Strength and Stiffness Parameters of Bangkok Clays for Finite Element Analysis

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ABSTRACT: Constitutive soil model and its parameters are the important issue in finite element analysis. Hardening soil model and Mohr-Coulomb model parameters of Bangkok clays for finite element analysis were evaluated in this study. To achieve this purpose, a case study of Sukhumvit MRT Station was selected to model in three dimensions with hardening soil and Mohr-Coulomb models. The instrumented data during construction was used to compare with the results from finite element analysis. PLAXIS 3D software was adopted as solving tool in this study. Lateral wall movement and ground surface settlement predictions were used to compare with the data. The outcomes were concluded that the hardening soil model characterised the Bangkok clay better than Mohr-Coulomb model in 3D finite element analysis for excavation.

Keywords: Finite element analysis; Constitutive soil model; Deep excavation; Lateral wall movement; Ground surface settlement,

1. INTRODUCTION

Strength and Stiffness parameters are important in the analysis of deformation. In general, the strength and stiffness of soil usually determine from laboratory or field tests; however, they may not be the optimal values. Therefore, further calibration with the numerical analysis may be required. As in Surarak (2011), the strength and stiffness parameters of Bangkok clays were studied based on the results of triaxial and oedometer tests from the laboratory. The calibrated soil parameters were adopted to 2D finite element modelling by Likitlersuang et al. (2013a).

Moreover, the study was extended to predict ground surface settlements due to tunnel excavations in Bangkok (Likitlersuang et al., 2014). This study aims to extend the previous studies on the strength and stiffness parameters which focuses on the sets of hardening soil model (HSM) and Mohr-Coulomb Model (MCM) in 3D finite element modelling. The same deep excavation case of the Sukhumvit MRT Station is still used. All the other settings are kept the same except the 3D modelling. The wall movements and ground surface settlement are estimated. PLAXIS 3D – commercial software was adopted in the modelling and analysis.

2. BANGKOK SUBSOILS CONDITION

Bangkok situates on very thick soft clay layer in which most of construction activities take place. The layer was underlaid by the alternative layers of sand and clay. Many researchers have conducted the studies on Bangkok soil. For instance, Likitlersuang et al. (2013a) generalised the Bangkok soil layers by data from various locations across Bangkok. The divided as Made Ground (MG), Bangkok Soft Clay (BSC), Medium Clay (MC), 1st Stiff Clay (1st SC), Clayey Sand (CS), 2nd Stiff Clay (2nd SC), and Hard Clay (HC). Likitlersuang et al. (2013c) determined the small strain stiffness characteristics for Bangkok clay focusing on two parameters, small strain shear modulus ($G_{\max}$) and reference shear strain ($\gamma_{0.7}$), based on laboratory and field test carried out at various locations throughout Bangkok city. In term of ground water condition under the surface, Bangkok suffered from drawdown of pore water pressure due to the deep well pumping. The pore water pressure was observed during the construction of Bangkok MRT Blue Line and reported in Likitlersuang et al. (2013b).

3. PARAMETERS CALIBRATION

A new version of PLAXIS provides an ability to simulate the soil tests (Brinkgreve et al., 2015). Triaxial testing results from many works perfromed at AIT (Surarak, 2011) were used to calibrate the hardening soil parameters for Bangkok soft and stiff clays. The triaxial tests and numerical calibration were reported in Surarak (2011). Nevertheless, the parameters were calibrated by PLAXIS simulation again in this study. The results of stress-strain relationship and stress path from PLAXIS simulation comparing with the triaxial tests with 3 different confining pressure were plotted in Figure 1 and Figure 2, respectively.

The results of stress-strain relationship and stress path from PLAXIS simulation for Bangkok stiff clay comparing with the triaxial tests with 3 different confining pressures were plotted in Figure 3 and Figure 4, respectively.

3.1 Mohr-Coulomb Model

Mohr-Coulomb Model (MCM) has been widely used to model the behavior of soil. The model is simple for practical application. Young's modulus (E) and Poisson's ratio (ν) are assumed to be constant and exhibit in linear stress-strain relationship. The MCM set for Bangkok subsoil was summarised in Table 1 after Likitlersuang et al. (2013a).

3.2 Hardening Soil Model (HSM)

Hardening soil model is one of the advanced soil constitutive modelling available in PLAXIS. The model adopted the non-linear stress-strain relationship. Hyperbolic relationship was used. The stiffness are stress-dependent. Further details of the model can be found in Schanz et al. (1999). Surarak et al. (2012) studied the HSM parameters for Bangkok subsoil by oedometer and triaxial tests. Then the results were calibrated numerically. Similarly, Likitlersuang et al. (2013a) also provided complete set of HSM parameters for Bangkok subsoil. In this study, the re-calibration of HSM parameters using PLAXIS soil test module was carried out and the results can be summarised in Table 2. The short explanation of HSM parameters is tabulated in Table 3.

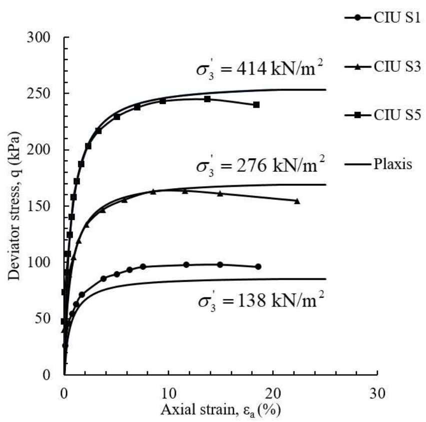


Figure 1 Hyperbolic stress-strain curves of Bangkok soft clay

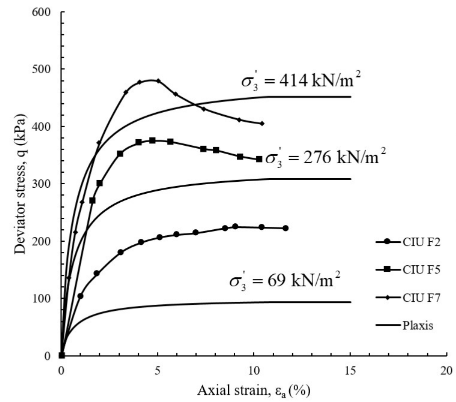


Figure 3 Hyperbolic stress-strain curves of Bangkok stiff clay

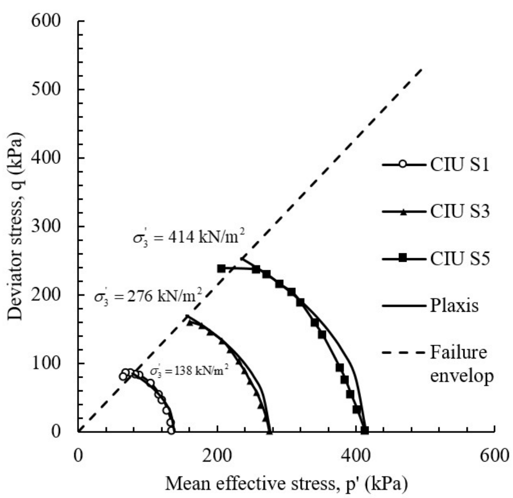


Figure 2 p'-q stress path of Bangkok soft clay

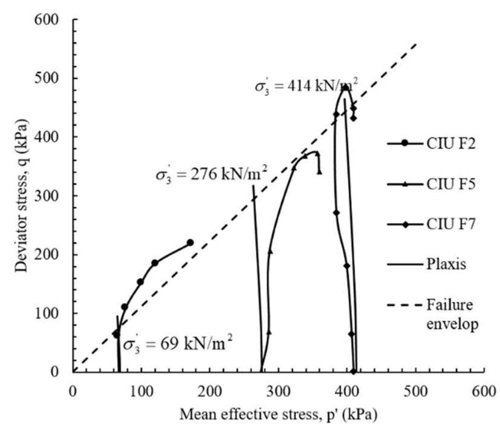


Figure 4 p'-q stress path of Bangkok stiff clay

Table 1 Mohr-Coulomb model parameters (Likitlersuang et al., 2013a)

Layer	Soil Type	γ_b (kN/m^3)	s_u (kPa)	c' (kPa)	ϕ' (°)	ψ' (°)	E_u (MPa)	E' (MPa)	ν	Analysis Type
1	MG	18	-	1	25	0	-	8	0.3	Drained
2a	BSC1	16.5	20	-	-	0	10	-	0.495	Undrained
2b	BSC2	16.5	39	-	-	0	20.5	-	0.495	Undrained
3	MC	17.5	55	-	-	0	27.5	-	0.495	Undrained
4	1st SC	19.5	80	-	-	0	40	-	0.495	Undrained
5	CS	19	-	1	27	0	-	53	0.25	Drained
6	2nd SC	20	120	-	-	0	72	-	0.495	Undrained
7	HC	20	240	-	-	0	240	-	0.495	Undrained

Table 2 Hardening soil model parameters (Likitlersuang et al., 2013a)

Soil type	γ_b (kN/m^3)	c' (kPa)	ϕ' (°)	ψ' (°)	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	ν_{ur}	m	K_0^{nc}	R_f	R_{inter}	Analysis type
MG	18	1	25	0	45.6	45.6	136.8	0.2	1	0.58	0.9	0.7	Drained
BSC	16.5	1	23	0	0.8	0.85	8.0	0.2	1	0.7	0.9	0.7	Undrained
MC	17.5	10	25	0	1.65	1.65	5.4	0.2	1	0.6	0.9	0.7	Undrained
1st SC	19.5	25	26	0	8.5	9.0	30.0	0.2	1	0.5	0.9	0.7	Undrained
CS	19	1	27	0	38.0	38.0	115.0	0.2	0.5	0.55	0.9	0.7	Drained
2nd SC	20	25	26	0	8.5	9.0	30.0	0.2	1	0.5	0.9	0.9	Undrained
HC	20	40	24	0	30.0	30.0	120.0	0.2	1	0.5	0.9	0.9	Undrained

Table 3 Hardening soil model parameters explanation

Parameter symbol	Parameter Description	Parameters evaluation
ϕ'	Internal friction angle	Slope of failure line from Mohr–Coulomb failure criterion
c'	Cohesion	y-intercept of failure line from Mohr–Coulomb failure criterion
ψ'	Dilatancy angle	Ratio of $d\varepsilon_v^p$ and $d\varepsilon_s^p$
E_{50}^{ref}	Reference secant stiffness from drained triaxial test	y-intercept in $\log(\sigma_3 / p^{ref}) - \log(E_{50})$ curve
E_{oed}^{ref}	Reference tangent stiffness for oedometer primary loading	y-intercept in $\log(\sigma_1 / p^{ref}) - \log(E_{oed})$ curve
E_{ur}^{ref}	Reference unloading/reloading stiffness	y-intercept in $\log(\sigma_3 / p^{ref}) - \log(E_{ur})$ curve
ν_{ur}	Unloading/reloading Poisson's ratio	0.2 (default setting)
m	Exponential power	Slope of trend-line in $\log(\sigma_3 / p^{ref}) - \log(E_{50})$ curve
K_0^{nc}	Coefficient of earth pressure at rest (NC state)	$1-\sin\phi'$ (default setting)
R_f	Failure ratio	$(\sigma_1-\sigma_3)_f / (\sigma_1-\sigma_3)_{ult}$

Remark: σ_1 is major principle stress (kN/m^2)

σ_3 is minor principle stress (kN/m^2)

p^{ref} is reference pressure (100 kN/m^2

4. CASE STUDY DESRIPTION

Sukhumvit MRT Station is one of the Bangkok MRT Blue Line, which is the first underground line in Bangkok. The station is 23 meters wide and 200 meters long. The length-to-width ratio is 8.7. Firstly, the station was modelled and analysed with 2D finite element analysis by Likitlersuang et al. (2013a). The station was constructed by top-down construction method with diaphragm walls (D-wall) as soil retaining structure. D-wall was 1 m thick and constructed down to 28 meters deep. 8 inclinometers and 1 surface settlement array (SS1) were installed around the station to observe the deformation of the wall as well as the surface settlement of the surrounding as shown in Figure 5. The finite element mesh of the Sukhumvit MRT Station depicted in Figure 6 consists of 295,081 elements with the average size of 3.96 m. The cross section A-A as shown in Figure 7 provide more detail of the construction activities as well as the soil layers. D-wall could be modelled by plate element in 3D FEA (Hsiung et al., 2016) D-wall, slabs and bored piles properties were highlighted in Table 4. The construction sequences of Sukhumvit MRT Station are summaried in Table 5. More detail of 3D FEA for Sukhumvit MRT Station can been found in Chheng and Likitlersuang (2018).

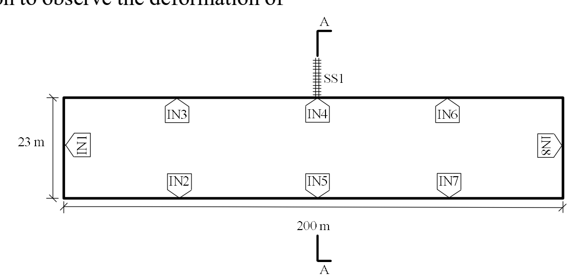


Figure 5 Sukhumvit MRT Station layout

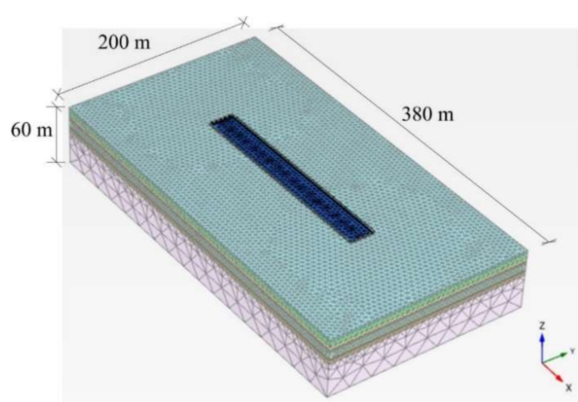


Figure 6 Finite element and mesh generation (295,081 elements and average size of 3.96m) (after, Chheng and Likitlersuang, 2018)

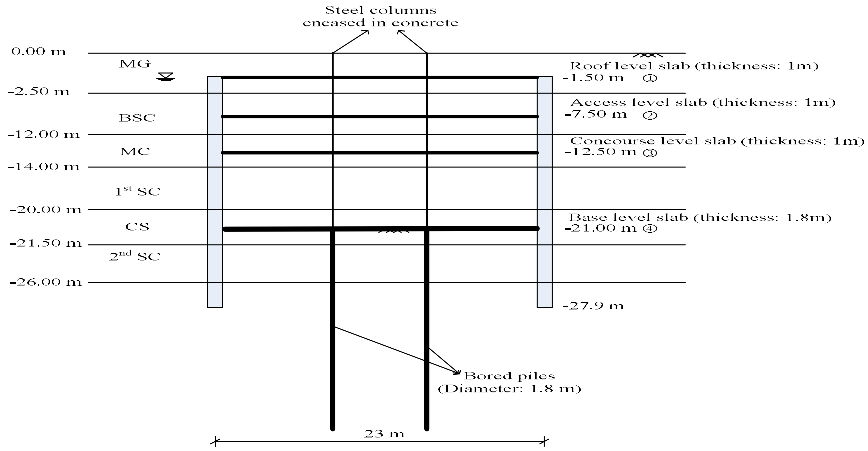


Figure 7 Cross section (AA) of Sukhumvit MRT Station

Table 4 Structural material parameters

Parameters	*d* (m)	*γ* (kN/m³)	*E* (MPa)	*ν*	*A* (m²)	*I* (m⁴)
D-wall	1.0	16.5	28,000	0.15	-	-
Base slab	1.8	25	28,000	0.15	-	-
Platform slab	1.0	25	28,000	0.15	-	-
Steel column	-	25	200,000	-	0.5	0.02
Bored piles (Massive circular pile)	1.8	25	28,000	-	-	-

Table 5 Construction sequences to be modeled in PLAXIS 3D

Sequences	Construction Activities
1	Wish-in-place of D-wall, bored piles, Steel column and excavation to the depth of 1.5 m for temporary prop installation.
2	Finished roof floor concrete casting and excavation to depth of 7.5 m
3	Finished second floor concrete casting and excavation to the depth of 12.5 m
4	Finished third floor concrete casting and excavation to the depth of 21 m

5. RESULTS AND DISCUSSION

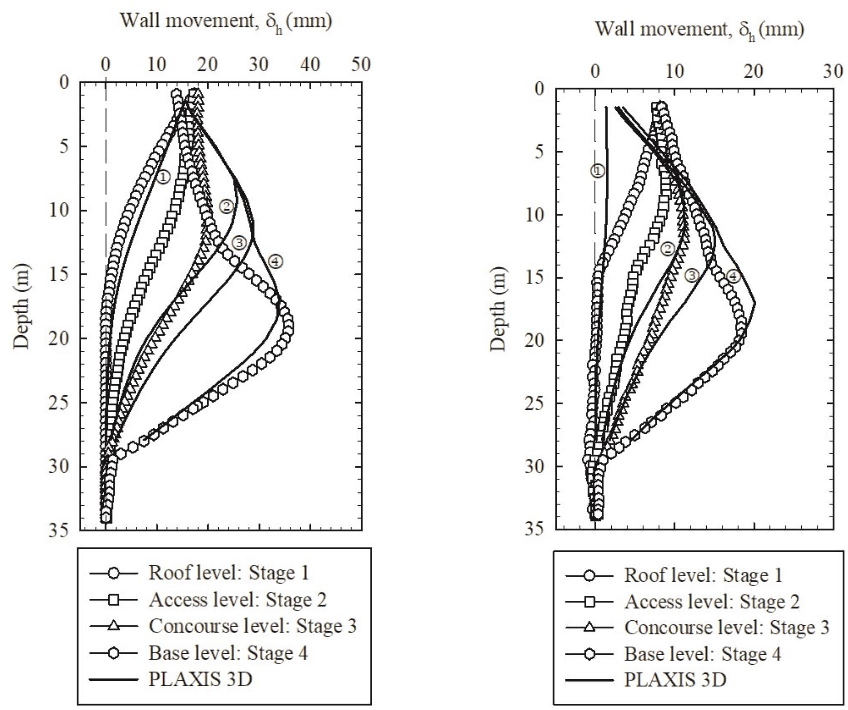
The wall movements estimation from HSM in 3D FEA agree well with the inclinometer reading from both long and short side as indicated in Figure 8. More interesting, the comparison between wall estimation from HSM and MCM in 3D for both long and short side was depicted in Figure 9. From the observation, the HSM provides the wall movement closer to the field instrumented data. Hence, the HSM can characterise soil in Bangkok better than MCM especially the transitional change of stiffness from small to large strain (Schanz et al.,1999).

The plots in Figure 10 infer that the HSM parameters presented in Table 2 were for 2D FEA and 3D FEA for deep excavation in Bangkok soft soil.

Ground surface settlements from HSM in 3D FEA were plotted in Figure 11. The plot compares the prediction from 3D FEA, measured data, and empirical relationship proposed by (Hsieh et al., 1998). It is observed that though the prediction from stage 1 is underestimated, the prediction of maximum ground surface settlement from stage 2 to stage 4 agree well with the measurement of SS1 as well as the trilinear relationship. The conclusion is that the 3D FEA provides well prediction of ground surface settlement compared to measured data.

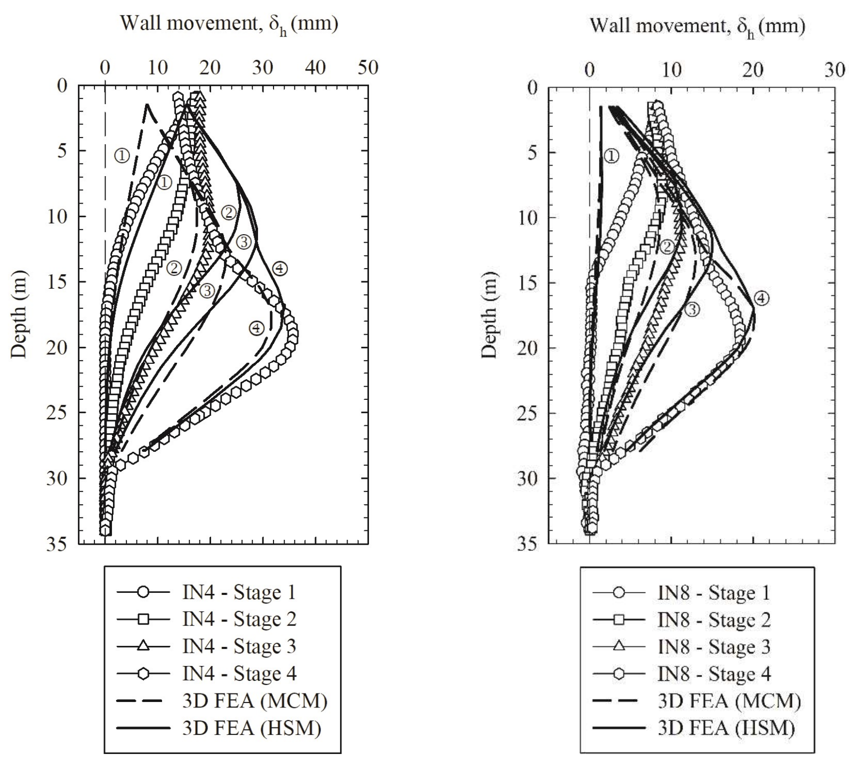
Figure 12 illustrates the comparison between the prediction of ground surface settlement by 2D FEA and 3D FEA. The graph shows that the prediction from 2D FEA (HSM) is less than the prediction from 3D FEA (HSM) from stage 1 to stage 3. However, the graphs coincide at the final stage of analysis.

Figure 13 provided a very clear distinction between the model of MCM and HSM. The HSM coincides with the measured data as well as the empirical relationship proposed by Hsieh et al. (1998). However, the MCM underestimates the ground surface settlement. Underestimation of ground surface settlement leads to less attention of damage to the surrounding infrastructures. Therefore, though 3D FEA is adopted, soil constitutive modelling is another crucial parameter in the numerical modelling.



(a) (b)

Figure 8 Comparison between 3D FEA with HSM and inclinometers: (a) IN4, (b) IN8 (after, Chheng and Likitlersuang, 2018)



(a) (b)

Figure 9 Wall deformation comparison between field data, MCM and HSM

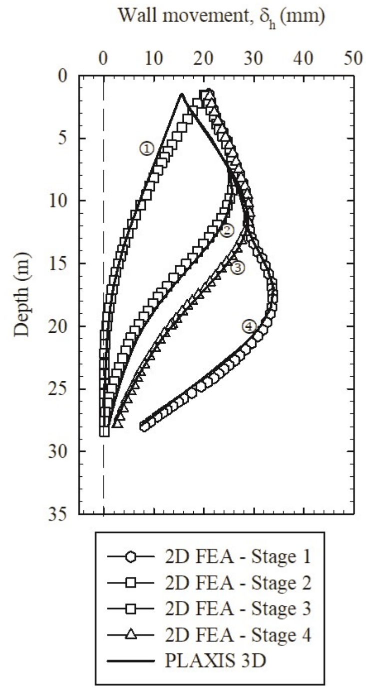


Figure 10 Comparison wall deformation between 2D FEA after Likitlersuang et al. (2013a) and 3D FEA with HSM at the middle of the long wall

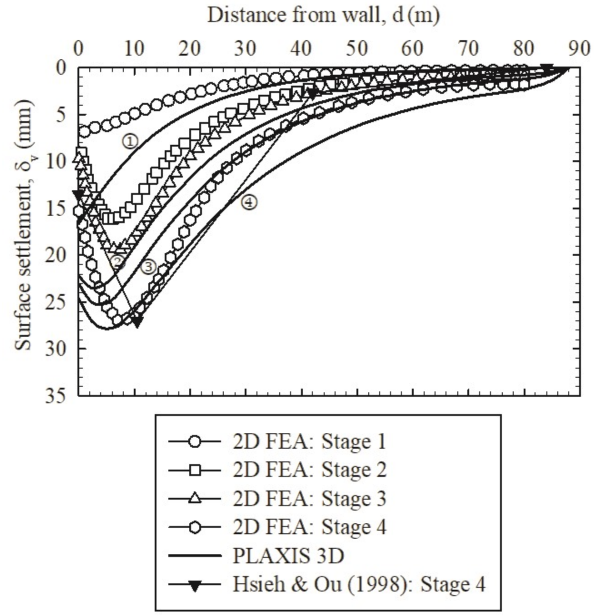


Figure 12 Comparison of ground surface settlement between 3D FEA with HSM and 2D FEA with HSM from Likitlersuang et al. (2013a)

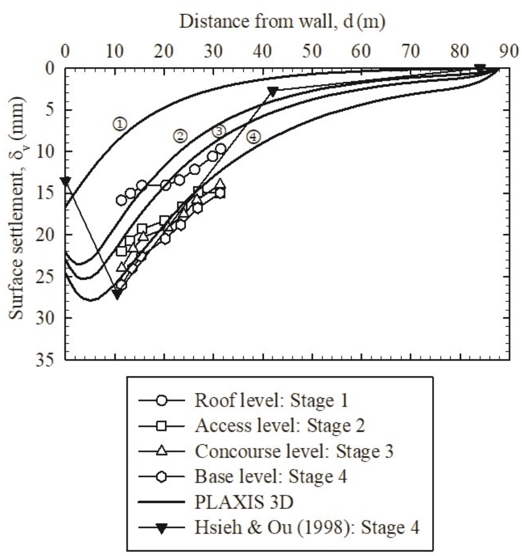


Figure 11 Comparison of ground surface settlement between 3D FEA with HSM, SS1 and empirical relationship

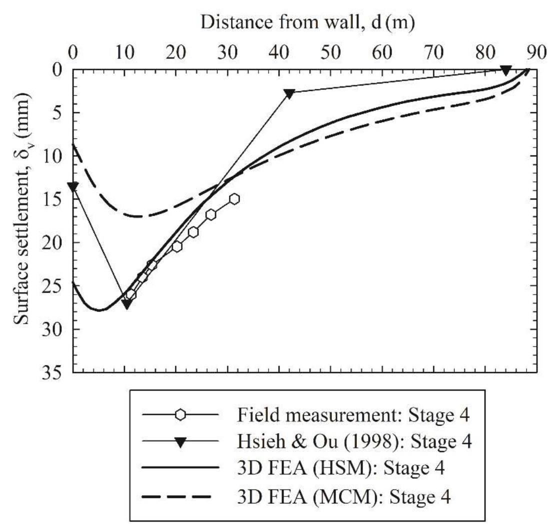


Figure 13 Comparison of ground surface settlement prediction at final stage

6. CONCLUSION

The study modelled and analysed the deep excavation in Bangkok using three-dimensionally finite element analysis. PLAXIS 3D software was used as finite element solver. Sukhumvit MRT Station was selected to verify the strength and stiffness parameters of Bangkok subsoil. The case study was previously studied by means of 2D FEA, in which the station was possessed in plane strain condition. The HSM and MCM were used in the analyses and the results from both models were compared. The results confirmed that the HSM offers better wall movement and ground surface settlement predictions both in 2D and 3D analysis. However, not only the constitutive modelling but also the modelling of the construction sequence are significant in the finite element analysis.

7. ACKNOWLEDGEMENT

This research was supported by the Ratchadapisek Sompoch Endowment Fund (2017), Chulalongkorn University (760003-CC). The second author wishes to thank the AUN/SEED-Net (JICA) for a scholarship during his study.

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