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Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
© 2012 Taylor & Francis Group, London, *ISBN 978-0-415-68367-8*

Numerical modeling of diaphragm wall behavior in Bangkok soil using hardening soil model

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ABSTRACT: A numerical study was performed incorporating the Hardening Soil model to examine its applicability in capturing the diaphragm wall behavior in Bangkok subsoils. The model was first calibrated for a well monitored excavation case in Bangkok. Then it was applied for three other cases for verification. The predicted wall and ground movement behavior compares reasonably with observed behavior, suggesting advantage of the soil model for application in Bangkok subsoils. Empirical correlations are proposed for estimating the Hardening Soil model parameters from undrained shear strength of soft clays and from SPT 'N' values for stiff to hard clays and sand of Bangkok subsoils.

1 INTRODUCTION

Diaphragm walls have been widely used as primary and permanent structural elements for supporting deep excavations in urban area of Bangkok. Due to the complex nature of the soil structure interaction, a realistic soil constitutive model is crucial in order to estimate the behavior and magnitudes of wall and ground movements.

Soil response to loading is nonlinear, inelastic and highly dependent on the magnitude of stress. This behavior has a significant influence on the stresses and displacements developed within the reinforced structure. The constitutive model commonly used to investigate performance of braced excavations in Bangkok is the linear-elastic perfectly plastic Mohr Coulomb yield criterion. It popularity continues although it does not always give a good fit for both magnitude and pattern for ground movements (Phienwej & Photayanuvat 1998, Hooi 2003). In general, its use leads to settlement troughs shallower and wider than those actually observed (Addenbrooke et al. 1997, Masin & Herle 2005) and it underestimates bending moments in diaphragm wall (Ng et al. 2005). It is, therefore, suggested to use a soil model that considers non-linear stress strain behavior, unloading stiffness, stress-dependent stiffness, hardening, and dilatancy.

In this study, two constitutive models were used in comparative analysis of deep excavations in Bangkok subsoils, i.e. the linear-elastic perfectly Mohr Coulomb model and the Hardening Soil model.

2 SUBSOIL PROFILE

Bangkok is situated on the flat topography of Bangkok Plain. Subsoils consist of a thick marine soft silty clay layer of 12–15 m in thickness. It is underlain by alternating layers of alluvial stiff to hard clay and dense to very dense sand to gravel. The soft clay which is well known as "Bangkok soft clay" has high water content (70–120%), high plasticity, low strength and high compressibility. (Phienwej et al 2007).The typical subsoil profile with geotechnical properties is given in Figure 1.

3 SELECTED ANALYSIS CASES

Four completed excavation cases are chosen for the comparative analysis made in this study.

3.1 *MRT Silom station*

Silom Station involved the deepest excavation made in the construction of first Bangkok underground MRT project of 20 km long rail length. The stacked-platform station has four levels of floor slab. The station was constructed underneath a road overpass bridge of which the piled foundation needed to be underpinned for the station construction. The first excavation depth was 6.45 m for casting of the roof slab and it was deepened to the final excavation depth of 32.55 m. A dense sand layer of the first Bangkok Sand was encountered from depth of 8.5 m above the final excavation level. Hence, the excavation required dewatering.

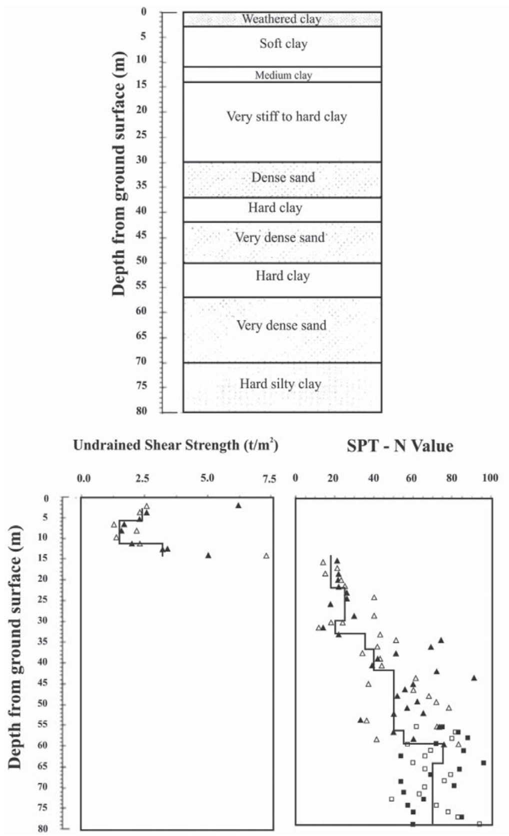

Figure 1. Typical Bangkok subsoils profile (Wonglert et al. 2008).

The diaphragm wall was toed into the Second sand layer at 46.5 m depth. The excavation was made by the top-down construction method utilizing concrete floor slabs as wall bracing.

3.2 *MRT Thiam Ruam Mit station*

Thiam Ruam Mit station is located beneath the carriageway of a wide city road. This station forms an interchange station and it has three levels i.e. platform, concourse and retail levels constructed within a diaphragm wall box. The station was constructed using the top down technique. Piles or barrettes and preformed columns were installed along the center of the station to provide mid span support to the slabs. The maximum excavation depth was 17.5 m and the toe of the diaphragm wall was at 22 m depth.

3.3 *Central Hospital of Bangkok*

Central Hospital is located in the old commercial area of Bangkok. The project included the construction of four level basements and one multipurpose recreational area. The main feature of the project was the split floor levels and a temporary steel transfer beam was used to transfer the load from north to south diaphragm walls. Maximum excavation depth was 20 m.

3.4 *Bangkok City hall car park*

The excavation was for construction of two-level underground car park, located in front of Bangkok City Hall in the area of the historical sector of the city. This construction site was surrounded by numbers of sensitive structures that posed many constraints, which called for the need of careful consideration in establishing design criteria and procedures of excavation (Thasnanipan et al, 2004). Diaphragm walls were founded at 16 m below ground level for the excavation depth of 6.6 m. Barrettes having same toe depth as bored piles were installed at 8 m spacing along with diaphragm wall panels.

Value engineering option and observational method were applied in this project. Phase 1 works comprised excavation to 2.2 m depth and with temporary struts installed at 1.8 m. The second stage of excavation involved excavation to 6.6 m depth with toe soil berms. A major modification was made during the course of the excavation involving replacing of cross-lot struts by inclined rakers for the north wall and removal of soil berm at east and west diaphragm walls.

4 FINITE ELEMENT ANALYSIS

Plane strain finite element analysis was made using PLAXIS version 8.5 software to simulate the selected excavation cases. The FEM mesh is made of 15-node triangular elements and has width 7 times the excavation width and depth 2.5 times the maximum excavation depth (e.g. for a case of excavation depth of 30 m and half width of 15 m, the mesh is 80 m deep and 105 wide). The undrained analysis using effective strength parameters of the Bangkok stratified subsoils. The effective frictional angles used are 23 degrees for soft clay, medium stiff clay and stiff clay, 27 degrees for silty clay and 36 degrees. A range of small cohesion is used for clayey soil layers. The input strength parameters are in accordance with the test results of the comprehensive geotechnical program made in the First Bangkok underground MRT project (Phienwej and Photayanuvat, 1998). The drawdown condition of Bangkok groundwater in the subsoils due to past deep well pumping was considered in the analysis. The drawdown is 22 m in the first sand layer.

5 CONSTITUTIVE MODELS

The Mohr Coulomb (MC) model and Hardening Soil (HS) model in PLAXIS code are used in the analysis in order to compare the prediction results of wall and ground movements so that assessment could be made on the better constitutive model for use in future deep excavations in Bangkok subsoils.

The MC model in PLAXIS adopts the linear elastic perfectly plastic constitutive law. It requires five parameters, i.e. E and ν for linear elastic behavior and c and φ for yield function and ψ as dilation angle for plastic deformation behavior. The HS considers non-linear stress strain behavior of soil according to the hyperbolic model and allows for shear and compression hardening (Schanz & Vermeer 1997). Total strains are calculated by stress dependent moduli, different for loading and unloading. Input parameters of the model consists of the strength parameters φ, c, and dilation angle ψ. Soil stiffness is defined by parameters E_{50}^{ref} and E_{ur}^{ref} (unloading-reloading modulus) for shear behavior and E_{oed}^{ref} for volumetric behavior.

Schanz & Vermeer (1997) reported that E_{50}^{ref} of sandy soils showed relationship with 1-D modulus E_{oed}^{ref}. Hence, if data on the oedometer modulus is given, it can be used to estimate the triaxial modulus. Generally, it is suggested that E_{50}^{ref} be equal to E_{oed}^{ref} whereas $E_{ur}^{ref} = 3E_{50}^{ref}$. This empirical relationship is adopted in the initial step of analysis in this study.

6 MODEL PARAMETERS

6.1 *Mohr Coulomb model parameters*

The model has been widely used in both research study and design practice in related to Bangkok soils and the characteristics and values of soil property parameters are well established. The stiffness parameters used in Silom and TRM stations of Bangkok Underground MRT project are adopted from the result of back-calculation study Hooi (2003).The suggested undrained soil modulus values of the soils are as follows:

Soft and Medium Clay:	$E_u = 500\ C'_u$
First Stiff Clay:	$E_u = 700\ N_{60}$
Clayey Sand:	$E_u = 900\ N_{60}$
Second Hard Clay:	$E_u = 1600\ N_{60}$
Third Hard Clay:	$E_u = 2500\ N_{60}$

where, E_u (kN/m^2) = undrained Young modulus, C'_u = corrected field vane shear strength of clay and N_{60} = corrected SPT 'N' values.

For Central Hospital and BMA project, the stiffness parameters were derived from the soil test data. Undrained shear strength of soft and medium clay was obtained from unconfined compressive strength. For stiff clay layers, the stiffness parameters were based on SPT 'N' values. For sand layers, it was estimated from E'/N relationship given by Burland and Burbidge (1985).

6.2 *Hardening soil model parameters*

Two sets of HS soil parameters were used in the initial run for purpose of calibration. The first set used E_{oed}^{ref} values in accordance with past laboratory oedometer test results on Bangkok soils (STS 2006). Then E_{50}^{ref} was assumed to have the same value as E_{oed}^{ref} and $E_{ur}^{ref} = 3E_{50}^{ref}$. For the second set, the parameters were derived from the MC parameter values by setting E_{50} of HS model at the midpoint of each layer to the E_{ref} of the Mohr-Coulomb model and deriving E_{50}^{ref} using Equation 1. E_{oed}^{ref} and E_{ur}^{ref} are assumed to be equal to E_{50}^{ref} and $3E_{50}^{ref}$ respectively.

$$E_{50} = E_{50}^{ref}\left[\frac{c\cos\varphi - \sigma_3'\sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right]^m \qquad (1)$$

7 HS MODEL CALIBRATION

For calibration, the predicted lateral displacement behavior of diaphragm wall by HS model is compared with the observed data of Silom Station using both sets of parameter as discussed above. Figure 2 compares the observed and pre-

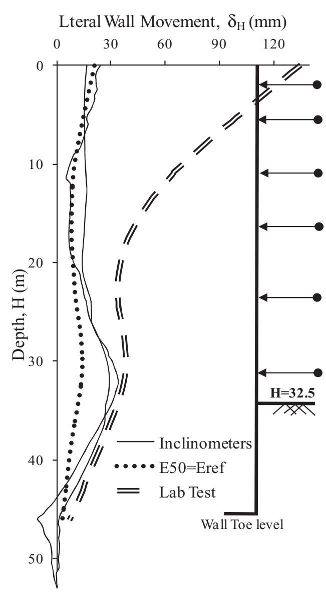

Figure 2. Predicted lateral ground movements using two sets of parameters of HS model.

dicted lateral ground movements at the wall for the last stage of excavation (32.5 m depth). The maximum lateral movement as predicted by using the parameters determined from laboratory test results is 136.5 mm. It grossly over-predicts the actual behavior, particularly at shallow depths. On the other hand, the second set of parameters gives reasonable prediction for early excavation stages (shallower excavation depths). However, it shows underestimation of the magnitude of ground movement at deeper depths in the sand layer, including the base level and below.

8 PREDICTED PERFORMANCE

To investigate the suitability of the HS model parameters for Bangkok subsoils, analysis of diaphragm wall behavior of Silom Station excavation was performed for comparative study of observed values of lateral ground movements and predicted values using adjusted parameters of HS model in comparison of the MC model prediction suggested by Hooi (2003).

The predicted ground movements are primarily influenced by soil stratigraphy and soil model parameters used. In this step, HS soil parameters of clayey soil layers are iteratively adjusted until the calculated results show reasonable agreement with the observed data. Then obtained HS model parameter values are compared with the MC model parameters of each of the soil layers. The back-calculated HS stiffness parameters of Silom Station excavation is summarized in Table 1.

8.1 *Lateral ground movement*

Figure 3 illustrates the comparison between observed and predicted lateral ground movements by using the MC and HS models. At the base excavation, inclinometers indicate slightly larger bulges than the predictions by both models. Generally, the HS model shows a better prediction than the MC model. The prediction by the former compares reasonably well with the observed magnitude and pattern.

The magnitude of the deflection predicted by MC model is overestimated near the base level. This is due to the fact that a stiffer unloading modulus is considered in the analysis by HS model.

8.2 *Bending moment*

It has been reported by previous researchers that the bending moment in the wall predicted by analysis using the HS model is comparatively higher than those obtained using the MC model. The finding in this study for Bangkok subsoil is in line with it.

Figure 4 shows the predicted bending moments by both models. The pattern and point of inflexion as predicted by both models are similar. The magnitude of maximum positive as well as negative bending moment as generated by HS model is slightly higher than that of the MC model.

8.3 *Ground surface settlement*

Figure 5 shows comparison between the observed and predicted surface settlements. As expected, the surface settlement trough predicted by the HS model

Table 1. Stiffness parameters in analysis of Silom station.

				Mohr coulomb parameters	Hardening soil parameters	
	Depth	SPT	Su	E’	E_{50}^{ref}	E_{ur}^{ref}
Soil layer	m	N60	kPa	MPa	MPa	MPa
Made ground	0–2			10.8	5.0	25
Soft clay1	2–7		17	8.3	4.2	33.6
Soft clay2	7–10		17–22	8.3–11.3	5.8	46.4
Medium clay	10–15		35	18.3	9.2	73.6
Stiff clay	15–19	15	75	38.3	10.2	102
Clayey sand	19–20	10		36.6	9.3	27.9
Silty clay	20–24	17		61.7	15.6	46.8
Silty sand1	24–27	27		88.4	27.0	81
Silty sand2	27–33	40		170	40.0	120
Silty sand3	33–37	26		83.5	26.0	78
Hard clay	37–45	16		90.5	17.0	170
2nd sand	45–67	48		230	36.0	108
2nd hard clay	67–80	22		217	23.9	239

Note: $E_{oed}^{ref} = E_{50}^{ref}$.

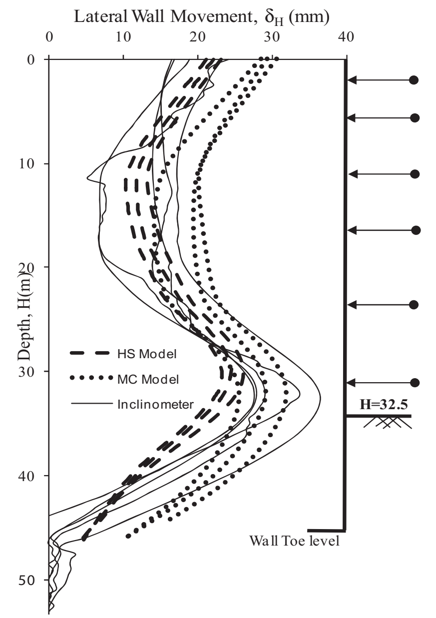

Figure 3. Observed and predicted lateral ground movements–Silom station.

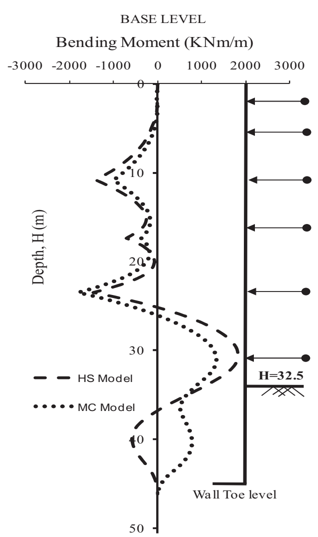

Figure 4. Predicted bending moments in D wall—Silom Station.

is much better than MC model prediction. It agrees very well with the observed settlement profile indicating the suitability of HS model in predicting the surface settlement trough whereas, the MC model predicts a much wider settlement trough. This is

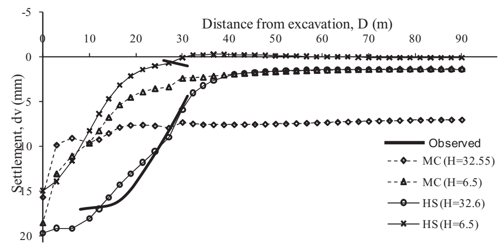

Figure 5. Observed vs. predicted surface settlement—Silom station.

Table 2. Correlations of hardening soil model parameters.

Soil description	E_{50}^{ref} (kN/m²)	E_{ur}^{ref} (kN/m²)	m (–)
Made ground	5000–7000	5 E_{50}^{ref}	0.5
Soft and medium clay	250 S_u	8 to 10 E_{50}^{ref}	1.0
Stiff clay	700 N_{60}	10 E_{50}^{ref}	0.85
Clayey sand & silty/sandy clay	900 N_{60}	3 E_{50}^{ref}	0.85
Medium to dense sand	750 N	3 E_{50}^{ref}	0.8
Dense to very dense sand	1000 N	3 E_{50}^{ref}	0.5
Hard clay	1100 N_{60}	10 E_{50}^{ref}	0.8
Dark grey clay	2500 N_{60}	10 E_{50}^{ref}	0.8

due to the fact that a more realistic difference in the unloading/loading stiffnesses used in the HS model.

9 EMPIRICAL DETERMINATION OF HS MODEL PARAMETERS

An attempt is made to establish empirical correlation between stiffness parameters of HS model parameters of Bangkok subsoils with common investigation soil properties, i.e. undrained shear strength S_u for soft and medium stiff clays and SPT "N" values for stiff clay and sand. The correlations are determined from the results of the calibration analysis of Silom Station described above. The values of stiffness parameters of HS model simulation that yield closest fit to the observed data are compared with the corresponding MC model parameters (Hooi, 2003). The derived correlations are given in Table 2.

10 MODEL VERIFICATION

For verification on the suitability of the HS model and the suggested empirical correlations of stiffness parameters for Bangkok soil, FEM analysis of three other excavation cases mentioned earlier are made.

10.1 *Thiam Ruam Mit station*

Figure 6a shows the observed lateral wall displacements of Thiam Ruam Mit Station excavation and the comparison with predictions using the MC and HS models. Inclinometers which were installed in south side of the station excavation showed wall movements in the braced mode. However, the third inclinometer showed the cantilever mode indicating difference in lateral restraints at ground level.

Both models predict the cantilever mode of wall deflection until the 3rd excavation level. The MC model over-predicts the wall deflection by 25% in the cantilever mode and almost by the same level at the toe of wall. The settlement trough predicted by HS model is shallower than that predicted by MC model and observation (Fig. 7a).

Figure 8a shows the comparison of the predicted bending moments. The profile of bending moments as predicted by HS model is higher than the MC model in the final stage of excavation.

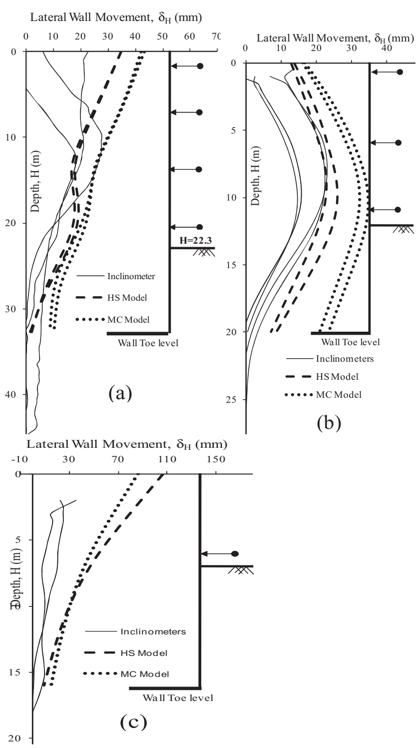

Figure 6. Predicted and observed lateral wall movements (a) Thiam Ruam Mit station; (b) Central Hospital; (c) BMA Car Park.

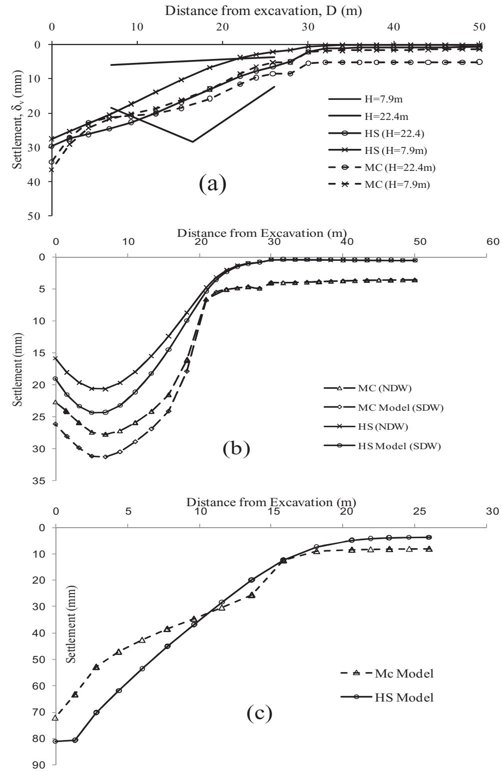

Figure 7. Predicted Settlement troughs (a) Thiam Ruam Mit station; (b) Central Hospital; (c) BMA Car Park.

10.2 *Central Hospital project*

Figure 6b shows comparison of the predicted and observed wall deflection. The observed wall movements are of the typical braced mode. The difference in deflections of two inclinometers is due to the difference between the excavation levels of north south wall. In this excavation case, the prediction by MC model using the empirical parameters grossly overestimates the values at all depths. On the other hand the prediction by HS model is quite reasonable. On the ground surface settlement, the observed settlement trough is not available for this case. HS model predicts shallower but narrower settlement trough as compared to the MC model, although the shapes of the trough are similar (Fig. 7b).

Both models predicted pretty much similar bending moments in the wall (Fig. 8b).

10.3 *Bangkok City hall car park excavation*

Figure 6c show lateral wall movement of the excavation (BMA Car Park).The mode of movement is of cantilever mode. In this case the predictions by both MC and HS models yield much

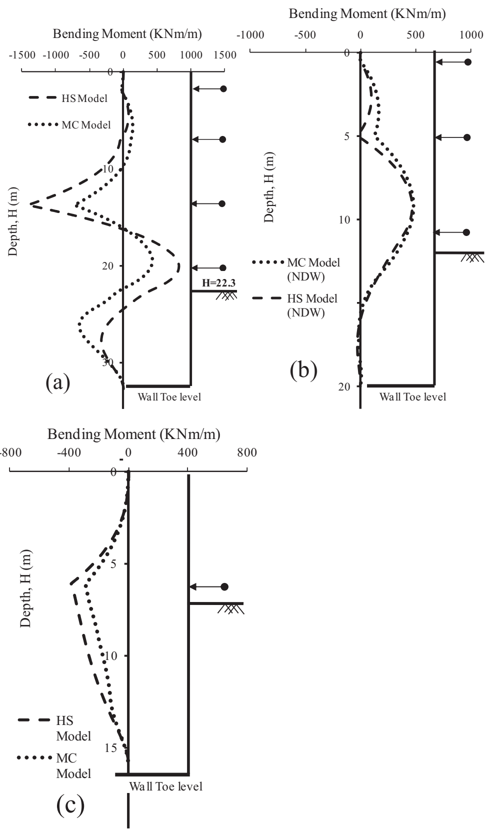

Figure 8. The Predicted bending moments (a) Thiam Ruam Mit station; (b) Central Hospital; (c) BMA Car Park.

over-prediction as compared to the observation and both are of the cantilever mode. The excavation in this project was only 6.6 m deep soft clay layer thus the cantilever mode still dictates the wall response. It appears that there is no advantage to use HS model in this type of excavation.

The predicted ground settlements and bending moment in the wall and are shown in Figures 7c and 8c, respectively. The predicted ground settlement troughs of the two models are not so different.

11 CONCLUSIONS

A numerical study is performed to appraise the validity of the Hardening Soil model for excavation in Bangkok subsoils. The following points can be concluded:

– The direct input of stiffness parameters derived from the lab test results showed erroneous wall movement predictions.
– The predicted deflection behavior of diaphragm wall shows good agreement with observed behavior by using the proposed empirical correlations in all cases except for the one with shallow excavation in the soft clay.
– The lateral deflection estimated by Hardening Soil model is smaller than that of the Mohr Coulomb model, resulted from higher unloading/reloading stiffness used.
– The Mohr Coulomb model overestimates wall toe movement as compared to Hardening Soil Model up to 50%.
– Settlement trough predicted by the Hardening Soil model is more realistic than that given by the Mohr Coulomb model.
– The wall bending moment estimated by Hardening Soil model are higher than that of Mohr coulomb model.
– The derived empirical correlations for estimating of Hardening Soil model stiffness parameters of Bangkok subsoils appear to be quite reasonable based on the verification results of few instrumented cases. However, further verification investigation is recommended.

ACKNOWLEGEMENTS

The authors would like to thanks PLAXIS b.v. for granting a license of PLAXIS software for educational use to Asian Institute of Technology for which the second author used to conduct MS thesis research on the topic. He thanks Seafco Public Company for giving him a scholarship for master degree study.

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