Lateral Movement of Rigid Diaphragm Wall and Associated Ground Movement of Deep Excavation in Bangkok Subsoil

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Abstract

Bangkok, a densely populated city with limited land availability, requires the construction of high-rise buildings with underground basements and parking spaces. Therefore, deep excavation work for underground structures is important and understanding the lateral displacement of retaining walls is crucial for assessing impacts on adjacent structures and preventing instability. Monitoring data of diaphragm wall movement from over 30 deep excavation projects in Bangkok was collected and analyzed to determine influencing factors and parameters of lateral movement of rigid diaphragm wall. Diaphragm walls' thickness is ranging from 0.6 to 1.50 m with toe depths between 14m and 65m, with excavation depths (He) varying from 6 to 36 m. Key parameters including the relationship between maximum lateral displacement and excavation depth, depth of maximum lateral displacement, soft clay depth influence, and the influence zone of the surface settlement were examined. The study found that maximum lateral wall displacements ranged from 0.10%He to 0.27%He for the top-down method, and from 0.20%He to 0.50%He for the bottom-up method. The maximum lateral displacement typically occurred at a depth between 0.5He to 1.5He. The results also suggest that the excavation induced ground settlement may be affected up to 2.5 times the excavation depth.

Keywords: Diaphragm wall, Lateral displacement, Deep excavation, surface settlement

1. Introduction

Deep excavations are commonly carried out in Bangkok for underground transportation, basement construction, and infrastructure projects. However, the city's subsurface conditions pose significant geotechnical challenges due to the presence of soft clay layers with low shear strength and high compressibility. These soil properties make excavation-induced ground movements a critical concern, as excessive lateral wall displacement and ground settlement can lead to structural damage and serviceability issues for adjacent buildings and infrastructure. To address these risks, rigid diaphragm walls are frequently employed as retaining structures in deep excavations. Extensive research has been conducted on retaining wall movements caused by excavation work in Bangkok. Phienwej and Gan (2003) [17] examined the characteristics of ground movements in the Bangkok subsoils. While their research provided insights into ground movements in this region, it was primarily based on a limited dataset of only 12 braced excavations. Aye et al. (2019) [3] conducted a study by gathering, analyzing, and interpreting field data on the behavior of rigid diaphragm walls in response to braced excavation projects across 30 sites in Bangkok and the wall thickness ranges from 0.6m to 1.0m, and the excavation depths varies from 6m to 21m. Likitlersuang et al., (2013) [11] performed a finite element analysis of the Bangkok MRT underground construction project and compared the results with field measurements. Teparaksa et al., (2019) [19] investigated the comprehensive assessment of diaphragm wall displacements by comparing the predictions of finite element method analysis with field measurements for two distinct construction projects in Bangkok, each utilizing different construction techniques. Previous studies on diaphragm wall movements in Bangkok have primarily relied on finite element analysis, and the available field monitoring data has been limited in scope, often lacking comprehensive consideration of various wall thicknesses, excavation depths, and a comparison of top-down and bottom-up construction methods. Consequently, updating the field-monitored data on diaphragm wall performance across a range of thicknesses and deeper excavation depths is necessary for guiding future deep excavation projects. This paper aims to provide a better understanding of the examination of diaphragm wall lateral displacement, as well as some of the parameters that influence wall movement.

2. Database of Deep Excavation

2.1 Typical Soil Profile

Bangkok rests upon thick alluvial deposits from the Quaternary era, primarily consisting of clay and sand layers extending over 400 meters in depth (Cox 1970) [6]. Table 1 shows the typical geotechnical parameters of Bangkok soil for diaphragm wall design.

As shown in Table 1, the typical soil profile in Bangkok features a thick, soft marine clay layer at the top, followed by a thin, medium clay layer, and then alternating stiff clay and dense sand layers. The soft clay has an undrained shear strength ranging from 10 to 25 KN/m^2, while the stiff and hard clay layers have undrained shear strengths around 150 and 200 KN/m^2, respectively. The dense sand layers are estimated to have internal friction angles between 31° and 33°. Excessive groundwater extraction led to a decline in pore water pressure from 1988 to 1997, causing land subsidence. This resulted in a ban on groundwater pumping in Bangkok in 1997, which allowed pore water pressure to recover until 2011. Currently the piezometric level of Bangkok is stable at 13 meters below ground level.

Table 1 Typical geotechnical parameters of Bangkok for diaphragm wall design

Depth (m)		Soil Description	γ_t (KN/m^3)	C_u (KN/m^2)	SPT N
From	To				
0	2	Fill and Weathered Crust	18.0	-	
2	13	Soft Clay	16.0	10-25	
13	24	Medium to Stiff Clay	18.0	50-140	
24	37	Medium to Dense Silty Sand (First Sand)	20.0		20-50
37	46	Hard Clay	20.0	>200	
46	60	Dense to very Dense Sand (Second Sand)	20.2	-	50-70

2.2 Summary of Database

The data analyzed in this study were obtained from deep excavation projects within the Bangkok subsoil. Diaphragm walls (D-wall) constructed in these projects primarily had thicknesses ranging from 0.6 m to 1.5 m. Figure 1 outlines key parameters for the top-down construction method, including the maximum excavation depth, embedded depth, and the depth of the soft clay layer. Figure 2 depicts the same parameters for the bottom-up construction method. In this study, the diaphragm wall depth for the top-down approach was generally greater than the bottom-up method. The soft clay layer typically ranged from 11 to 15 meters, with an average depth of approximately 13 meters. The D-wall toe depth varied significantly, ranged from 14 meters to 65 meters. Excavation depths across the projects ranged from 4 meters to 36 meters. These studies highlight the differences in design considerations and excavation conditions between the top-down and bottom-up construction methods.

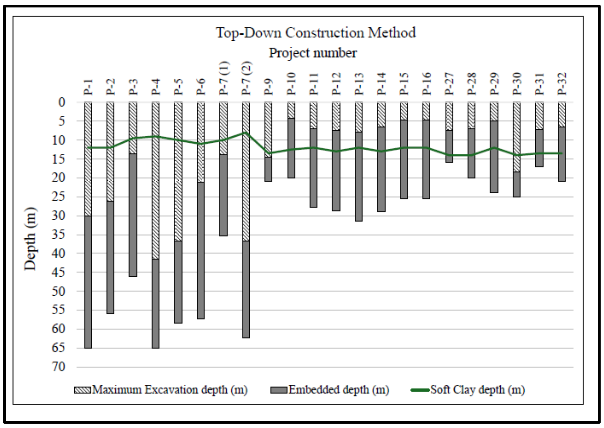

Fig. 1 Maximum excavation depth, embedded depth and soft clay depth profile for top-down construction method

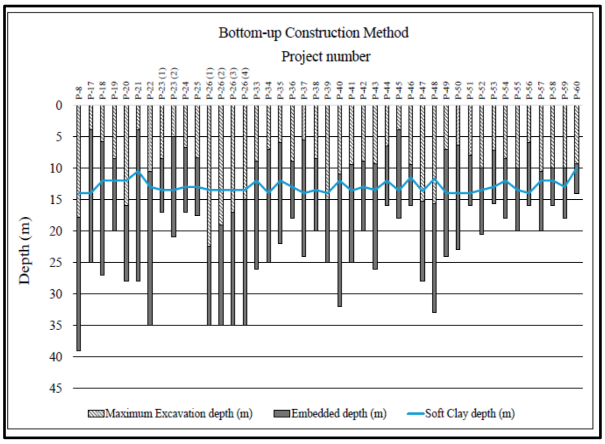

Fig. 2 Maximum excavation depth, embedded depth and soft clay depth profile for bottom-up construction method

3. INTERPRETATION OF RESULTS

The data on lateral displacement of the diaphragm wall has been analyzed, and the factors affecting the wall's behavior have been interpreted.

3.1 Effect of construction method on wall movement

The relationship between maximum lateral wall displacement and maximum excavation depth for both the top-down and bottom-up construction methods are shown in Figure 3.

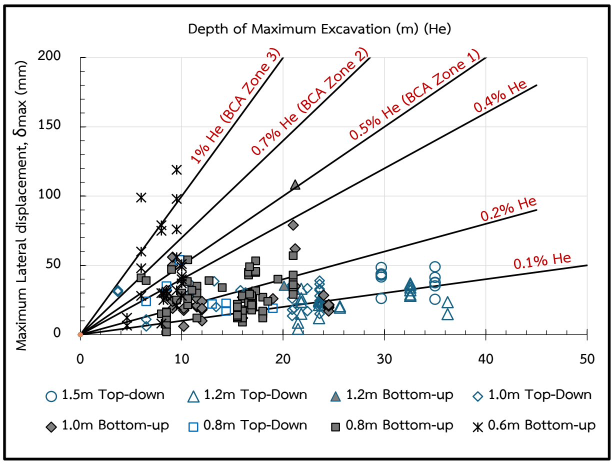

Fig. 3 Measured Maximum Lateral Displacement (δmax) versus Maximum Excavation Depth (He)

According to the graph, the average lateral displacements for the different Diaphragm wall (D-wall) thicknesses for the top-down methods are as follows: 0.12% He for 1.5 m, 0.1% He for 1.2 m, 0.22% He for 1.0 m, and 0.27% He for 0.8 m. For the bottom-up methods, the average lateral displacements are 0.23% He for 1.0 m, 0.2% He for 0.8 m and 0.5% He for 0.6 m. The observations made in this study align with the findings of Boonyarak et al. (2024) [5], who also reported similar trends in the displacement behavior of diaphragm walls. And the top-down method generally leads to lower lateral displacements than the bottom-up approach. This is due to the increased stiffness from the slab in the top-down technique, which improves the overall diaphragm wall stability during excavation. Table (2) presents average lateral displacements for diaphragm wall constructions from other studies conducted in various soil types. The global data in the Table is intended solely to explore findings in various parts around the world.

Table 2. Summarized average lateral wall displacement reported by various researchers

Study	Ground Condition	Wall type	Average δmax/He (%)
Ou et al. (1993) [15]	Soft Clay (Taipei Soft Soil)	D-Wall (bottom-up method)	0.4
Phienwej et al. (1995) [16]	Soft Clay (Bangkok)	D-Wall (bottom-up method) (thickness 0.8 to 1.0m) D-Wall (top-down method) (thickness 0.8 to 1.0m)	0.4 0.2
Li et al. (2015) [12]	Silty Clay	D-Wall	0.2
Zhang and Goh (2016) [20]	Residual soils	D-Wall with 4 struts.	<0.1
Hsiung et al. (2016) [8]	Loose to medium dense sands	D-Wall (bottom-up method)	0.32
Hefny et al. (2020) [9]	Sandy Silty Clay - very dense to fine sand	D-Wall	0.11

Boonyarak et al. (2024) [5] pointed out that wall thickness had minimal influence on the lateral displacement of diaphragm walls for both construction methods. This finding aligns with the present study, which similarly indicates negligible variations in displacement due to differences in wall thickness. However, for the bottom-up construction approach, the largest lateral displacement occurs in diaphragm walls, with lower rigidity diaphragm walls particularly that of thickness 0.6 m. Notably, the 0.6 m diaphragm wall displacement falls within the Zone 2 and Zone 3 categories of the Singapore Building and Construction Authority guidelines (BCA 2013) which requires caution when constructing near sensitive structures [4]. Excessive displacement in these zones can impact nearby infrastructure, necessitating careful management during construction.

3.2 Observed depth of maximum lateral wall movement

Identifying the depth of maximum lateral displacement in diaphragm wall construction is crucial, as it can reveal potential weak points. Strengthening measures, such as supplementary support or reinforcement, can be applied at this crucial depth to enhance stability. Monitoring systems can also be implemented in this critical zone to ensure structural integrity. The relationship between the depth of maximum lateral displacement ($H\delta_{max}$) and excavation depth (He) is shown in Figure 4.

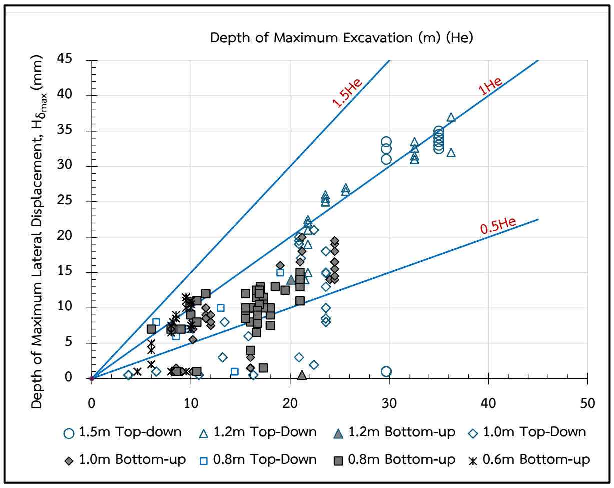

Fig. 4 Measured Depth of Maximum Lateral Displacement ($H\delta_{max}$) versus Maximum Excavation Depth (He)

In Figure 4, around 57% of the observations lie in the range of 0.5 He to 1.5 He. In this study, the maximum lateral displacement consistently occurred at depths between 0.5 He and 1.0 He times the excavation depth below the ground surface, regardless of the diaphragm wall thickness. Furthermore, a maximum lateral displacement of 28% was observed at the top of the wall. The results indicate that the depth of maximum lateral displacement, $H\delta_{max}$, does not differ significantly between bottom-up and top-down excavation methods, aligning with the conclusions drawn by Boonyarak et al. (2024) [5]. Moormann (2004) [13] have shown that the maximum lateral displacement of the wall for most deep excavations in soft soil was observed at a depth of 0.5H to 1.5H below the ground surface. Phienwej and Gan (2003) [17] found that the maximum lateral displacement often occurs during the initial excavation stages and is strongly influenced by the free-standing height of the wall, typically ranging from 1.0 to 3.0 meters. Notably, the current study found that the depth of maximum lateral displacement, $H\delta_{max}$, is mostly located above the maximum excavation depth.

3.3 Soft clay depth influence

Understanding the influence of soft clay thickness on wall behavior is crucial for developing more effective design strategies, safety and stability of diaphragm wall-supported deep excavations. Figure 5 depicts the relationship between depth of soft clay and excavation depth ratio with normalized maximum lateral displacement of the diaphragm wall in Bangkok subsoil. The study investigated two common scenarios: Case 1, where the excavation depth is less than the soft clay depth (Hsc>He), and Case 2, where the excavation depth exceeds the soft clay depth (He>Hsc). In bottom-up construction, the data indicates that lateral displacements are more significant when the excavation depth is less than the depth of the soft clay layer. In these situations, the system displays reduced structural integrity, and the wall's decreased rigidity especially for thinner diaphragm walls (0.6m thickness) causes substantially greater lateral displacements. In contrast, when the excavation extends deeper than the soft clay layer, the lateral displacement decreases due to the enhanced confinement and increased stiffness provided by the underlying stronger soil layers.

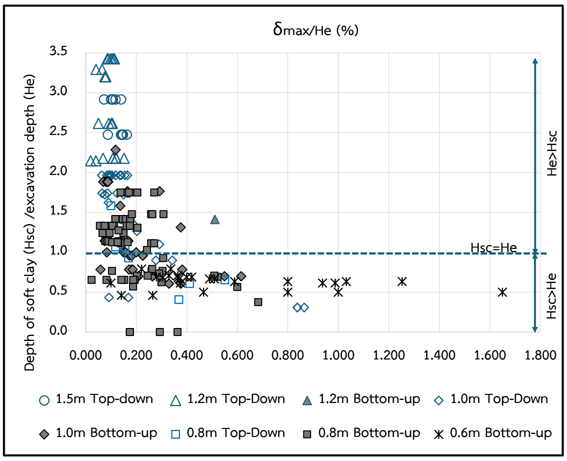

Fig. 5 Relationship between Normalized Maximum Lateral Displacement versus Soft Clay Depth and excavation depth ratio

The top-down construction method is less sensitive to the depth of soft clay compared to the bottom-up method. This is due to the greater axial rigidity of permanent slabs, which provide stronger lateral support and minimize elastic shortening, effectively limiting wall movement. This demonstrates the efficiency of the top-down method in controlling displacement, even in challenging ground conditions. According to Boonyarak et al., (2024) [5], accounting for the relative depth of soft clay layers is critical in diaphragm wall design, as it significantly impacts lateral displacement, especially in shallow excavations where the potential for excessive movement is greater.

3.4 Prediction of Surface Settlement from Measured Wall Lateral Displacement

Previous researchers often used numerical finite element models to predict excavation-induced surface settlement. Aye et al. (2006) [1] adopted Bowles' suggestion that ground settlement is a function of ground loss due to retaining wall deflection, and calculated settlements at specified distances by assuming a parabolic settlement distribution within the influence zone. By using the method proposed by Aye et al. (2006) [1], surface settlement can be calculated from diaphragm wall movements measured by inclinometers, without the need for FEM analysis.

Depending on the ground settlement influence distance, geotechnical instrumentation and monitoring can be planned within the affected zone. This study considers the MRT Silom station for settlement prediction. The findings from Phienwej et al. (2012) [18] study which used the Hardening Soil and Mohr-Coulomb models to predict Silom Station results and compared them to actual measurement data, are included in Figure 6 and compared to the current investigation's results.

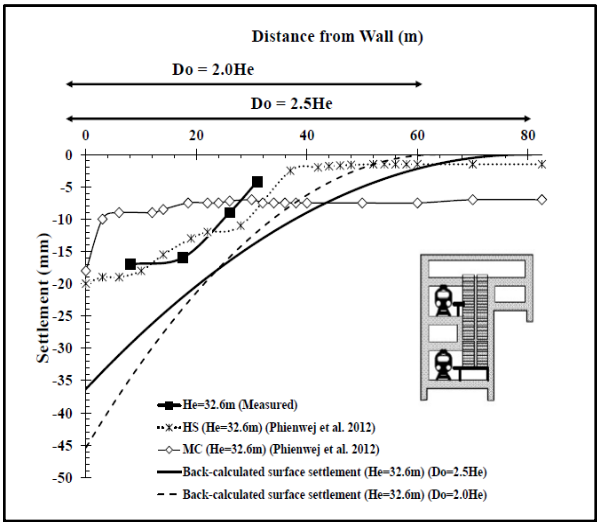

Fig. 6 Back-calculated surface settlement with different influence distance from the wall

According to Figure (6), the maximum excavation depth for Silom station is 32.6m. The influence zone behind the wall was considered as 2.5 times the excavation depth (2.5He) and 2.0 times the excavation depth (2.0He). The predicted influence distance behind the wall was calculated as 65 m for 2.0He, and 82 m for 2.5He. The maximum predicted surface settlement was 46 mm at the 2.0He influence distance, and 36 mm at the 2.5He influence distance. The field monitoring results of the surface settlement points were within the predicted surface settlement profile calculated using the method proposed by Aye et al., (2006) [1] and influence distance of 2.5He is more reliable. Boonyarak et al. (2024) [5] recommended that the influence distance from the wall can be taken as 2.5 times the excavation depth, which is consistent with the findings of the current study. Maher et al., (2022) [14] summarized and examined the settlement influence zone based on the findings of numerous researchers and shown in Table (3).

Table 3. Summary of the Reported Settlement Influence Zone for rigid wall types by various researchers

Study	Ground Condition	Influence zone (D_0)
Leung and Ng (2007) [10]	Soft clay and sands	2He
	Stiff clay	3He
El-Nahhas (2006) [7]	Nile alluviums	1.5 – 2.0He
Abdel-Rahman and El-Sayed (2009) [2]	Nile alluviums	3.8 He (shallow found.) 2.2 He (deep found.)
Zhang et al. (2018) [21]	Bukit Timah granite residual soil	2-3 He
Hefny et al. (2020) [9]	Sandy silty clay, dense to fine sand	2 He

Maher et al., (2022) [14] highlighted that the mean settlement influence zone (D_0) typically extends to 2.0He in soft clays, 3.0He in stiff clays, and 2.0He in sands.

4. Conclusions

This study investigates the key factors affecting lateral displacements of diaphragm walls over 30 deep excavation projects within Bangkok's soft soil conditions. The data analyzed were obtained from the deep excavation projects supported by the diaphragm walls, varying in thickness from 0.60m to 1.5m, constructed using both top-down and bottom-up methods. The following conclusions can be drawn from the analysis:

(a) The lateral displacement of the diaphragm wall is minimally affected by construction methods and wall thickness, if wall rigidity is sufficient ensuring minimal impact on deflection.
(b) The maximum lateral displacement typically occurs between 0.5He and 1.5He, due to the lower axial rigidity of the soil beneath the excavation compared to the base slab.
(c) Lateral displacement is influenced by soft clay depth in bottom-up construction methods. From the analyzed results, lateral wall displacement is higher when soft clay depth > Excavation depth (Hsc>He) in bottom-up method.
(d) The field monitoring data for surface settlement points falls within the empirically predicted surface settlement profile calculated from the lateral wall movement, suggesting this approach can provide a reasonable initial estimation without needing complex and time-consuming numerical modeling. The influence zone for the ground surface settlement behind the wall can be taken as 2.5 times the excavation depth.

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References

[1] Aye, Z.Z., Karki, D., and Schulz, C. (2006). Ground movement prediction and building damage risk-assessment for the deep excavations and tunneling works in Bangkok subsoil. *In International Symposium on Underground Excavation and Tunnelling.* Vol. 281. Bangkok. p. 297.

[2] Abdel-Rahman, A.H., & El-Sayed, S.M. (2009). Foundation subsidence due to trenching of diaphragm walls and deep braced excavations in alluvium soils. In *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4)* (pp. 1935-1938). IOS Press.

[3] Aye, Z. Z., Boonyarak, T., Chea, S., Roth, C., & Thasnanipan, N. (2019). Rigid diaphragm wall response to deep excavation works in Bangkok. In *Proceedings of the 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering,* Taipei, Taiwan, 14–18 October 2019, pp.14-18.

[4] Building and Construction Authority. (2013). BCA BC 15.0.3 VOL 11. BCA Singapore.

[5] Boonyarak, T., Aung, A.Y., Kamchoom, V. and Aye, Z.Z. (2024). Diaphragm wall lateral movement in deep excavations in Bangkok clays: impacts and influencing factors. *Canadian Geotechnical Journal*, (ja) (DOI: 10.1139/cgj-2024-0058.)

[6] Cox, J.B. (1970). Shear strength characteristics of the recent marine clays in Southeast Asia. *Journal of Southeast Asian Society of Soil Engineering*, 1(1): 28.

[7] El-Nahhas, F.M. (2006). Tunnelling and supported deep excavations in the Greater Cairo. In Keynote Paper at the Int. Symposium on Utilization of Underground Space in Urban Areas. International Tunnelling Association & Egyptian Tunnelling Society, Sharm El-Sheikh, Egypt, pp. 27-56.

[8] Hsiung, B.C.B., Yang, K.H., Aila, W. and Hung, C. (2016). Three-dimensional effects of a deep excavation on wall deflections in loose to medium dense sands. *Computers and Geotechnics*, 80, pp.138-151.

[9] Hefny, A., Al-Atroush, M.E., Abualkhair, M. and Alnuaimi, M.J. (2020). Three-dimensional response of the supported-deep excavation system: Case study of a large scale underground metro station. *Geosciences*, 10(2), p.76.

[10] Leung, E.H. and Ng, C.W. (2007). Wall and ground movements associated with deep excavations supported by cast in situ wall in mixed ground conditions. *Journal of geotechnical and geoenvironmental engineering*, 133(2), pp.129-143.

[11] Likitlersuang, S., Surarak, C., Wanatowski, D., and Balasubramaniam, A.S. (2013). Analysis of ground movements induced by MRT construction: a case study of Bangkok MRT Blue Line project. In *18th Southeast asian geotechnical conference (18SEAGC) & inaugural AGSSEA conference,* 1AGSSEA Singapore. pp.673-680

[12] Li, D., Li, Z., and Tang, D. (2015). Three-dimensional effects on deformation of deep excavations. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 168(6), pp.551-562.

[13] Moormann, C. (2004). Analysis of wall and ground movements due to deep excavations in soft soil based on a new worldwide database. *Soils and foundations*, 44(1), pp.87-98.

[14] Maher, T., Basha, A.M., Abo-Raya, M.M., and Zakaria, M.H. (2022). General deformation behavior of deep excavation support systems: A review. *Global Journal of Engineering and Technology Advances*, 10(01), pp.039-057.

[15] Ou, C.Y., Hsieh, P.G., and Chiou, D.C. (1993). Characteristics of ground surface settlement during excavation. *Canadian geotechnical journal*, 30(5), pp.758-767.

[16] Phienwej, N., Akawanlop, K., and Balasubramaniam, A. (1995). Comparative Evaluation of Ground Movements Associated with Braced-excavation in Bangkok Soft Clay. In *10th Asian Regional Conference on Soil Mechanics and Foundation Engineering,* Beijing, pp. 341-344.

[17] Phienwej, N., and Gan, C.H. (2003). Characteristics of ground movements in deep excavations with concrete diaphragm walls in Bangkok soils and their prediction. *Geotechnical Engineering*, 34(3), pp.167-176.

[18] Phien-Wej, N., Humza, M., and Aye, Z.Z. (2012). Numerical modeling of diaphragm wall behavior in Bangkok soil using hardening soil model. *Geotechnical aspects of underground construction in soft ground*, pp.715-722.

[19] Teparaksa, W., and Teparaksa, J. (2019). Comparison of diaphragm wall movement prediction and field performance for different construction technique. *Underground Space*, 4(3), pp.225-234.

[20] Zhang, W., and Goh, A.T.C. (2016). General behavior of braced excavation in Bukit Timah Granite residual soils: A case study. *ISSMGE International Journal of Geoengineering Case Histories*, 3(3), pp.190-202.

[21] Zhang, W. G., Goh, A.T.C., Goh, K.H., Chew, O.Y.S., Zhou, D., and Zhang, R. (2018). Performance of braced excavation in residual soil with groundwater drawdown. *Underground Space*, 3(2), pp.150-165.