Effect of Different Soil Type at Diaphragm Wall Tip on Diaphragm Wall Behavior

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Abstract

Currently, there is a glowing demand for underground construction especially in Bangkok city center due to land price and limitation in building height by law. In most cases for Bangkok subsoil, the profile in the construction sites has no to little variation. However, in one of the most recent underground land development projects, True Digital Park Phase 2, variation in soil layer was encountered where sand and clay layer was found between -19.00 to -23.00 m at different boring logs. This paper presents 0.80 m. thick diaphragm wall behavior which is used for underground automatic car park construction with its tip located at different soil type. The underground consists of 4 storeys with 13.20 m. excavation depth with 3 layers of temporary bracing system. During construction movement of diaphragm wall was carefully monitored and compared with Finite Element Method (FEM) analysis results.

Keywords: Diaphragm Wall, Bangkok subsoil, Deep Excavation, Soil Variation

1. Introduction

In the past decades, there has been an increasing demand for underground basement construction in Bangkok due to limitation of land and height by Thai law. In most cases, soil investigation showed uniform soil layer within the construction site unless large area project. However, in True Digital Park Phase 2 project, variation of soil layer in the site was detected even the site area is relatively small of about 14,000 m^2. The fluctuation of soil profile was found between -19.00 m to -23.00 m among six boreholes. This project is located at Sukhumvit road adjacent to the predecessor, True Digital Park Phase 1. The building is 66.80 m. tall providing 13 floors of superstructure and 4 floors of substructure. The underground space is intended to be an automatic underground car park to maximize parking capacity (in total 648 automatic parking slots). However, it should be noted that automatic car park requires large opening of basement slab promoting difficulty in construction and, may be, higher displacement due to lower axial capacity of basement slab [1]. To tackle with high movement, circular excavation can be used [2] but this is not the case for this project.

This paper presents 0.80 m thick diaphragm wall behavior (D-wall) which was used as a soil retaining structure during and after construction as a permanent underground wall. The tip of D-wall is at -21.00 m. located in the fluctuation layer. This means that D-wall toe sits in the different type of material in the same site. The method of construction was bottom-up construction with 3 layers of temporary bracing at -1.50 m, -4.50 m and -9.00 m. as illustrated in Fig. 1. There are four basement floor at -2.00 m (B1), -5.10 m. (B2), -7.65 m (B3) and -10.50 m. (B4) with the mat foundation thickness of 2.50 m.

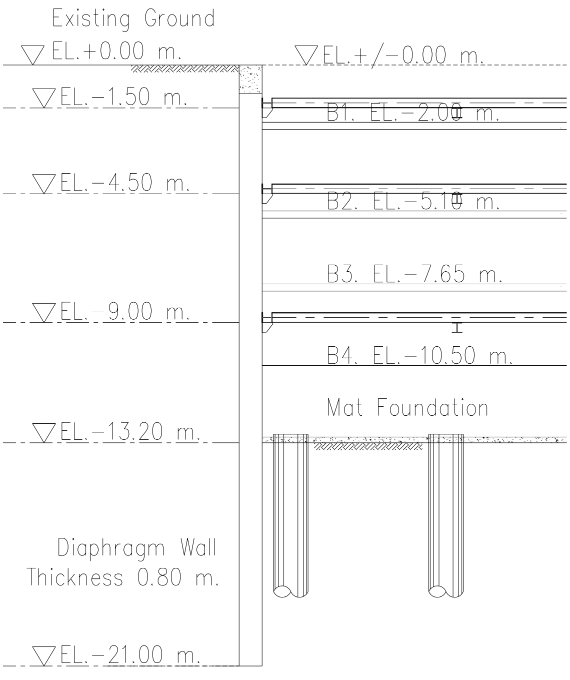


Fig. 1 Cross section of underground structure

The maximum depth of excavation is 13.20 m. from ground surface including lean concrete. The opening in basement slab is located at B2 and B3 for mechanical automatic car park system, water storage, ventilation system and mechanical room for the whole building. Finite Element Method (FEM) analysis was performed to predict and design the D-wall for both cases of soil profile. During construction, D-wall horizontal movement was monitored and was then compared with FEM prediction.

2. Soil Investigation

There was soil investigation of six boreholes (BH-1 – BH-6) before project design. The location of boreholes in the construction site is presented in Fig. 2. It was quite typical Bangkok subsoil profile starting from Bangkok soft clay layer of 12.00 m. with 2.50 m. fill material on the top surface. From 12.00 – 15.00 m., medium clay was encountered and followed by stiff clay layer from 15.00 m.

The interesting point was that there were 2 boreholes (BH-4 and BH-5) showing a thin sand layer from -19.00 m. to -23.00 m. where it was absent in the other four boreholes as can be seen in Fig.3. The author also compared the soil investigation with Phase 1 construction. It was found that the first sand layer was also encountered in Phase 1 project starting from -19.00 m. to -21.00 m. The soil profile for analysis is summarized with soil properties in Fig.4 and Table 1.

In both Phase 1 and 2, there was no on-site piezometer data. Thus, typical Bangkok groundwater condition was employed in the analysis. In the past, Bangkok groundwater table was at level -23.00 m. below ground surface [3]. Due to land subsidence, Thai government has prohibited groundwater pumping promoting an increase in groundwater table [4]. At present, the groundwater table is at about -13.00 m. as shown in Fig. 5 [5].

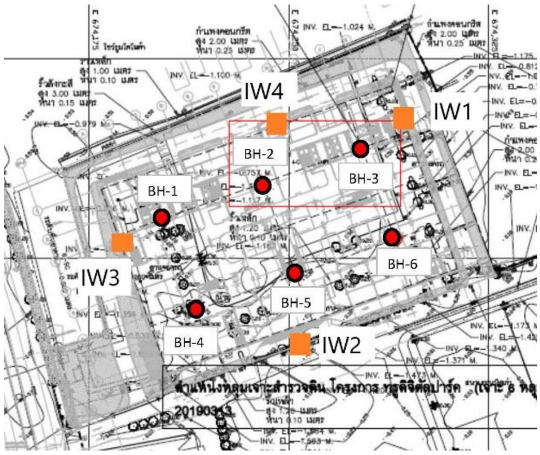


Fig. 2 Location of six boreholes and four inclinomters

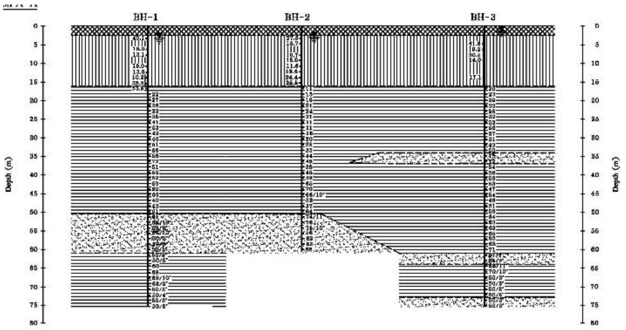


Fig. 3a Soil Profile BH1-BH3

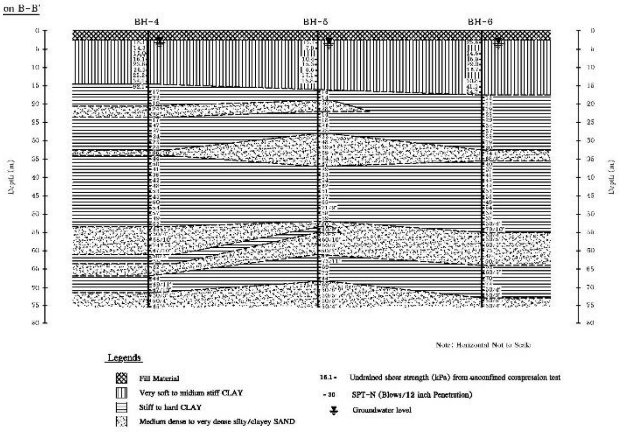
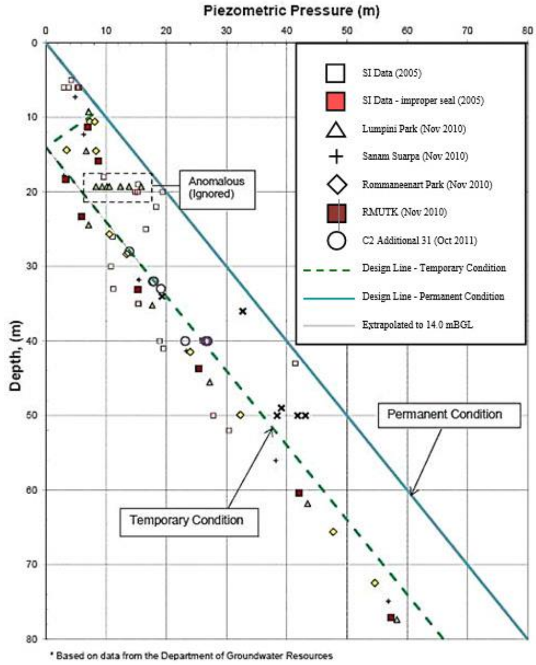


Fig. 3b Soil Profile BH4-BH6

Fig. 4 Soil profile summary with soil properties



* Based on data from the Department of Groundwater Resources

Fig. 5 Typical Bangkok piezometer pressure profile [5]

Table 1 Soil Engineering Parameters

Depth (m.)	Description	Total Unit Weight (kN/m^3)	Shear Strength, Su (kN/m^2)	SPT N-Value (Blows/ft)	Eu (kN/m^2)	E' (kN/m^2)
0.00-2.50	Fill Material	18.00	25.00	-	12,500	-
2.50-5.00	Soft Clay	16.50	18.00	-	9,000	-
5.00-9.00	Soft Clay	15.50	13.00	-	6,500	-
9.00-12.00	Soft Clay	15.00	18.00	-	9,000	-
12.00-15.00	Medium Clay	16.50	30.00	-	18,000	-
15.00-19.00	Very Stiff Clay	18.00	60.00	15	60,000	-
19.00-23.00*	Very Stiff Silty Clay	19.61	117.32	23	117,320	-
19.00-23.00**	Medium Silty Sand	19.61	-	23	-	46,000
23.00-30.00	Very Stiff Sandy Clay	19.61	152.98	30	152,980	-
30.00-35.00	Very Stiff Sandy Clay	19.61	253.40	40	253,400	-

Note: Eu = Undrained Young's Modulus, E' = Drained Young's Modulus

19.00-23.00 = Summarized from BH4 and BH5,*

*19.00-23.00** = Summarized from BH1, BH2, BH3 and BH6.*

3. Finite Element Method (FEM) Analysis for Diaphragm Wall behavior

3.1 Design Criteria

The behavior of soil retaining structure can be predicted using Finite Element Method (FEM) analysis. The obtained results are presented in terms of bending moment, shear force and wall displacement. All the construction sequences were included in the analysis starting from the first excavation step to casting ground floor.

As described previously, soil investigation showed variation in soil profile between -19.00 m to -23.00 m. It was better to do conservative design. Two soil profile models were used for two cases of FEM analysis. The only different in those two models was material between -19.00 m to -23.00.

Mohr-Coulomb soil modelling was employed in FEM analysis. Undrained Young's Modulus (Eu) of clay layer was correlated from undrained shear strength whereas Drained Young's modulus (E') of sand layer was correlated from SPT (Standard Penetration Test) N-Value. The correlations used in the analysis are as follow;

Eu = 500 – 700 Su (kN/m^2) for soft and medium clay layer
Eu = 1000 Su (kN/m^2) for stiff clay layer
E' = 2000 N (kN/m^2) for sand layer

The above correlation was obtained from back-analysis of field performance of many Bangkok construction projects [6].

3.2 Ground surcharge

Ground surcharge of 10 kN/m^2 was set for six meters from the D-wall in the FEM analysis to simulate possible external loading such as machinery load and storage load. This surcharge was simulated at all construction sequences. However, in practice, any external load behind the D-wall was not allowed in order to minimize wall displacement.

3.3 Construction Sequences

All the construction sequences were simulated in FEM analysis to design reinforcement in D-wall. Contractor had to carefully follow this sequence during construction. Any changes to the sequence have to be rechecked with the D-wall reinforcement.

The construction sequences modeled in the analysis are as follow

1. Excavate to below temporary bracing strut layer 1.
2. Install bracing strut layer 1 and excavate to below bracing strut layer 2.
3. Install bracing strut layer 2 and excavate to below bracing strut layer 3.
4. Install bracing strut layer 3 and excavate to the final depth.
5. Construct mat foundation and remove bracing strut layer 3.
6. Cast slab B3 and B2 and remove bracing strut layer 2.
7. Cast slab B1 and remove bracing strut layer 1.
8. Cast ground floor.

4. Finite Element Method Analysis Results

In calculation, construction sequences were included step by step. Each sequence resulted in output in terms of bending moment, shear force and wall displacement. Example of deformed mesh at sequence final depth and final construction stage are illustrated in Fig. 6 and Fig. 7 respectively. All the bending moments and shear forces induced in D-wall in each step were combined and presented in terms of bending moment and shear force envelop together with steel reinforcement as presented in Fig. 8 and Fig. 9 accordingly. There are two data set in each figure expressing results from different cases; sand and clay layer in -19.00 to -23.00 m.

It can be seen that the difference in soil profile just in between -19.00 m to -23.00 m. promotes significant contrast in both bending moment and shear force envelop. If sand layer is presented, bending moment seems to become lower in the excavation face while higher in soil face. For shear force, the difference seems to be minimal except at the mat foundation (between -10.50 to -13.00 m.) and bracing layer 3 (-9.00 m.).

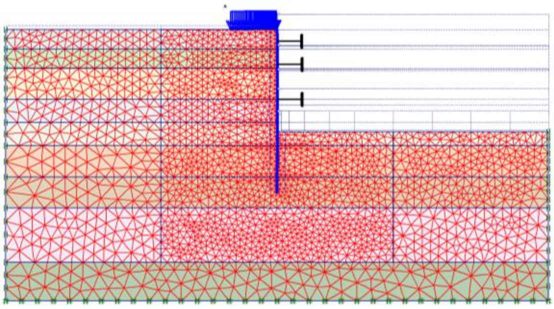


Fig. 6 Deformed mesh at the final depth

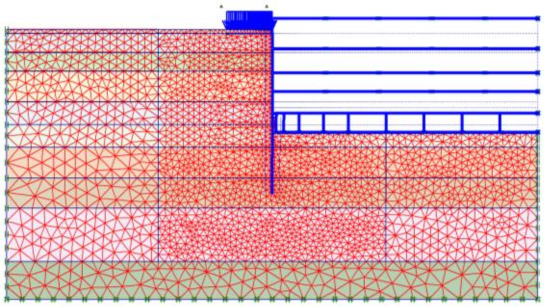


Fig. 7 Deformed mesh at the final construction step

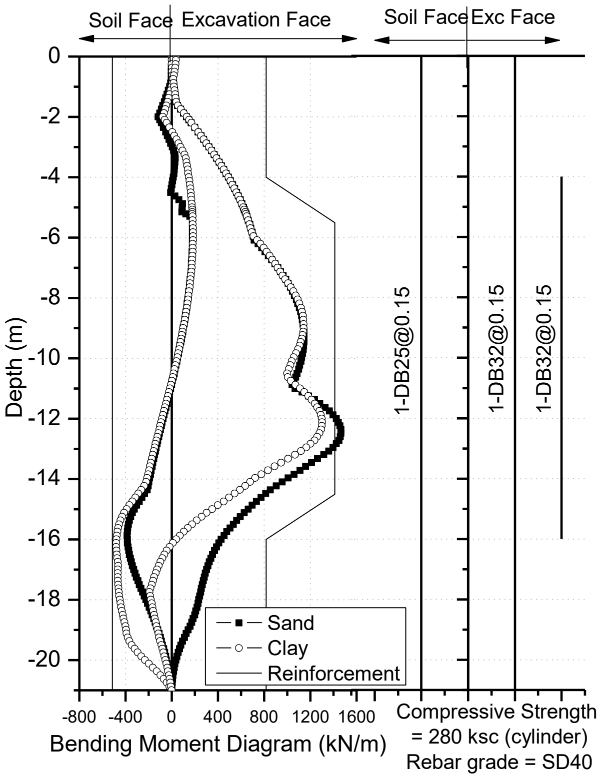


Fig. 8 Bending moment envelop and main reinforcement

Regarding the design of D-wall, load factor of 1.5 is used. The capacity of the reinforcement shall cover both bending moment and shear force envelop to ensure safety at every construction step. (See Fig.8 and Fig 9)

5. Diaphragm Wall Displacement and Safety control during construction

Results obtained from FEM analysis are bending moment, shear force and displacement. The two formers are typically used for main and stirrup rebar design while the latter is employed for safety control during construction. The results of analysis showed that the maximum horizontal displacements are 53.47 mm and 47.78 mm for sand and clay case, respectively. The maximum wall displacement was employed to set a trigger level as shown in Table 2. It can be categorized in three stages as alarm, alert and action using the percentage of the maximum wall displacement value obtained from FEM analysis. During construction, wall displacement is monitored using inclinometer. Once the displacement reaches alarm, alert action level, there are steps to follow as indicated in Table 2.

There were four inclinometers (IW1 – IW4) installed in the D-wall at each side of the building to measure horizontal displacement during construction as presented in Fig. 10. The reading was taken at every construction step. The field measurement at final underground construction stage (after the first bracing removal) was then plotted with the FEM prediction results as presented in Fig. 11.

Regarding FEM analysis result, it can be seen clearly that horizontal displacement in the case of sand layer between -19.00 m to -23.00 m is larger than the case of stiff clay layer. This different is mostly contributed by toe movement with different of 20.64 mm. (22.80 mm. for sand case and 2.16 mm for clay case). The huge difference might be due to higher soil stiffness.

For field performance, the maximum displacements at final stage for each inclinometer are presented in Table 3. The reading of inclinometer was taken in two directions; perpendicular (A) and parallel (B) to the D-wall. Noted that, ideally, the reading in parallel direction to D-wall should be zero. Any value in (B) direction indicates possible rotation of inclinomter installation. The reading of IW4 showed the largest D-wall movement with value over the maximum predicted by FEM. The depth of the maximum displacement is also shallower from the others (see Fig. 11). The reason behind this is still unclear. It is believed that it might be due to the opening of basement slab adjacent to the D-wall for underground automatic car park mechanical system installation. [7]

IW2 is inclinometers closed to boring logs which presented sand layer between -19.00 to -23.00 m (see Fig. 2 and 10). It showed lowest horizontal displacement which is contrast with the FEM analysis. However, it is important to note that the inclinometer measure the horizontal displacement relatively to the toe displacement. Thus, the actual toe displacement cannot be detected. In Fig. 11, the darkest black line showed FEM predicted with reduction of toe movement. The correctted maximum horizontal movement prediction of D-wall tip in sand layer significantly dropped to approximately 30.00 mm. (7 mm. lower than field record). In addition, movement profile of IW2 also showed little of cantilever mode at the top part. While excluding movement at tip, quantitatively, FEM prediction agrees with field performance that sand layer promotes lower horizontal movement.

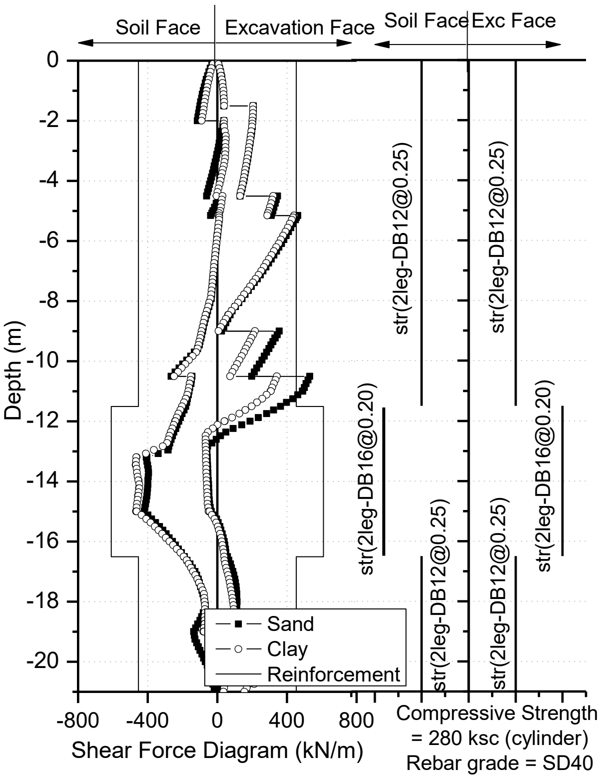


Fig. 9 Shear force envelop and stirrup reinforcement

Table 2 Trigger level for safety control

Trigger Level	Wall Displacement (mm.) "Sand Case"	Wall Displacement (mm.) "Clay Case"	Safety Criteria
Alarm level (70% of DV)	37.43	33.44	Inform designer to review CS
Alert level (80% of DV)	42.78	38.22	Inform all parties to review CS
Action level (90% of DV)	48.12	43.00	Stop construction and revise the CS
Maximum	53.47	47.78	

Note: DV = Design Value, CS = Construction Sequence

IW1, IW3 and IW4 are inclinometers closed to boring logs which showed clay layer between -19.00 to -23.00 m (see Fig. 2 and 10). Fem prediction movement is 47.78 mm. with minial toe movement while field performace detected 40.64 mm, 41.31 mm and 58.65 mm for IW1, IW3 and IW4 respectively. IW4 showed very large movement which might because of aforementioned reason. IW1 and IW3 showed lower maximum horizontal movement than FEM analysis. Behavior of wall movement also different as there was no movement detected at the top in case of field monitoring.

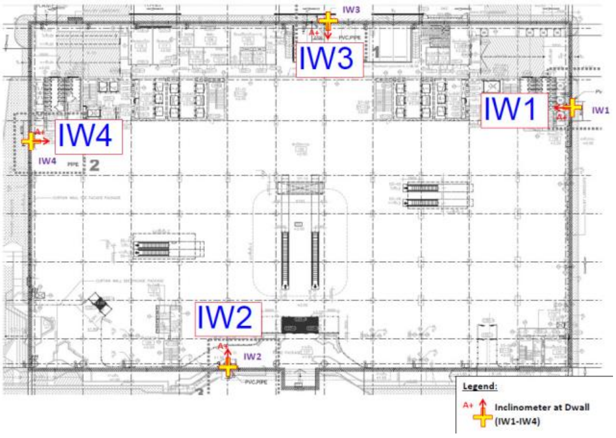


Fig. 10 Inclinometer Locations

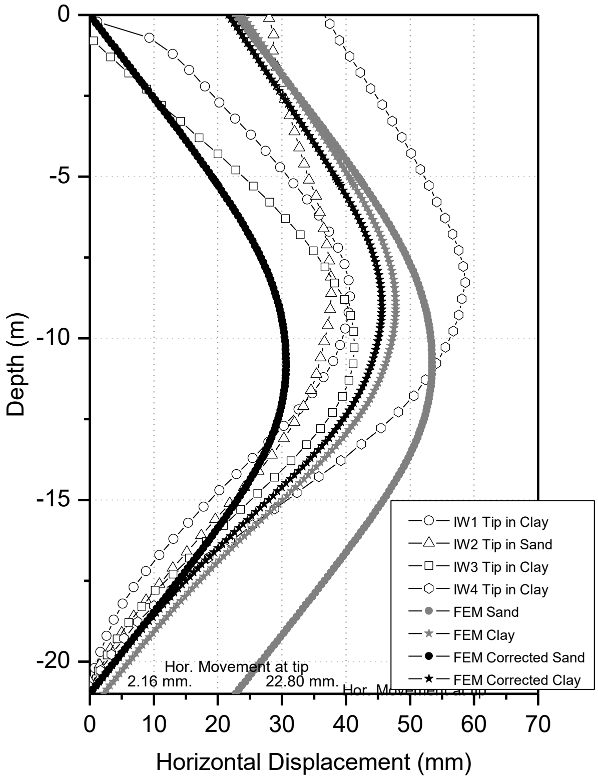


Fig. 11 Field measurement and FEM results of D-wall horizontal displacement

Table 3 Maximum Horizontal Displacement

Inclinometer number	Wall Displacement (mm.) at final stage
IW1 (A)	40.64
IW1 (B)	6.02
IW2 (A)	37.71
IW2 (B)	9.81
IW3 (A)	41.31
IW3 (B)	3.86
IW4 (A)	58.65
IW4 (B)	6.87

6. Conclusion

FEM analysis was carried out to predict D-wall behavior and design D-wall reinforcement for True Digital Park Phase 2 underground structure in the case that there was a variation in soil layer between -19.00 m to -23.00 m. The FEM result showed that D-wall horizontal displacement especially at toe can be much larger if the tip of D-wall sits in the sand layer due to lower soil stiffness. D-wall movement had been monitored throughout the whole underground construction using installed inclinometers. The field performance of D-wall showed similar horizontal displacement for both sand and clay cases in terms of maximum movement. This might be due to the fact that inclinometer installed in the D-wall read displacement relative to the toe (set toe movement as zero). Hence, the actual toe displacement cannot be measure. This indicate that when the D-wall is in the sand layer, there might be unknown toe movement. While excluding toe movement, the field record quantitively agrees with FEM prediction that wall movement was lower in case of sand layer at tip. There was also one inclinometer exhibited relatively much larger movement which might be because of large opening for mechanical automatic car park system in basement slab.

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