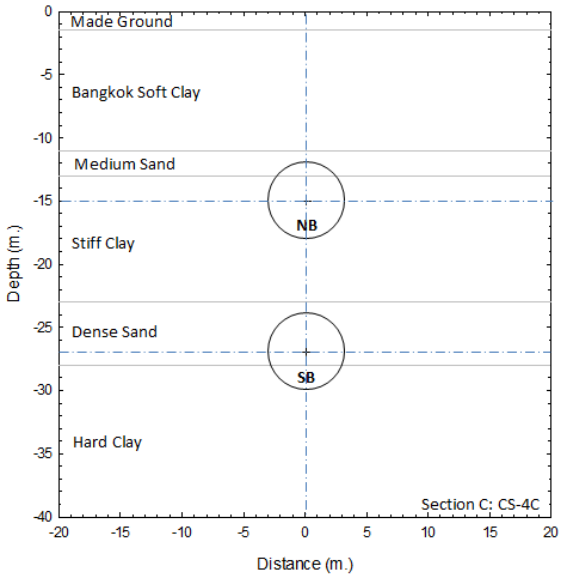
3 FINITE ELEMENT MODELLING

3.1 Studied sections

Two different sections of twin tunnels, as presented in Fig. 2, were selected for the case studies. Section A:23-AR-001 (Fig. 2(a)) is a side-by-side pattern, but section C:CS-4C (Fig. 2(b)) is a top-bottom pattern.



(a) Section A:23-AR-001 (side-by-side pattern)



(b) Section C:CS-4C (top-bottom pattern)

Fig. 2. Soil profiles of two sections analysed in the current study

The typical Bangkok subsoil consists of alternate layers of sand and clay. Field exploration and laboratory tests from the project show that the subsoils,

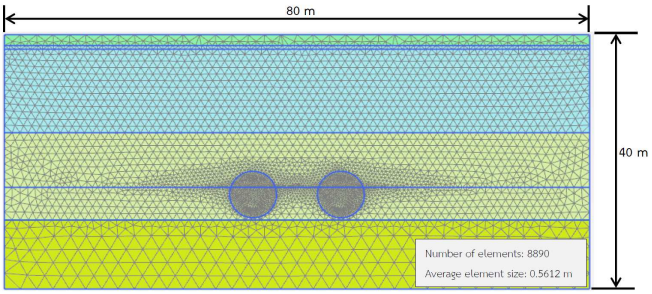
down to a maximum drilling depth of approximately 60 to 65 m, can be roughly divided into Made Ground (MG), Bangkok Soft Clay (BSC) to Medium Clay (MC), First Stiff Clay (1stSC), First Dense Clayed Sand (CS), Second Very Stiff Clay (2ndSC) to Hard Clay (HC), Second Dense Sand and then following by Hard Clay. The soil profiles of both sections, as adopted in finite element analysis, are illustrated in Fig. 2. A brief summary of the shield tunnelling parameters and the subsoil conditions encountered during the project is given in Table 1. More details of the shield tunnelling of the Bangkok MRT Blue Line can be found in Suwansawat (2002).

Table 1. Summary of shield tunnelling parameters and subsoil conditions

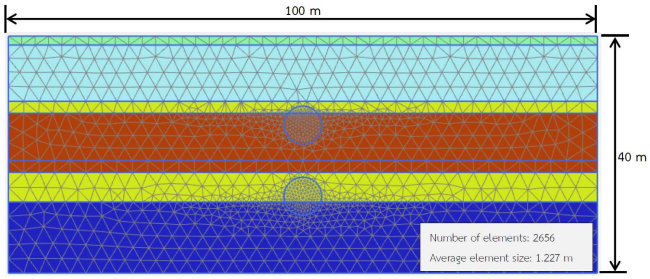
Parameters	Section A:23-AR-001		Section C:CS-4C	
	SB	NB	SB	NB
Face pressure, p_f (kN/m^2)	40-80	40-80	100-170	200-210
Grout pressure, p_g (kN/m^2)	120	120	400-450	380
Penetration rate (mm/min)	30-60	30-60	30-60	60-70
Percentage of grout filling (%)	120	120	150	150
Subsoils condition encountered	Stiff clay		Dense sand, Hard clay	Medium sand, Stiff clay

3.2 Finite element model

Figure 3(a) and (b) depicts finite element mesh generation of Section A:23-AR-001 and C:CS-4C, respectively. The lateral movements were restricted on the left and right boundaries, and both the lateral and vertical movements were restricted on the bottom boundary. The geometry of the model mesh generation was selected so that the conditions were satisfied. The geometry of the model mesh generation was selected so that the conditions were satisfied. For the finite element model shown in Fig. 3, the number of elements are 8890 with the average size of 0.5 m and 2656 with the average size of 1.2 m for Section A:23-AR-001 and C:CS-4C, respectively. The finer mesh size was created in the area between twin tunnels, which extends at least two times the tunnel's diameter from both sides of the tunnel invert.



(a) Section A:23-AR-001



(b) Section C:CS-4C

Fig. 3. Finite element model and mesh generation

3.3 Input parameters

The soil constitutive model adopted herein was the Hardening Soil Model (HSM) (Schanz et al., 1999). The HSM was 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 for the frictional hardening and an associated flow rule is assumed for the cap hardening. A total of 10 input parameters are required in the HSM, as tabulated in Table 2. Schanz *et al.* (1999) explained in detail the formulation and verification of the HSM and its parameters determination.

Table 2. List of hardening soil model parameters

Parameter	Description
ϕ'	Internal friction angle
c'	Cohesion
R_f	Failure ratio
ψ	Dilatancy angle
E_{50}^{ref}	Reference secant stiffness from triaxial test
E_{oed}^{ref}	Reference tangent stiffness from oedometer test
E_{ur}^{ref}	Reference unloading/reloading stiffness
m	Exponential power for stiffness
ν_{ur}	Unloading/reloading Poisson's ratio
K_0^{nc}	Coefficient of earth pressure at rest (NC state)

The strength and stiffness parameters used in this study were calibrated against the laboratory results from drain triaxial and oedometer tests (Surarak et al., 2012). Table 3 presents the parameters from the HSM analysis for the MG, BSC, MC, 1stSC, CS, 2ndSC and HC layers. All soil layers are assumed to have no dilatancy ($\psi = 0^o$). More detail of the parametric studies for Bangkok clays along the Bangkok MRT Blue Line can be found in Surarak et al. (2012) and Likitlersuang et al. (2013a, 2013b). In addition, the influences of soil parameter variation on the finite element analysis of a deep excavation in Bangkok subsoils were previously studied by Likitlersuang et al. (2013a).

The tunnel lining was modelled using the plate element with EA = 8000 MN/m and EI = 56 MNm^2/m.

For the modified grout pressure method, the grout material, which fills the physical gap, was modelled by a linear elastic continuum element. The elastic modulus of the grout was assumed as 7.5 and 15 MN/m^2 for the fresh and hardened grouts, respectively. The drawdown pore water pressure was adopted for all the studied models.

Table 3. Input soil parameters for hardening soil model (HSM)

Soil type*	γ_b (kN/m^3)	c' (kPa)	ϕ' (^{o})	ψ (^{o})	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)
MG	18	1	25	0	45.6	45.6	136.8
BSC	16.5	1	23	0	0.8	0.85	8.0
MC	17.5	10	25	0	1.65	1.65	5.4
1stSC	19.5	25	26	0	8.5	9.0	30.0
CS	19	1	27	0	38.0	38.0	115.0
2ndSC	20	25	26	0	8.5	9.0	30.0
HC	20	40	24	0	30.0	30.0	120.0

Table 3. (continue)

Soil type*	ν_{ur}	m	K_o^{nc}	R_f	k_x (m/day)	k_y (m/day)
MG	0.2	1	0.58	0.9	8.64x10^{-2}	4.32x10^{-2}
BSC	0.2	1	0.7	0.9	4.32x10^{-4}	6.85x10^{-6}
MC	0.2	1	0.6	0.9	8.64x10^{-4}	2.05x10^{-6}
1stSC	0.2	1	0.5	0.9	8.64x10^{-4}	1.92x10^{-6}
CS	0.2	0.5	0.55	0.9	8.64x10^{-4}	1.92x10^{-6}
2ndSC	0.2	1	0.5	0.9	8.64x10^{-3}	9.59x10^{-7}
HC	0.2	1	0.5	0.9	1.73x10^{-4}	1.92x10^{-6}

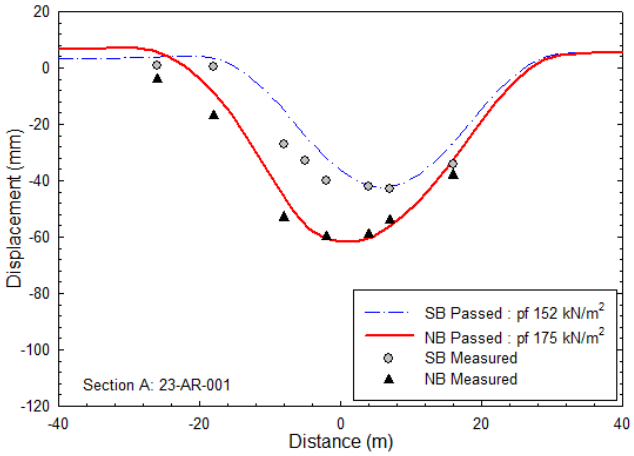
*Remarks: MG = Made Ground; BSC = Bangkok Soft Clay; 1stSC = First Stiff Clay; CS = Clayed Sand; 2ndSC = Second Stiff Clay; HC = Hard Clay

4 ANALYSIS RESULTS

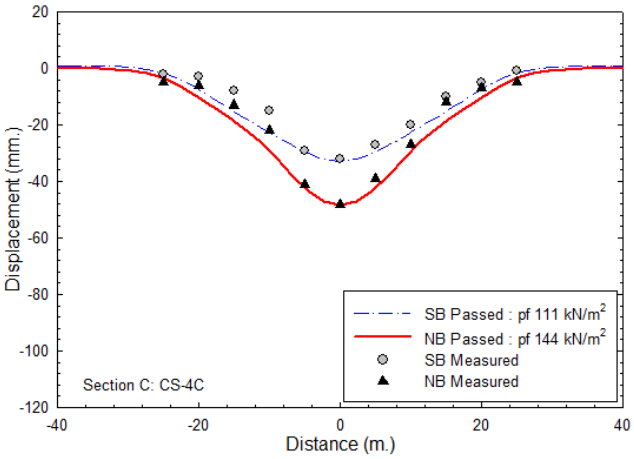
4.1 Model calibration against short term data

The modified grout pressure method is a three step calculation for tunnelling simulation, which is applied to the finite element analyses. In the modified grout method, the face and grout pressures were modelled by an applied pressure which increased linearly with depth. The unit weight of the slurry and grout material were assumed to be 12 and 15 kN/m^3, respectively. In the first attempt, the average face and grout pressures, as measured from the earth pressure chamber and the shield tail, were used as the face and grout pressures of the TBM records. Using the measured face and grout pressures gave an over-prediction of the ground settlement, when compared to the field measurements during construction. Furthermore, using very low face pressures of 45 and 40 kN/m^2 for the case of Section A has led to an unstable (near failure) analysis. It is obvious that a higher magnitude of face pressure was needed to achieve a reasonable settlement prediction. This is perhaps understandable, because the face pressure is a measurement of the slurry pressure inside the chamber.

In the second attempt, it was decided that a series of finite element back-analyses by using the best fitting parameters. The results of the finite element calculations of both sections are shown in Figs. 4(a) and 4(b), respectively. The face pressure (p_f) and grout pressure (p_g) were selected until the results fitted with the surface settlements after construction. It is noted that all the clay layers (Bangkok Soft Clay, Medium Clay, First and Second Stiff Clay and Hard Clay) were modelled as undrained, but the Made Ground and Clayey Sand layers were modelled as drained at this stage.



(a) Section A:23-AR-001

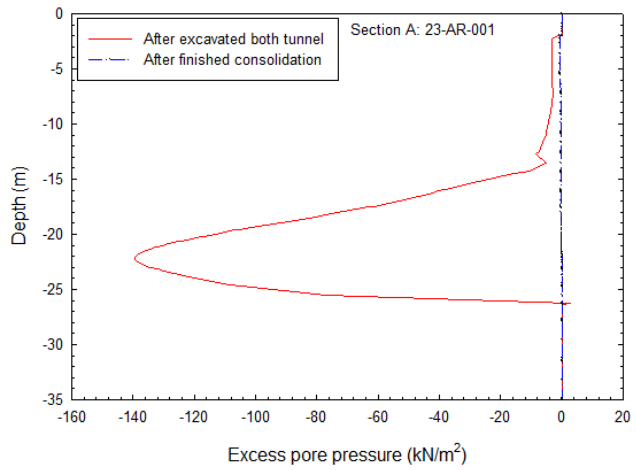


(b) Section C:CS-4C

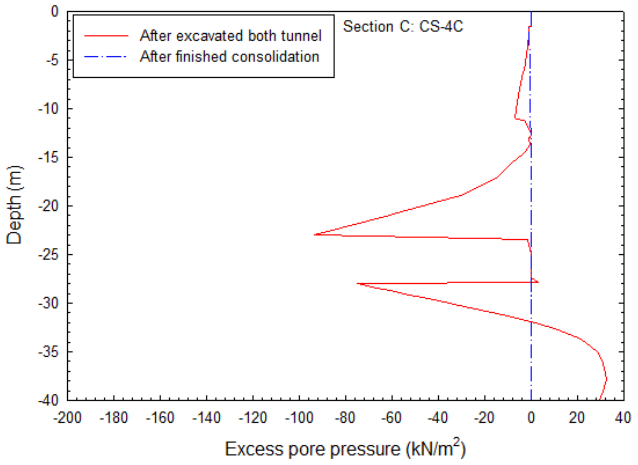
Fig. 4. Results of finite element analysis in short term

4.2 Long term prediction

The finite-element model and its input parameters were firstly calibrated against the field measuring data of ground surface settlements after construction finished, as explained above. The excess pore water pressure generated from the tunnelling simulation by the modified grout method, as presented in Fig. 5, could be further used to process a coupled consolidation analysis based on Biot's theory (Vermeer and Brinkgreve, 1993). The consolidation analysis requires the input of anisotropy permeability coefficients (k_x and k_y) as summarised in Table 3. The analysis results can be used to predict the long-term behaviour of tunnels.



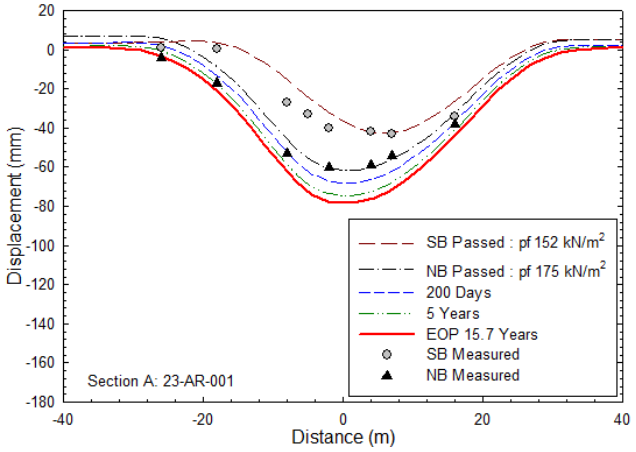
(a) Section A:23-AR-001



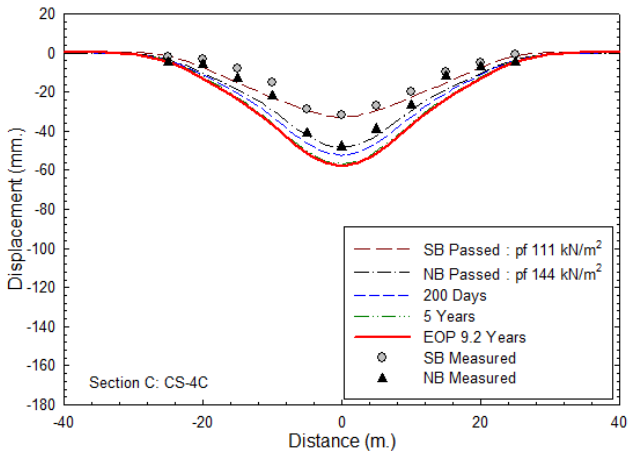
(b) Section C:CS-4C

Fig. 5. Excess pore water pressure distribution at the centre of twin tunnels

The results of the long-term analysis of both sections are shown in Figs. 6(a) and 6(b), respectively. The end of primary consolidation takes around 15.7 and 9.2 years for Section A:23-AR-001 and C:CS-4C, respectively. The consolidation settlements mainly increase in the 200 days and almost completely during the fifth year.



(a) Section A:23-AR-001



(b) Section C:CS-4C

Fig. 6. Long-term prediction of surface settlements

5 CONCLUSION

This study presents the 2D finite element analysis of the shield tunnelling based on modified grout method. Firstly, all the clay layers (Bangkok Soft Clay, First and Second Stiff Clay and Hard Clay) within the selected soil profiles were modelled as undrained. The resulting ground movements were compared with the field measurements immediately after construction (short term). Next, the long-term analysis based on coupled consolidation was continuously carried out. The results from the consolidation analysis could be used to predict the long-term ground settlements and the end of primary consolidation. In this paper, the two cross sections with a side-by-side and top-bottom configurations were selected for studied cases. The following conclusions were drawn from the case studies:

1) Simplified 2D finite element modelling can be used reasonably to solve the 3D problems of tunnelling-induced ground surface settlements. The case study from the Bangkok MRT discussed in this paper shows that 2D finite element modelling is still very useful for solving 3D problems (e.g. tunnelling-induced settlement) in geotechnical practice.
2) The modified grout method provides a sensible degree of matching for the predicted surface settlement profiles. However, it should be restricted to limited tunnelling cases depending upon the shield operating and ground conditions.
3) The values of the calculated face pressure were higher than the measured one. The higher calculated face pressure probably resulted because the actual supporting pressure consisted of the slurry pressure inside the shield chamber, the soil arching in front of the shield, and some supports from the shield element (i.e. shield blades).
4) Comparing to other simplified methods such as contraction method and stress reduction method, the modified grout method is the only method that provides reasonable excess pore water pressure

profiles. It can then process the long-term analysis.

5) Due to limitation of long-term monitoring data from the Bangkok MRT Blue Line project, the case studies presented here employ the short-term data to calibrate the finite-element modelling. However, the finite-element models can be used to predict the ground response in long-term condition.

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