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BEHAVIOR AND PERFORMANCE OF A DIAPHRAGM WALL FOR AN UNDERGROUND AUTOMATIC CAR PARK IN BANGKOK

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ABSTRACT: Currently, the use of underground automatic car parks is becoming increasingly popular in Bangkok as it can help maximize space usage without ramps. However, an automatic system requires large openings in the basement slab, resulting in the slab possibly having insufficient axial capacity. This paper focused on one of the latest underground automatic car park construction projects in Bangkok's city center, True Digital Park, which comprises a total of four basements with a 13.20 m maximum excavation depth, including mat foundation and lean concrete. An 800mm-thick diaphragm wall (D-wall) was proposed to serve as a soil-retaining structure with 3 layers of full-temporary bracing. The Finite Element Method (FEM) with the Mohr-Coulomb soil model was employed for the D-wall design and horizontal movement prediction, and the actual construction of the basement and building have since been completed. The field performance of the D-wall construction was evaluated through horizontal movement using installed inclinometers. During every stage of construction, including soil excavation and bracing installation, horizontal displacement was monitored carefully and strictly controlled to minimize the D-wall movement. The monitoring results showed suitable agreement with the FEM analysis. However, movement of the retaining wall was detected during upward construction, even though the basement was fully cast, suggesting insufficient axial basement slab capacity as well as care and control for similar projects. This article describes the construction and monitoring of the project together with field performance results.

Keywords: Deep excavation, Field monitoring, Diaphragm wall, Underground automatic car park

1. INTRODUCTION

Bangkok, one of the world's largest developing cities, is currently undergoing several underground construction projects to optimize land usage, including government infrastructures and private skyscrapers. There have been many studies regarding the theoretical method for the stability of underground excavation [1, 2] and the ground movement induced by soil excavation [3-5]. However, research on actual construction projects remains limited, especially for underground automatic car parking.

Car parking is one of the most recommended functions for underground space usage as it allows for maximizing space in the superstructure area. Automated systems for car parking are becoming more popular in Bangkok as they provide maximum usage space without the need for car ramps [6]. However, the automatic system necessitates the construction of many large openings for vehicle elevators and mechanical systems, resulting in potential insufficiency in the axial capacity and stiffness of the underground basement slab and high retaining wall displacement during construction. In some cases, where project space allows, a circular shape [7] or anchor [8-10] is preferred for the retaining structure as it can guarantee much smaller horizontal displacement for the wall.

Recently, a high-rise, mixed-used building for office and retail use with four basement stories in the substructure was constructed in central Bangkok. The basement floors are intended to be mechanical spaces and an underground automatic car park as it helps maximize parking space by eliminating driving paths and ramps. The four basements (B1 – B4) are at elevations of EL.-10.50 m, -7.65 m, -5.10 m, and -2.00 m with a maximum excavation depth of -13.20 m from the ground including 20-cm-thick lean concrete. A diaphragm wall (D-wall) of 0.80 m thickness and 21.0 m length penetrating a stiff clay layer was employed as a soil-retaining structure for bottom-up construction. The first meter of the D-wall is a cap beam. During excavation, three layers of temporary steel bracing were used at EL. -1.50 m, -4.50 m, and -9.00 m for lower wall displacement [7] with a platform system working machines.

A typical section of temporary bracing and basement floor is presented in Figure 1. There are several openings on basement floors B2 and B3, as shown in Figures 2 and 3, including openings close to the D-wall (marked as a crossed dotted line) for the mechanical system and five openings in the middle for car transferring lifts. This paper presents the soil-retaining structural design, FEM comparison, and discussion of detected D-wall movement during upward construction at the basement level.

2. RESEARCH SIGNIFICANCE

Research on underground automatic car park construction in soft soil areas remains limited as it has only recently become popular among developers in Thailand. Warnings regarding excessive retaining wall movement during construction have been verbally announced among Thailand's practicing engineers, as the mechanical system generally requires significant headroom and many openings in the slabs. The significance of this study is to provide a well-documented report on a case of an underground automatic car park in a soft clay area where movements were detected during upward construction at slab levels. It has been suggested that force transfer in the basement slab be verified.

3. SOIL CONDITIONS

Six boreholes of 75 m depth were created to investigate the soil conditions at the site for both pile and soil retaining wall design. The soil consisted of a 12 m thick soft clay layer followed by 3 m of medium clay. There was a stiff clay layer up to approximately EL.-35.00 m from the ground surface. It should be noted that there was a variation between EL.-19.00 m to EL.-23.00 m, where four boreholes revealed very stiff silty clay and the other two boreholes showed medium silty sand. Soil profile and properties are presented in Figure 4.

The tip of the D-wall was designed at the soil variation level. The difference in soil material affected D-wall behavior in terms of bending moment, shear force, and D-wall displacement during construction [11].

The groundwater conditions for Bangkok soft clay are in hydrostatic condition starting from -1.0 m. In the past, deep well pumping promoted the drawdown of soft, medium, and first stiff clay. The piezometric level of the Bangkok aquifer was reduced and constant at EL.-23.0 m [12, 13], which is beneficial to practicing geotechnical engineers in terms of higher effective stress and dry conditions during underground construction. However, Thailand's government has enforced the prohibition of deep well-pumping for approximately 20 years to solve the problem of land subsidence [14], so the current piezometric level has increased to roughly -13.0 m, as illustrated in Figure 5 [15]. An increase in the groundwater table in Bangkok promotes difficulty not only in soil excavation works (uplift pressure) but also in pile driving [16].

For this project, there was no piezometer installed. Therefore, the typical groundwater level of EL.-13.00 m was used in the design. The factor of safety (FS) against uplift pressure during construction was computed. The result of FS was 1.67, which is sufficient for temporary excavation.

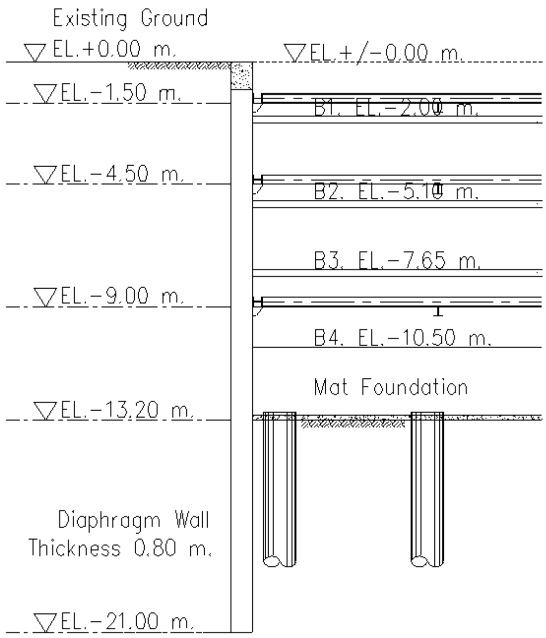

Fig. 1 Typical section of bracing and basement

4. ANALYSIS OF DIAPHRAGM WALL BEHAVIOR BY FINITE ELEMENT METHOD (FEM)

4.1 Design Criteria for a Diaphragm Wall

The behavior of the D-wall can be predicted by numerical analysis using the Finite Element Method (FEM). The diaphragm wall behavior, the result of FEM, is presented in terms of bending moment and shear force induced in the diaphragm wall as well as lateral displacement. The steps for soil excavation, bracing installation, as well as strut preloading [17], are simulated in the FEM analysis. The casting of basement floor, and the step for removal of the strut system are also combined in the FEM analysis of the diaphragm wall.

Mohr-Coulomb soil modeling was employed. The Undrained Young's modulus (Eu) of each soil layer was correlated with undrained shear strength (Su), while the drained modulus (E') was correlated with the Standard penetration SPT (Standard Penetration Test) N-value in the sand layer.

The correlation of Eu and Su as well as E' and N-value can be explained as follows.

- For a soft to medium clay layer, Undrained Young's modulus

  (EU) = 500 – 700 Su (Undrained Shear Strength)
- Stiff to very stiff silty clay layer

  Eu = 1000 Su
- Sand layer

  E' = 2000(N) SPT-N-Value (kN/m^2)

The above correlation between Eu-Su and E'-N(value) is based on the back analysis from various

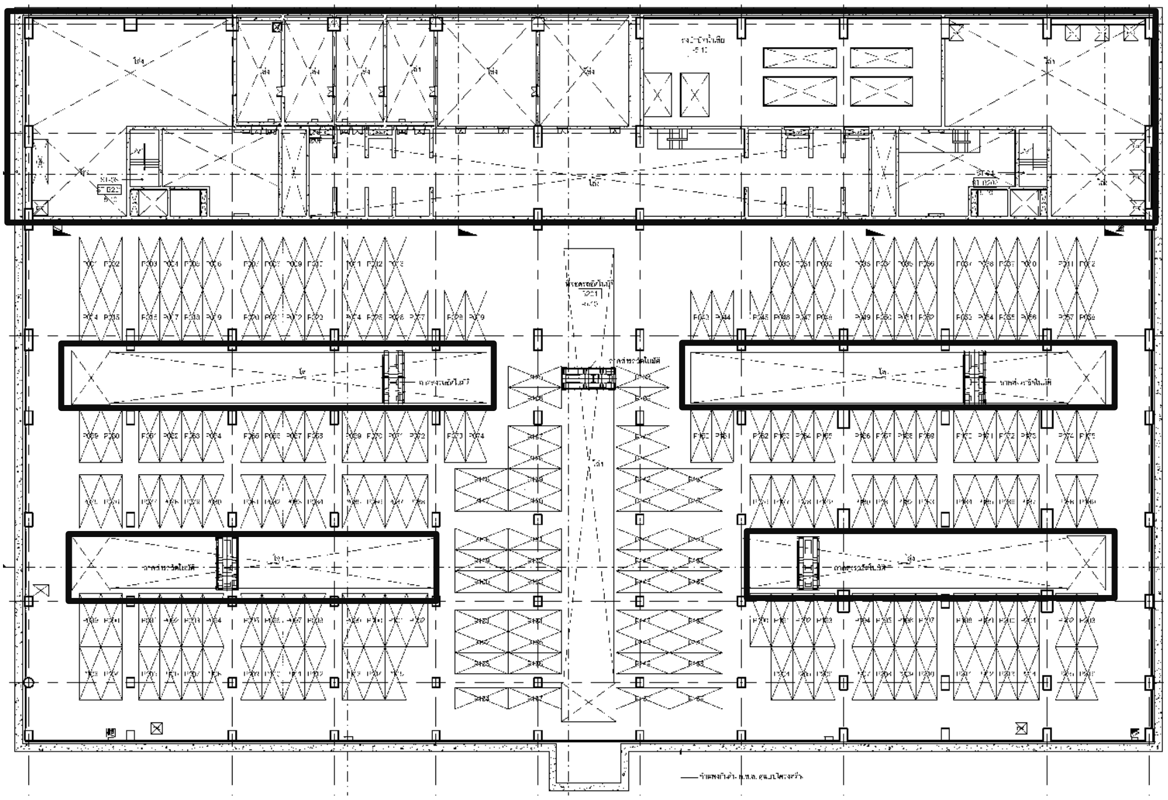

Fig. 2 B2 floor plan (openings are marked with bold rectangular boxes)

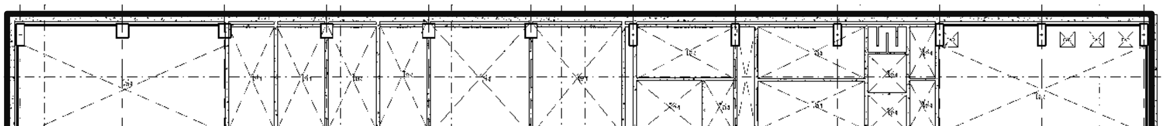

Fig. 3 B3 floor plan (openings are marked with bold rectangular boxes)

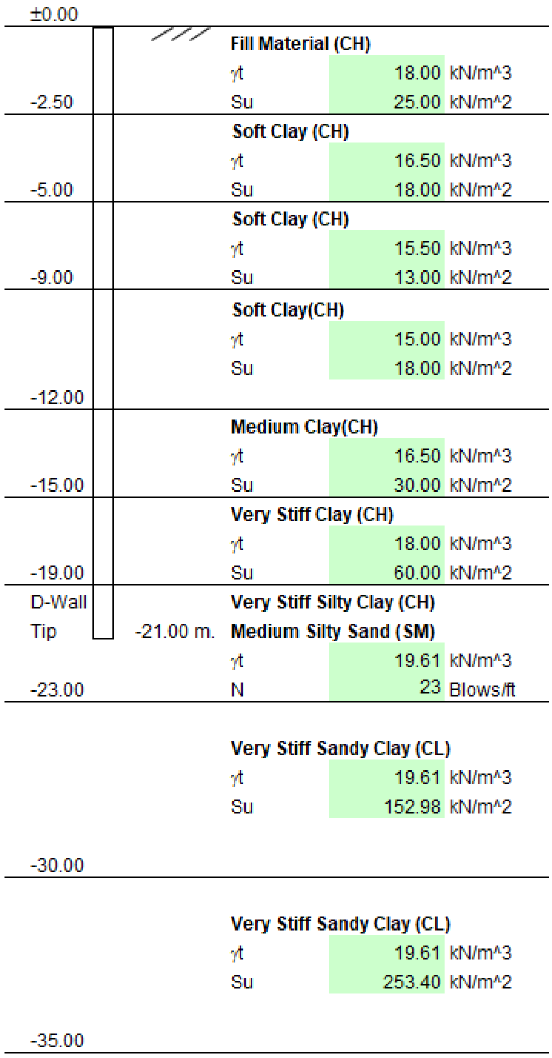

Fig. 4 Soil Profile

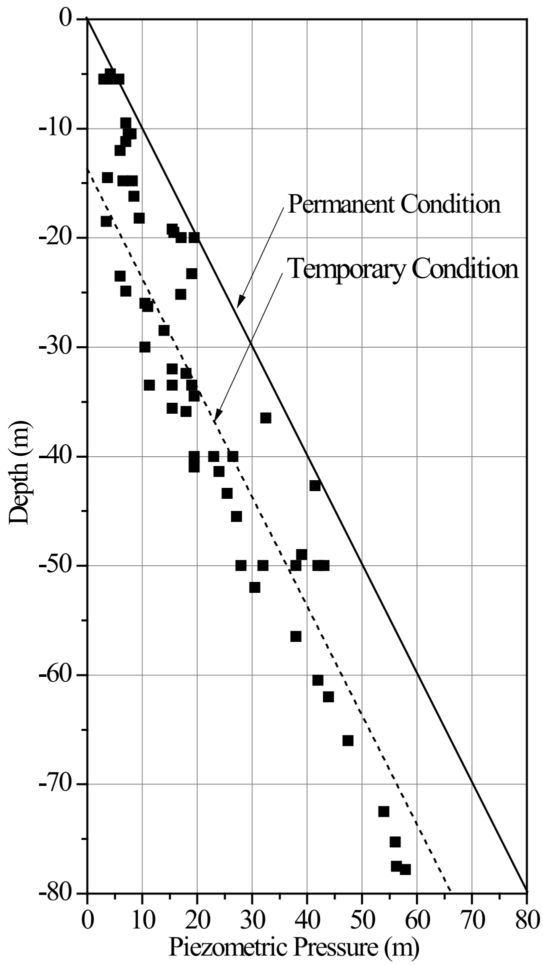

Fig. 5 Groundwater conditions (replotted after [12])

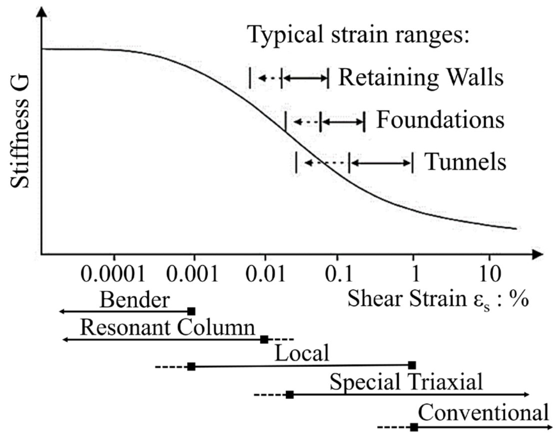

Fig. 6 Relationship between soil stiffness and shear strain level (after [19])

basement excavation projects using FEM analysis compared with field measurement. It should be noted that the stiffness for other types of retaining walls may be different [18] as it depends on the shear strain of the system [19] (see Fig. 6). The D-wall can be categorized as a rigid wall that promotes relatively minor strain compared to steel sheet pile. Thus, the soil stiffness of rigid wall models, such as D-wall and pile wall, is larger than that of the flexible wall model.

The aforementioned correlation has been well studied and widely used for soil retaining wall design in Bangkok for many projects such as the Central Embassy Department Store [20], Bank of Thailand Head Office Building [21-23], Rosewood Hotel [24] and a high-rise building in the city center of Bangkok [25]. It should be noted that only SPT was carried out for the stiff clay layer. There was no sample recovery to test for soil properties in the laboratory. Thus, the value for soil shear strength of stiff clay was correlated with the field SPT test result, as proposed in [26].

4.2 Surcharge on the diaphragm wall

The ground surface surcharge behind the diaphragm wall was assumed at 10 kN/m^2 for a 6 m width to simulate the machinery load. This ground surface was applied during excavation, basement casting, and completion of the basement work.

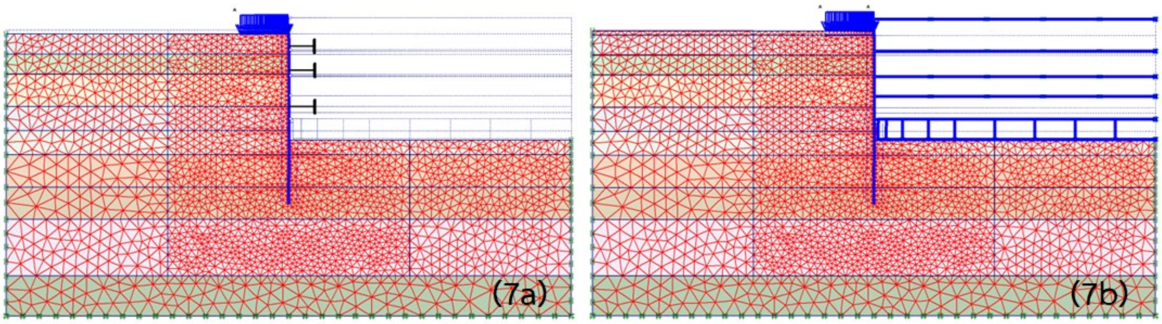

Fig. 7 Deformed mesh at (a) the final depth excavation and (b) the final stage

4.3 Groundwater table

The groundwater of the Bangkok subsoil is in drawdown condition due to deep-well pumping. As deep-well pumping has been prohibited, the groundwater table has been increasing recently to EL.-13.00 m below the ground surface. This groundwater level was used in the model during the excavation and construction of the substructure.

5. FINITE ELEMENT ANALYSIS RESULTS

All the construction sequences, starting from the first excavation to the final stage after construction and consolidation, were modeled in the FEM analysis using Mohr-Coulomb as a failure criterion. The first sequence was initial excavation to install the first strut layer. The second sequence was carried out after the first strut installation, which was excavation to the second strut layer level. The process continued until reaching the final depth, as shown in the terms for deformed mesh illustrated in Figure 7a. It should be noted that, since there was variation in soil investigation, two models with stiff clay and medium sand layer between -19.00 to -23.00 m were developed, as discussed elsewhere [11].

Upward construction was started by casting the mat foundation and removal of strut layer 3. The second strut layer was removed in the next stage after casting the basement levels for B2 and B3. Subsequently, B1 was cast followed by the removal of strut layer 1. The FEM model was completed at the construction step for the groundwater table at -1.00 m, and consolidation took place for long-term simulation, as presented in Figure 7b.

All the basement floors were modeled to obtain the axial forces at every step for the structural engineer to recheck the reinforcement, especially at the openings close to the D-wall. The moment and shear envelopes for both the stiff clay and medium sand layers were then employed to design the D-wall reinforcement, as illustrated in Figures 8 and 9, respectively. In addition, the presented moment envelope was summarized from all construction stages including the final stage where consolidation occurred. It can be seen that the reinforcement covered the predicted maximum moment in both cases with a load factor of 1.5.

6. SAFETY CONTROL AND MONITORING OF DIAPHRAGM WALL DISPLACEMENT

6.1 Safety Control

Not only were the bending moment and shear force obtained from the FEM analysis, but also the horizontal D-wall movement. The maximum horizontal displacement of every construction step was used to set the trigger level for safety control during construction, as shown in Table 2. The predicted maximum horizontal movement was separated into 3 levels by percentage with 70% as the alarm level, 80% as the alert level, and 90% as the action level. During basement construction, inclinometers were read periodically following the construction step. If the horizontal reading showed a higher value than the trigger level, the procedure demonstrated in Table 2 was carried out.

In some cases where the inclinometer reads excessive horizontal displacement, the designer can increase the reading interval from every construction to every week as a precaution. The countermeasures shall also be recommended.

6.1 D-wall Displacement during Construction

Four inclinometers were installed at each side, as illustrated in Figure 10. The inclinometers were read after the completion of every construction step. The final reading showed horizontal displacement of 40.64 mm, 37.71 mm, 41.31 mm, and 58.65 mm for IW1 to IW4, respectively.

All of the inclinometer readings (IW1 – IW4) were compared to the FEM prediction, as presented in Figure 11. The movement of IW1, IW2, and IW3 agreed well with the FEM analysis in terms of the shape of the movement. However, the observed values for displacement were lower than the FEM prediction by between 22%-29%. It should be noted that the inclinometer cannot detect toe movement since it reads displacement relative to the toe. The difference in results may be attributed to the aforementioned reason. A larger movement at the top of the D-wall at IW2 was discussed previously. The IW4 reading appeared to differ from the others and the FEM prediction. This may be attributed to very large movement at the initial stages due to a weak local strut at the inclinometer area [27]. Figures 12 to 15 demonstrate the monitoring of movement during the upward construction of IW1 to IW4, respectively. Trigger level and level of basements and mat foundation are also drawn. The highest inclinometer reading of IW4 is shown in Figure 15 together with trigger level and basement levels. There was significant movement at the very initial stages where the inclinometer reading showed cantilever behavior. The movement first touched the alarm level during excavation to a final depth of -13.20 m. The horizontal movement continued during upward construction until the completion of basement construction at 58.65 mm, which was more than the predicted maximum value.

During upward construction after casting the mat foundation and removal of the third strut to the end of substructure construction, there was significant movement detected at the basement floor levels.

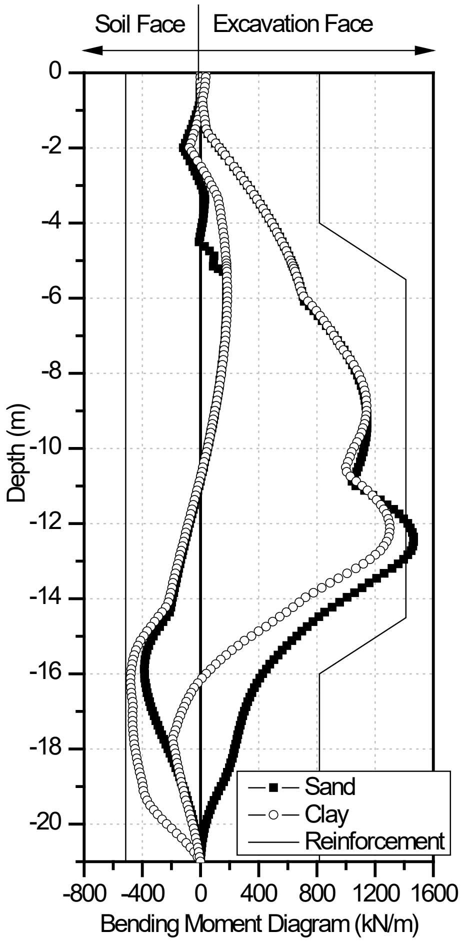

Fig. 9 Bending moment envelope and reinforcement.

Movement at the mat foundation level (10.50-13.00 m) at IW2 and IW4 was detected after the completion of construction for basement levels B2 and B3 and the removal of the 2nd strut (see Table 3). As the mat foundation was cast and the strength of the concrete was verified to be more than 75% of the design value, displacement at this mat foundation zone should have been minimal.

Table 2 Trigger level and safety control

Trigger Level	Disp. (mm.)	Safety Criteria
Alarm Level (70 % of DV)	37.43	Inform the designer to review CS
Alert Level (80 % of DV)	42.78	Inform all parties to review CS
Action Level (90 % of DV)	48.12	Stop construction and revise the CS
Maximum	53.47	

Note: Disp. = Displacement, DV = Design Value, CS = construction sequence

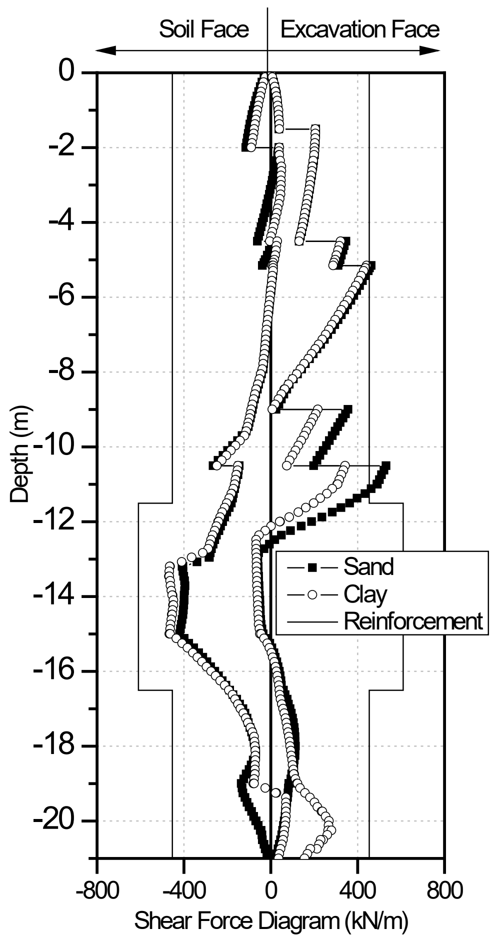

Fig. 10 Bending moment envelope and reinforcement.

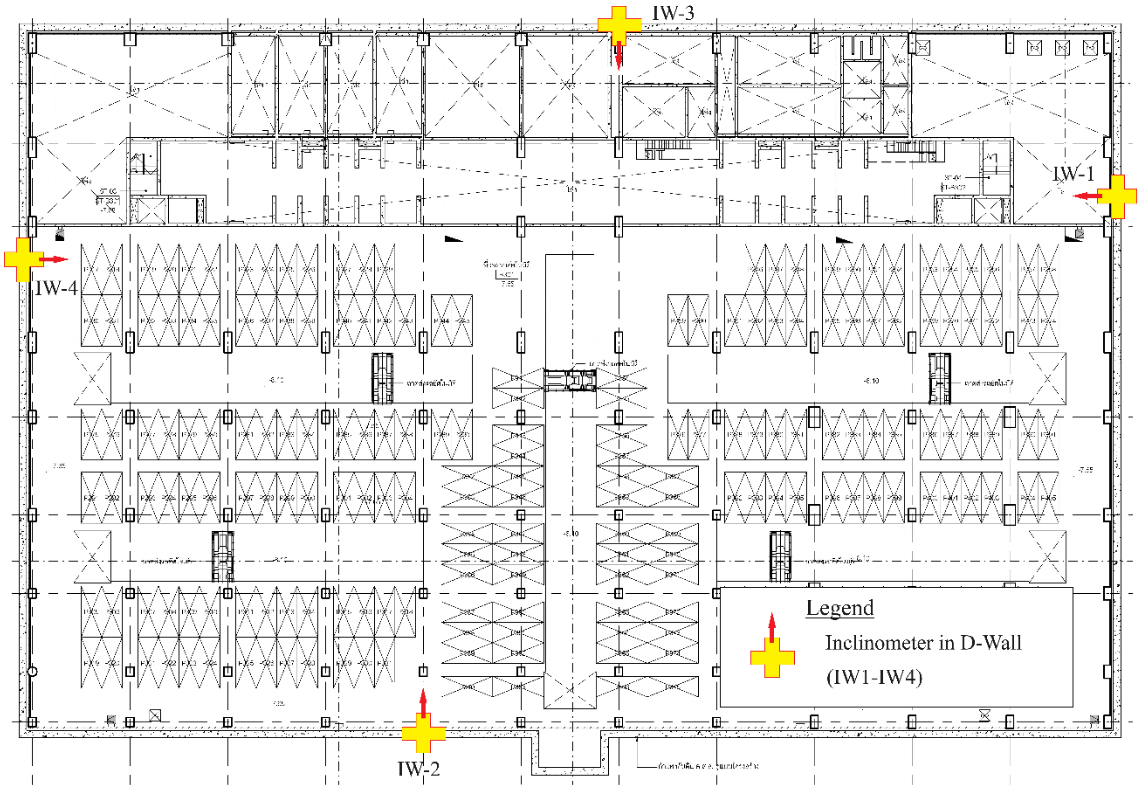

Fig.10 Inclinometer location

Table 3. Movement at each basement level during upward construction

Basement Level	Differential Hor. Disp. (mm.)	
	After casting B2-3 and 2nd strut removal	After casting B1 and 1st strut removal
B1 -2.00 m.		
IW1	-	3.70
IW2	-	8.63
IW3	-	0.44
IW4	-	5.76
B2 -5.10 m.		
IW1	3.05	1.48
IW2	8.59	4.72
IW3	0.13	-0.36
IW4	6.11	2.98
B3 -7.65 m		
IW1	3.51	0.85
IW2	6.43	2.47
IW3	2.12	-1.23
IW4	5.78	1.54
MF -10.50 m.		
IW1	2.80	-0.04
IW2	3.33	0.86
IW3	2.68	-1.58
IW4	4.02	0.60

Note: MF = Mat Foundation, Hor. = Horizontal, Disp. = Displacement

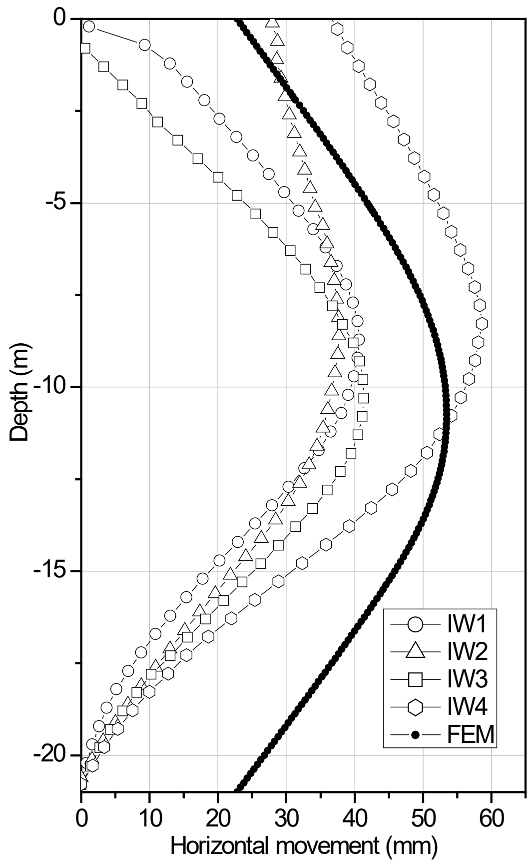

Fig. 11 Inclinometer readings and FEM prediction

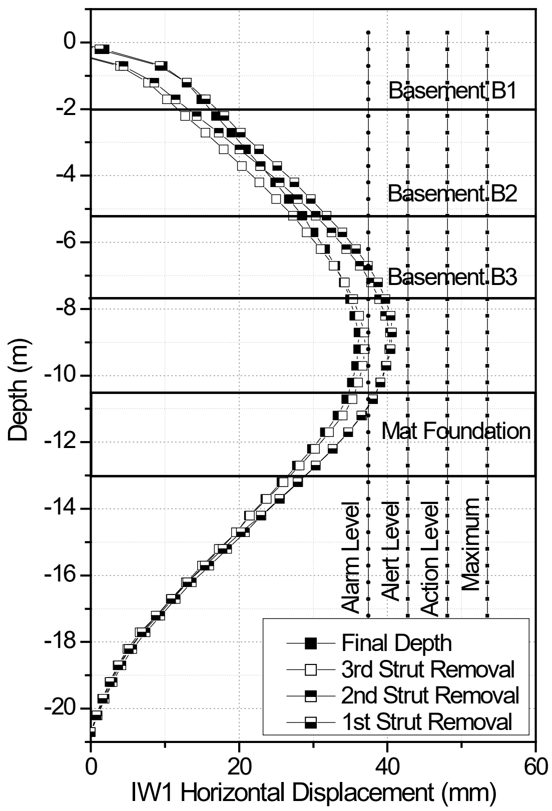

Fig. 12 Inclinometer readings for IW1

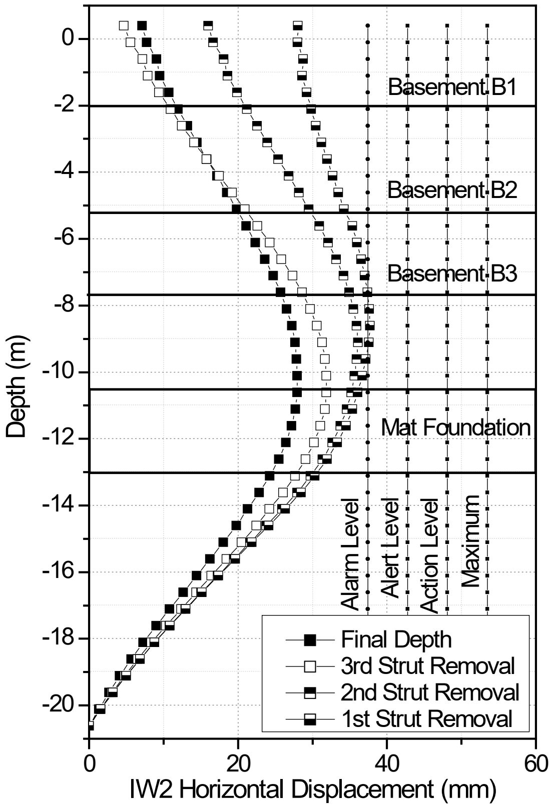

Fig. 13 Inclinometer readings for IW2

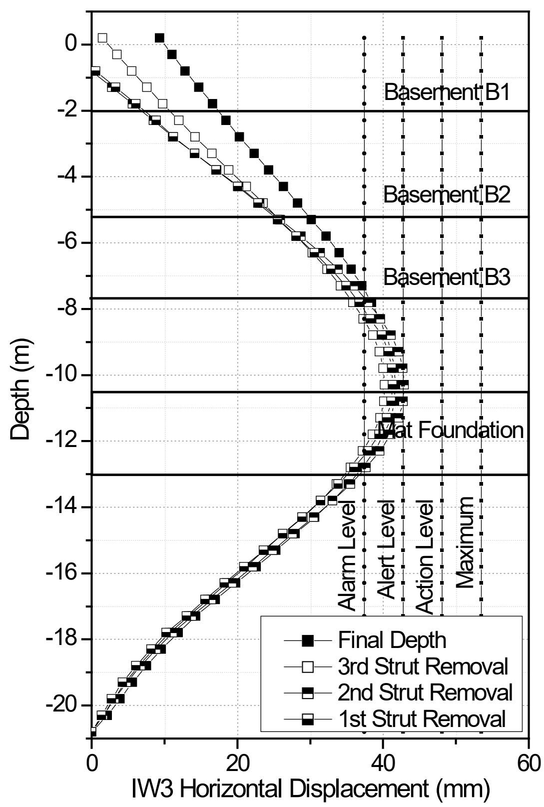

Fig. 14 Inclinometer readings for IW3

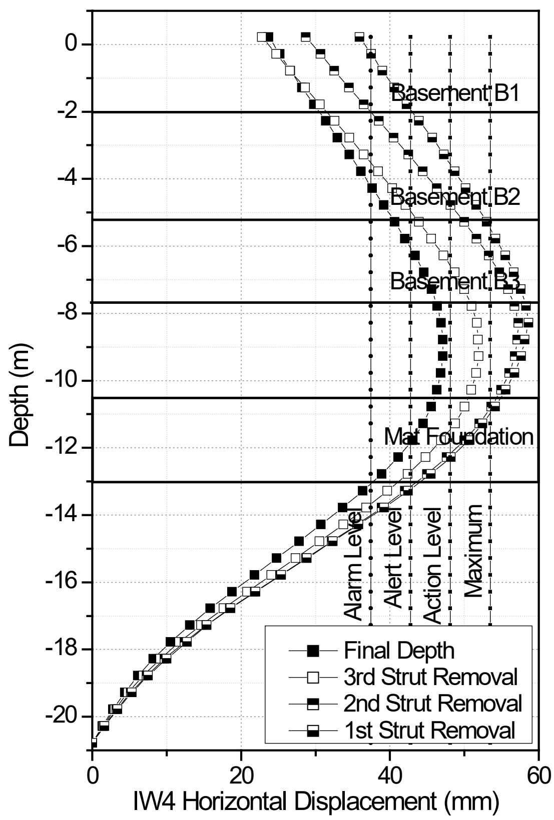

Fig. 16 Inclinometer readings for IW4

Similar behavior for D-wall movement at the B2 and B3 levels (-5.10 and -7.65 m.) after casting basement slab B1 and removal of the first strut can also be found at IW2 and IW4 (see Fig. 13 and 15). The strength of the B2 and B3 slabs was confirmed to be more than 75% before the removal of the strut. Horizontal movement at these two levels should have been limited due to the existence of basement concrete slabs. Table 3 summarizes the monitored horizontal displacement at each interval of the construction stage during upward construction, starting from final depth excavation to removal of the first strut. The maximum movement of 8.59 and 8.63 mm were found at slabs B2 and B1 after B2-3 casting and B1 casting, respectively.

It was suggested to do a visual investigation and inspection of the D-wall and all basement slabs after casting the basement B1 floor, but no cracks or damage were observed. Several photographs of the D-wall and basements B2 and B3 during the survey are shown in Figures 15 and 16, respectively.

The construction continued to the superstructure as there was no observed damage at the basement structures. At the time of writing this paper, the entire building had been completed and would soon be operational.

Fig. 15 Photo of B3 after bracing layer 2 removal.

Fig. 16 Image of B2 after bracing layer 2 removal.

7. CONCLUSIONS

The construction of an underground basement for a high-rise, mixed-use building in Bangkok's city center was designed for use as an underground automatic car park. Many openings in the sub-structure basement slab were necessary for car elevators and the mechanical systems in the building. A diaphragm wall, designed using FEM analysis, was employed as a soil-retaining structure. All the construction sequences were simulated in the FEM to design steel reinforcement covering every phase of construction. The diaphragm wall behavior and displacement were predicted and compared with field inclinometer monitoring data. The performance of the basement construction was found to be exceptional as most of the observed displacement values were lower than predicted, except for IW4. The results of FEM agreed well with the field performance in terms of wall displacement shape. However, unusual horizontal movements at the basement slab levels and mat foundation level were detected during upward construction. The movement at these levels should have been limited because of the existence of basement slabs. All the structures were verified before progressing to the construction of the superstructure. According to this case report, it is advisable to verify basement slab strength and force transfer for underground construction projects that necessitate the inclusion of many openings or high spans. To date, the building used for the case study in the current work has been completed and will soon be operational.

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