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GEOTECHNICAL ASPECTS OF DEEP EXCAVATION IN SOFT CLAY

Maha R. El-Kassas[a*], Sayed M. Ahmed[b], and Tamer M. Srouor[c]

[a] Graduate M.Sc. student, Structural Engineering Department, Ain Shams University, Egypt
[b] Associate Professor of Geotechnical Engineering, Structural Engineering Department, Ain Shams University, Egypt
[c] Assistant Professor of Geotechnical Engineering, Structural Engineering Department, Ain Shams University, Egypt

ملخص

التصميم والإنشاء في التربة الطينية اللينة عادة ما يكون مرتبط بصعوبات كثيرة، ولأن هذة التربة تتأثر بالتشكلات الحادثة للمنشآت الساندة للحفر العميق وتمتلك مقاومة للقص ضعيفة، فإنها قد تؤدي الي أضرار إنشائية خلال الإنشاء وأيضا على مدار عمر المشروعات، فمن الممكن ان تسبب هبوط او إماله في المنشآت الحديثة أو في المنشآت القديمة التي تكون قريبة من منطقة الحفر، فمن المهم جداً دراسة تأثير الحفر العميق على التربة الطينية اللينة.

. خلال هذا البحث، تم اعداد نماذج تحليلية باستخدام طريقة العناصر المحددة لدراستين لمشروعين سابقين لهما قياسات حقلية وافية. تم التحليل العددي لهما باستخدام نموذج تصلب التربة. أظهر كلا النموذجين اتفاق كبير في النتائج العددية مقارنًة مع النتائج الحقلية. تم إجراء دراسة برامتريه لدراسة تأثير الانكماش الحراري للبلاطات الداعمة، عمق اختراق الحائط في التربة، وجساءة الحائط على نتائج تشكلات الحائط. بالإضافة الي ذلك تم اجراء دراسة برامترية لدراسة تأثير نماذج مختلفة من التحليل العددي على نتائج تشكلات الحائط.

Abstract

The soft clay soil is sensitive to deformations and possesses small shear strength. Therefore, understanding the factors affecting the performance of deep excavations, the ability to predict the behaviour of the support system, and the associated ground deformations are important problems. This paper represents two case studies with well-documented data of field measurements, which were numerically analysed. The case histories represent the top-down construction and the typical/conventional down-top construction. The analyses were performed using the finite element program PLAXIS 2D. The hardening soil small strain model was implemented in the analyses. After verification of the numerical model, a parametric study was performed on the case study to investigate the effect of thermal shrinkage on the strutted slabs, the penetration length on the supporting wall, and the stiffness of the walls on the resulting deformation. Moreover, a parametric study was performed on the different material models in PLAXIS 2D.

Keywords

Deep excavation; soft clay; top-down construction method; down-top construction method; Finite element.

1- INTRODUCTION

Two case studies, namely, Sukhumvit MRT Subway Station in Bangkok and Chicago State Subway Renovation, were used to validate the utilized approach and to calibrate the constitutive parameters derived mainly from field data and index parameters. The two cases were monitored; these measurements were being used to compare actual field deformations and the calculated ones using the finite element method.

The case study (Sukhumvit MRT Subway Station) represents the top-down construction, while the other case study (Chicago State Subway Renovation) represents the typical/conventional down-top construction. The two different construction techniques were selected to investigate the construction methodology on the ground and structure responses for deep excavation in soft clay.

The Hardening soil small strain model (HSs) was utilized to model the soil during the excavation following the recommendation of PLAXIS 2D. The loading modulus E_{50} in the HS model should be determined from the tri-axial testing of undisturbed samples. As obtaining such samples is difficult in soft Clay, the approach presented by Richard J. Finno et al., 2005 to obtain the modulus (E_{50}) using the undrained shear strength (S_u) and the effective vertical stress (σ_v').

2- CASE STUDIES

2.1 Sukhumvit Subway Station, Bangkok, Thailand Case Study

Sukhumvit MRT station is an underground station in the Blue Line in Bangkok. It is located in a congestion area and surrounded by many commercial and residential buildings.

Based on the field and laboratory studies (Surarak, 2010), the soil profile comprises the following layers; Bangkok soft clay (BSC), medium clay, stiff clay, and hard clay. The groundwater was encountered at a depth of 1.5 m below the ground surface.

The field vane shear and the lab triaxial (CK_o-U) tests were performed for the soft to medium stiff and the stiff to hard clays to identify the undrained shear strength. Both tests were conducted along the alignment of the Bangkok MRT Extension projects. The results from the field and lab tests to evaluate the values of the undrained shear strength showed that an undrained ratio is ranging between 0.22 and 0.3.

Sukhumvit station was constructed by the top-down construction method with an excavation width 23m. The retaining system was a 1m thick diaphragm wall. The diaphragm wall was used as a part of the permanent structure. Three Levels of concrete slabs were used as struts for the diaphragm walls, as shown in Figure (10).

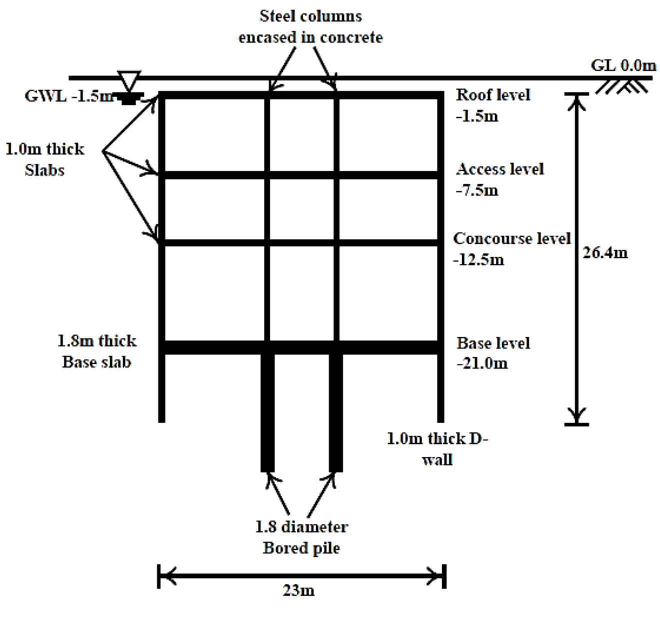

Figure (10): Geometry of the Sukhumvit Station (after, Surarak, 2011)

2.2 Chicago-State Subway, Chicago, USA Case Study

The Chicago Department of Transportation (CDOT) authorized the renovation and expansion of the existing subway station. The station renovations which were constructed by using the cut and cover technique. The excavation extended to 12.2m to expose the current subway station and tunnels. The project layout, including the monitoring system and cross-lot struts numbers and distributions, is shown in Figure (**11**).

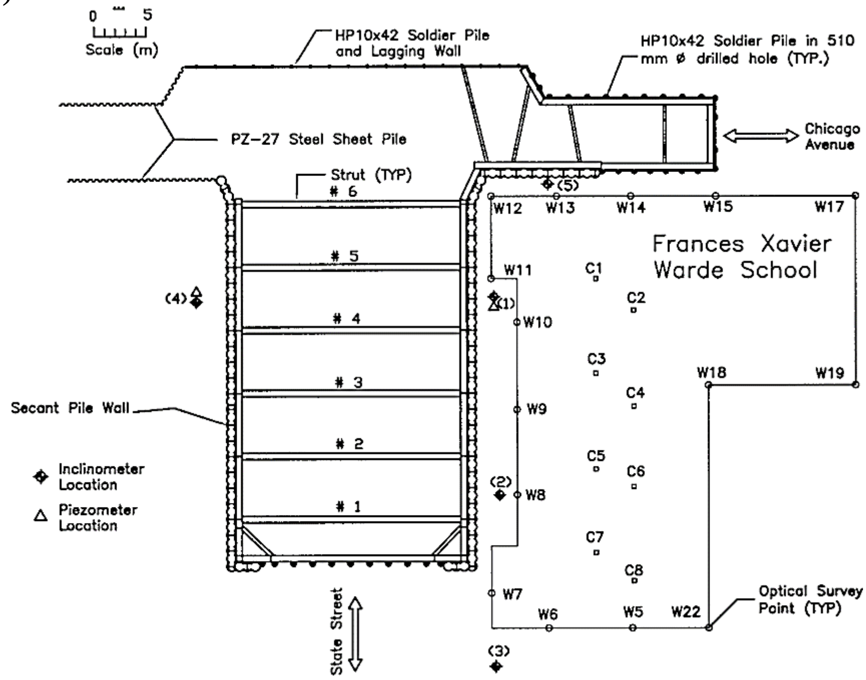

Figure (11): Plan view of Chicago renovation of state street subway and the monitoring instruments (after, Finno & Calvello, 2005)

Based on the field and laboratory studies (Finno and Calvello 2005), the soil profile comprises the following layers; Upper and Lower Blodgett (soft clay), Deerfield (medium stiff clay), Park Ridge (stiff to very stiff clay), and Tinely (hard clay). The elevations are given in terms of Chicago City Datum (CCD), as shown in Figure (3).

The undrained shear strength was determined from the field vane test, unconfined compression test, pocket penetrometer test, and triaxial test. Also, it could be determined from the index properties data which were performed on soil samples at or next to the project site. The slightly over consolidation ratio (OCR) in the soft clay layer was considered around 1.0 (Roboski 2001).

Renovation of Chicago State Street was constructed using the down-top construction method. The excavation pit had a width of 24m. The retained system used for the project was a secant pile wall with three levels of support.

Figure (12) shows a section view of the excavation support system. The top-level of supports consisted of cross-lot pipe struts. Tieback anchors were used for the second and third levels of support.

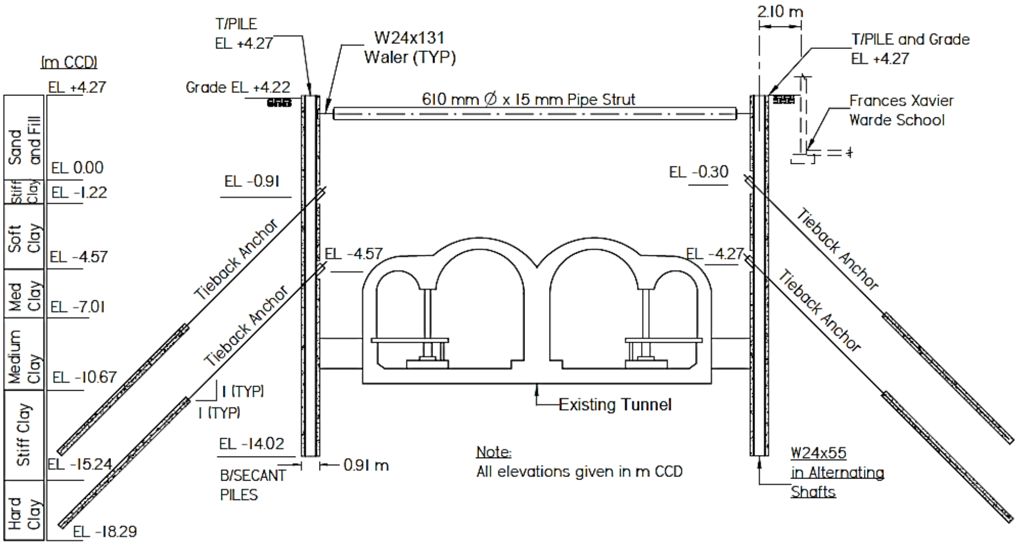

Figure (12): Section view of the support system (after, Finno and Calvello 2005)

3- VALIDATION OF THE TWO CASE STUDIES

The PLAXIS 2D plane-strain finite program was used to verify the case studies. The models consist of only half of the box stations, as the stations are symmetric. The Hardening soil small strain model (HSs) was used to represent the performances of the deep excavation, as recommended by the program manual. The stiffness parameters in loading (E_{50}^{ref}) that could effectively be estimated from laboratory data conducted on undisturbed samples. As undisturbed samples in soft clays are prohibitively difficult, the following approximation was adopted in the analyses (Finno and Calvello 2005):

$$E_{50}/S_u = 800\ S_u/\sigma_v' \qquad (1)$$

Where Su is the undrained shear strength, and σv’ is the effective vertical stress.
The HSs model applies the initial shear modulus (G_0). Recalling to Fahey and Carter (1993), a relation between small-strain stiffness (E_0) and secant stiffness (Es) in terms of (1/Fs=Mobilization factor (t/t_{max})) was devised as in Equation 2.

$$\frac{E}{E_0} = 1 - \left(\frac{1}{fs}\right)^{0.3} \qquad (2)$$

3.1 Validation Analysis of Bangkok Case Study

Four phases of analyses were chosen to represent the stages of excavations. The results of each phase were determined at the time of execution of each slab of the three platform slabs, and base slab. At the construction of the four slabs, the thermal shrinkage effect on the four slabs was considered and represented by a temperature change of 35 °C following the recommendation of Dong et al. (2014).

The diaphragm wall, platform slab, base slab, column, and pile were modeled as plate elements. The concrete stiffness of the diaphragm wall was tentatively reduced by 30 percent ($E_{concrete}$ x 0.7) to account for the cracking due to the moment straining actions (Ou 2006).
The Hardening soil model (HSM) and the Small strain model (HSs) were used to represent the Bangkok soils and their parameters, as summarised in Table 1 and Table 2. After determining both soil and structural parameters, the analysis was carried using these parameters. The horizontal movements of the wall were generated as a result of

excavation. The lateral deformations resulting from the finite element analysis and the extracted lateral deformations from the monitoring instruments at the four phases are shown in Figure (13).

Table 1: HSM parameters for Bangkok soil

Soil layers	BSC Soft clay	MC Medium clay	SC 1 Stiff clay	SC 2 Stiff clay	HC Hard clay
γ_b (KN/m^3)	16.5	17.5	19.5	20	20
c' (kPa)	2	5	8	12	24
ϕ'(°)	24	26	28	28	28
E_{50}^{ref} (MPa)	10.1	62.2	76.8	109.4	172.4
E_{oed}^{ref} (MPa)	5.1	31.1	38.4	54.7	86.2
E_{ur}^{ref} (MPa)	30.41	186.4	230.4	328.3	517.4
υ_{ur}	0.2	0.2	0.2	0.2	0.2
m*	1	1	1	1	1
R_f*	0.9	0.9	0.9	0.9	0.9
K_o^{nc}*	0.59	0.56	0.53	0.53	0.53

* m: power for the stress-level dependency of stiffness
*R_f: failure ratio q_f/q_a (default =0.9)
* K_0^{nc}: K_0-value for normal consolidation

Table 2: HSs model parameters for Bangkok soil

Soil layers	BSC Soft clay	MC Medium clay	SC 1 Stiff clay	SC 2 Stiff clay	HC Hard clay
Shear modulus G_0^{ref} (MPa)	22.2	136.8	168.9	240.6	379.3
Shear strain $\gamma_{0.7}$	0.034	0.03	0.025	0.025	0.025

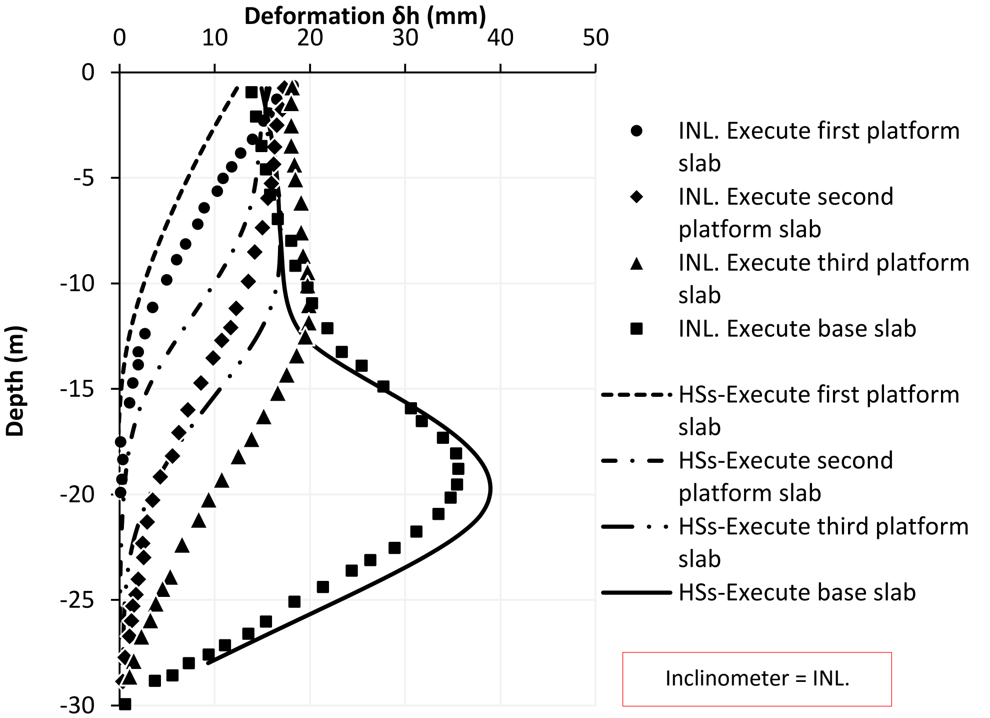

Figure (13): Comparison between the monitoring and the finite element results for the Bangkok case study

3.2 Validation Analysis of Chicago Case Study

Three phases of analyses were chosen to simulate stages of excavation. These phases represented excavation soil to levels (-1.8), (-4.8), and (-7.9) CDD (Chicago city datum).

The Secant pile was modeled as a plate element. Strut and tiebacks were modelled as a node-to-node anchor. The concrete stiffness of the secant pile wall was tentatively reduced by 30 percent ($E_{concrete}$ x 0.7) to account for the cracking due to the moment straining actions (Ou 2006).

The Hardening soil model (HSM) and the Small strain model (HSs) were used to represent the Chicago soil and their parameters, as summarised in Table 3 and Table 4.

All soil parameters of soil, secant pile wall, strut, and tiebacks were set in a finite element model. The lateral deformations resulting from the finite element analyses and the extracted lateral deformations from the monitoring instruments at the three phases are shown in Figure (14).

Table 3: HSM parameters for Chicago soil

Soil layers	Soft clay	Medium clay	Stiff clay	Very stiff clay
γ_b (KN/m^3)	18	18	19	19
c' (kpa)	1	1	1	1
$\phi'(°)$	22	28	32	35
E_{50}^{ref} (Mpa)	7.6	15	67	85
E_{oed}^{ref} (Mpa)	4	7.5	33	42
E_{ur}^{ref} (Mpa)	23	45	200	254
υ_{ur}	0.2	0.2	0.2	0.2
m	1	1	1	1
R_f	0.9	0.9	0.9	0.9
K_o^{nc}	0.625	0.53	0.47	0.42

Table 4: HSs model parameters for Chicago soil

Soil layers	Soft clay	Medium clay	Stiff clay	Very stiff clay
Shear modulus G_0^{ref} (MPa)	17	33	147	187
Shear strain $\gamma_{0.7}$	0.02	0.017	0.015	0.015

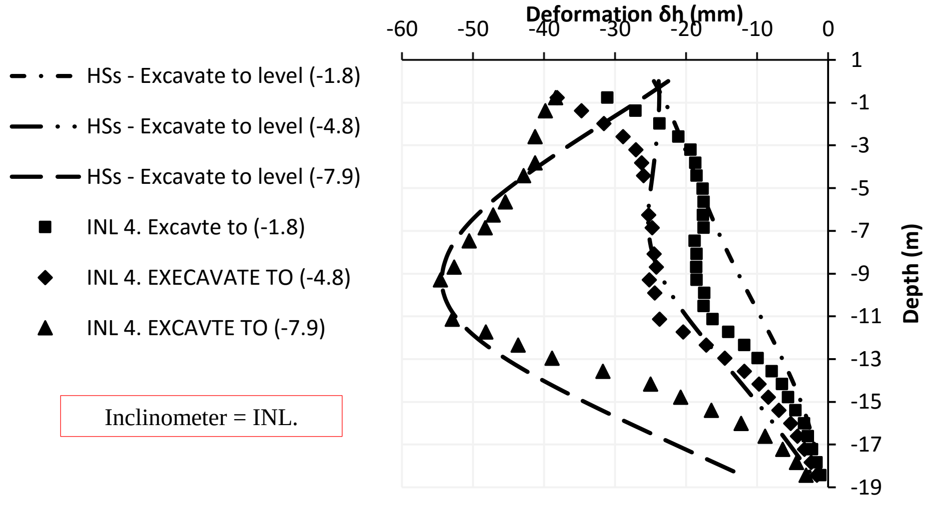

Figure (14): Comparison between the monitoring and the finite element results for the Chicago case study

4- PARAMETRIC STUDY

4.1 Thermal Shrinkage Effect

The concrete structures (e.g., diaphragm walls, floor slabs, and piles) may be exposed to the thermal contraction and expansion, cracks, and creep during the curing process. This thermal shrinkage caused due to hydration,chemical reaction, and the variation of ambient temperature. The horizontal support system (e.g., floor slabs, beams) is usually tied to the retaining wall, which constrains all possible degrees of freedom. The real connections may not be rigid, and rotations may be allowed so that gaps may be developed during the excavation. An additional wall displacement may occur to make the horizontal support in compression and interact with the retaining wall. This further wall displacement can also be considered by the thermal shrinkage of the horizontal support. The thermal shrinkage effect of concrete structural elements can be added in the numerical analysis through the combination of a coefficient of thermal α expansion and a temperature change (ΔT). The average value of α is 10^{-5}/°c. The temperature varies in the concrete during the curing process. Figure (15) shows the relationship between different temperature change (ΔT) and the max lateral deformations of the diaphragm wall (δ_{hm}) at different wall thicknesses and lengths. The results show a close linear relationship.

Figure (**16**) also shows the relationship between temperature change (ΔT) and the max vertical settlement of soil at different wall lengths ($L_{D.W}$). The results also indicate a linear relationship.

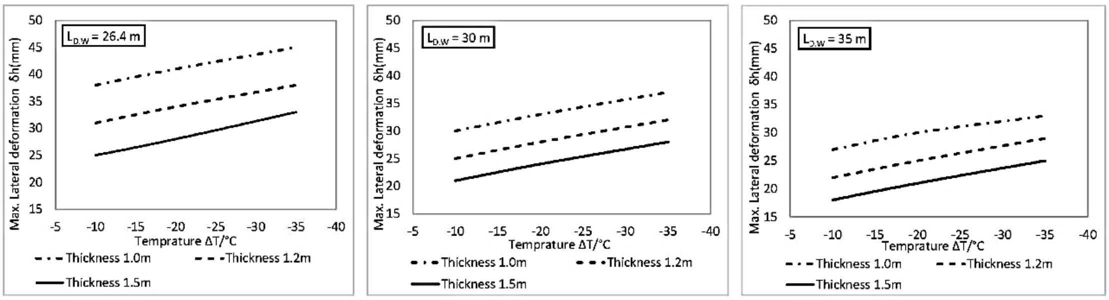

Figure (15): Relationship between maximum lateral deformation and temperature change

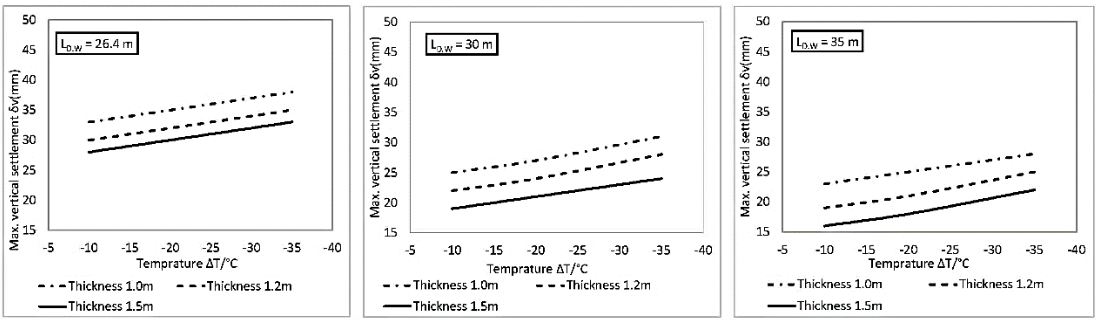

Figure (16): Relationship between maximum vertical settlement and temperature change

4.2 Wall Thickness Effect

The diaphragm wall was considered the main support element for excavation, so its depth is a very critical factor. It has a significant effect on deformations of soil and wall itself. Change of diaphragm wall depth (t) was adopted to find out its influence on deformations. Variable thicknesses of the diaphragm wall were applied in analysis, such as 1.2m and 1.5m. Figure (17) shows the relationship between the lateral wall deformations change (δ_h/ δ_h at t=1.0m) and the wall thickness at fixed wall-length 30m. Also, Figure (18) shows the relation between the vertical settlement change (δ_V/ δ_V at t=1.0m) and the wall thickness.

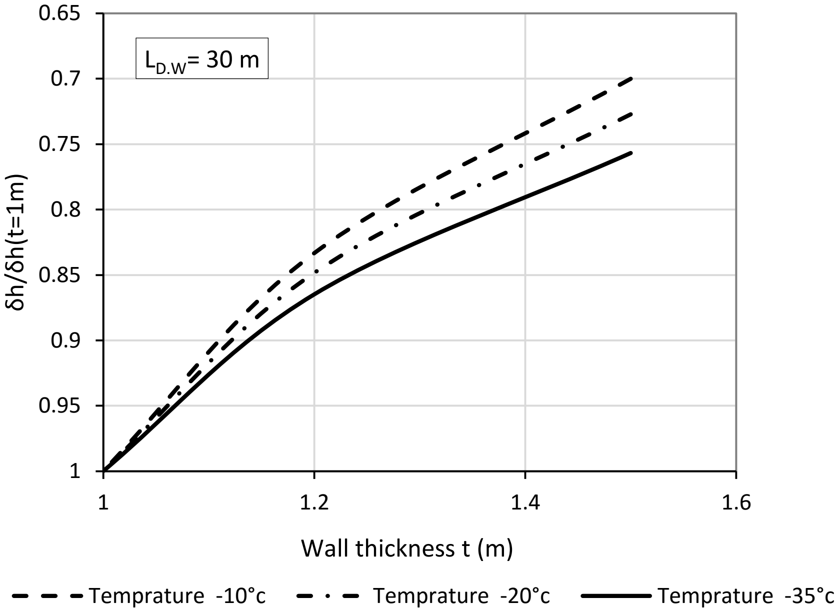

Figure (17): Relation between lateral deformation change and wall thickness

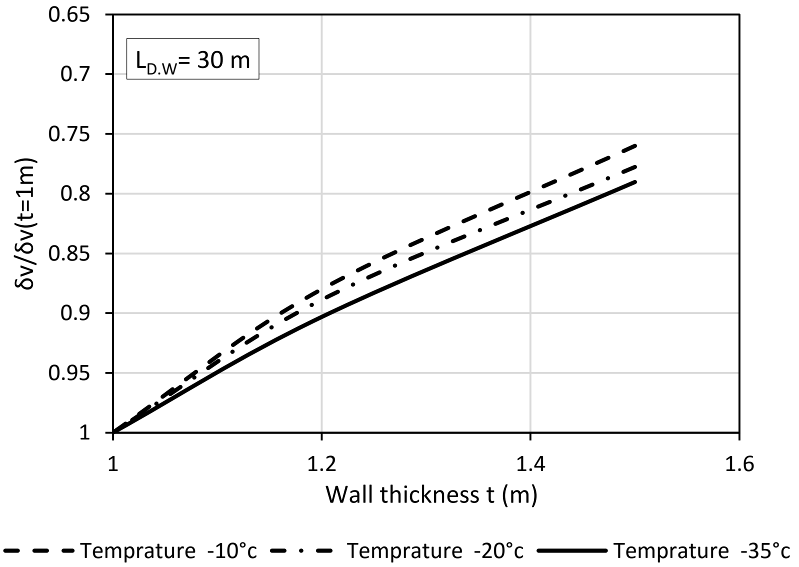

Figure (18): Relation between vertical settlement change and wall thickness

4.3 Diaphragm Wall Length Effect

The impact of diaphragm wall length is an essential factor as it supports the excavation. The effect of diaphragm wall length on horizontal and vertical deformation is necessary. Figure (19) shows the relations between the lateral deformations change (δ_h/ δ_h at $L_{D.W}$ =26.4m) and wall-length at wall thickness 1.0 m. Also, Figure (20) shows the relationships between the vertical settlement change (δ_V/ δ_V at $L_{D.W}$ =26.4m)and the wall-length.

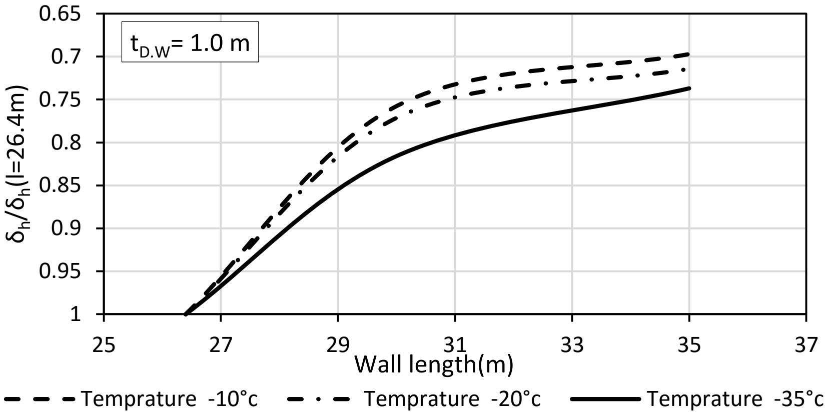

Figure (19): Relationship between lateral deformation change and the wall-length at wall thickness (t =1.0m)

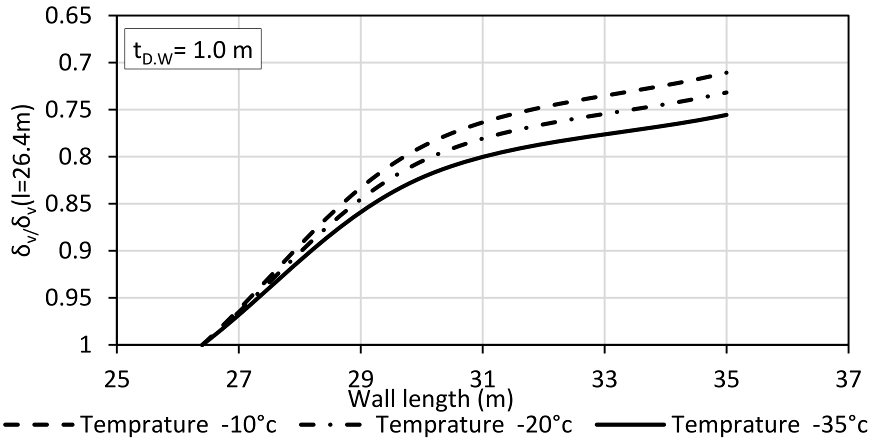

Figure (20): Relationship between the vertical settlement change and the wall-length at wall thickness (t =1.0m)

4.4 Analysis with Different Constitutive Models

The parameters used in Mohr-Coulomb are different from the Hardening soil model. The Linear-Elastic Perfectly Plastic Mohr-Coulomb model involves five input parameters, i.e., Young's modulus (E) and Poisson's ratio (ν) for soil elasticity; cohesion (c), friction angle (φ) and dilatancy angle (ψ) for soil plasticity. In the Modified Mohr-Coulomb model, the stiffness outside the excavation pit (behind the wall) is E, and inside the excavation is 3E, as shown in Figure (21).

Figure (22) shows the results of lateral deformations of the wall for the different constitutive models.

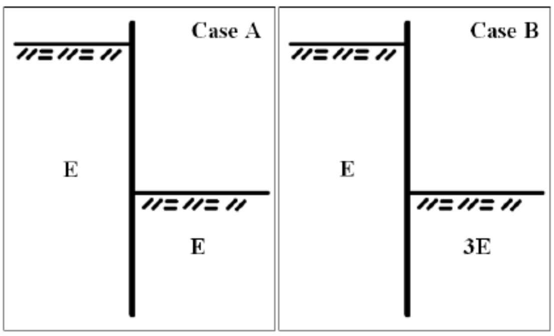

Figure (21): Case (A) for Mohr-Coulomb and case (B) for Modified Mohr-Coulomb (after, Johansson and Sandeman, 2014)

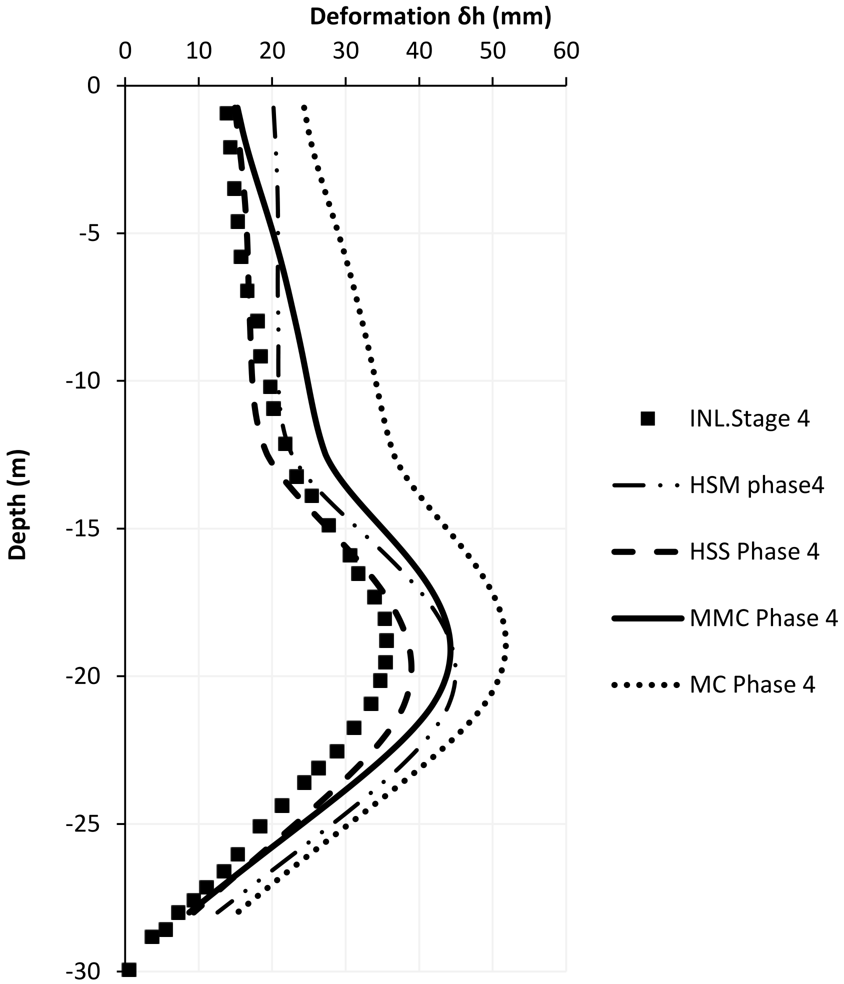

Figure (22): Comparison between different constitutive models

5- Conclusions

1. Through the analysis of the two case studies using the approach proposed by Finno and Calvello (2005) to determine the loading stiffness parameter (E_{50}), the results of the wall deformations were compatible with the measured deformations from the site.

2. In the case of Bangkok, the thermal shrinkage effect on slabs should be considered in the analysis of the system as it has a noticeable impact on the deformations. The temperature change is regarded as 35°, referring to Dong et al. (2014).

3. In the case of construction by the top-down method of the method, although the depth of excavation up to 21m, the diaphragm wall moved 35 cm (field measurements), but conversely in the case of construction by the down-top method and the depth of excavation 12m, the secant pile wall moves 55 cm (field measurements). Based on the results of the movements of the walls for the two construction techniques, the top-down method showed less deformations.

4. From the parametric study of Bangkok, it observed that the shrinkage of the supported slabs has a significant effect on the wall deformation, and ground settlement in all the construction phases. Therefore, the effect of the thermal shrinkage should be taken into consideration in design of a deep excavation shoring system. On the other hand, the wall thickness has a noticeable impact on wall deformations, and the wall-length has a pronounced effect on the last phase of soil excavation on the wall deformations.

5. From the comparison between different constitutive models, The Mohr-coulomb model gives values of deformations higher than the values from the modified Mohr-Coulomb; conversely, the hardening soil model showed values of deformations compatible with Modifies Mohr-coulomb model. The lateral deformations from the Small-Strain Hardening soil model are less than the deformation of the Hardening soil model. The most compatible model with the inclinometer reading is the Hardening soil model small strain.

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