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Ground Surface Settlement Induced by Diaphragm and Buttress Walls Installation: Numerical Study

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ABSTRACT: In construction practices, diaphragm walls are a cast-in-situ reinforced concrete retaining wall that are constructed using a slurry supported trench method. The installation process includes slurry supported trench excavation, placing the reinforcement cage, concrete casting and curing. This installation process would modify the in-situ stress state in the soil close to the trench and generate ground surface settlements, which might be significant compared to those induced by the main excavation. Also, the construction of buttress walls, a concrete wall that perpendicular to diaphragm walls, might generate additional ground surface settlement, and this issue has not been investigated. For clarify this issue, a series of three-dimensional finite element analysis was performed to quantify the amount of ground surface settlement induced by the diaphragm and buttress walls installation process using the Wall Installation Modeling (WIM) method. Results show that the installation of buttress walls inside or outside the excavation zone did not yield significant additional ground surface settlement outside the excavation zone because the diaphragm wall was completed first before the construction of the buttress wall. But, the construction of outer buttress walls could widen the settlement zone.
Keywords: Excavation, Settlement, Installation, Buttress wall, Diaphragm wall.

1. INTRODUCTION

In construction practices, diaphragm/buttress/cross walls are a cast-in-situ reinforced concrete retaining wall constructed using a slurry supported trench method. The installation process includes slurry supported trench excavation, placing the reinforcement cage, concrete casting and curing. This installation process would modify the in-situ stress state in the soil close to the trench and generate ground surface settlements, which might be significant compared to those induced by the main excavation.

The installation effects of diaphragm wall have been investigated using the three-dimensional numerical analyses and found that the soil stress redistribution might be generated due to the installation of diaphragm walls and its quality of construction (Gourvenec and Powrie 1999, Ng and Yan 1999, Comodromos et al. 2013). Schäfer and Triantafyllidis (2006) compared the results from the Wall-Installation-Modelled (WIM) method and the Wished-In-Place (WIP) method using three-dimensional finite element analysis of TNEC excavation project in Taipei basin (Ou et al. 1998). They concluded the WIP method would underestimate 15-20% of the ground surface settlements and the wall deflections compared to the WIM method. Also, the construction of buttress walls might generate additional ground surface settlement, and this issue has not been investigated.

For clarify this issue, three-dimensional finite element analyses (Brinkgreve et al., 2013) were performed to quantify the amount of ground surface settlement induced by the diaphragm and buttress walls installation process using the WIM method.

2. WALL INSTALLATION MODELLING (WIM) METHOD

The WIM method analysis followed the procedures which were done by Schäfer and Triantafyllidis (2006). **Fig 1** presents the three-dimensional finite element model for the WIM model. The depth of the trench (H_t) was 33 m, and the excavation length was 56 m. The model represents a plane section which comprises fifteen diaphragm wall panels and seven buttress wall panels. The Hardening Soil (HS) model (Schanz et al, 1999) was adopted to simulate the soil behavior, including the clay (CL) and the silty gravel (GM) under the undrained and drained conditions, respectively. The model parameters of soils were typical values for the Taipei silty clay and the Taipei silty gravel (Lim and Ou 2017; Hsieh et al 2016). **Table 1** lists the input parameters for the WIM model analysis. 10-node tetrahedral elements were employed to simulate the soil and trench volume. Soil movements normal to the four vertical sides were restrained while they were restrained in all directions at the bottom of the geometry.

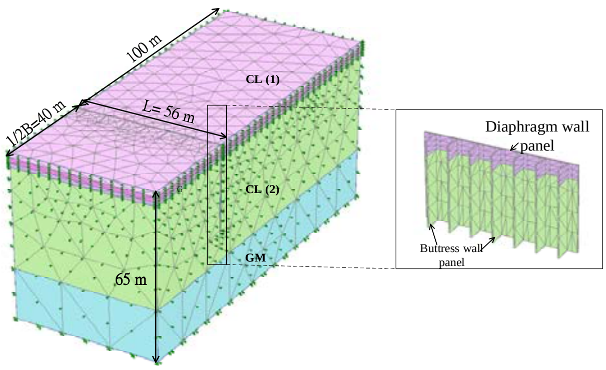


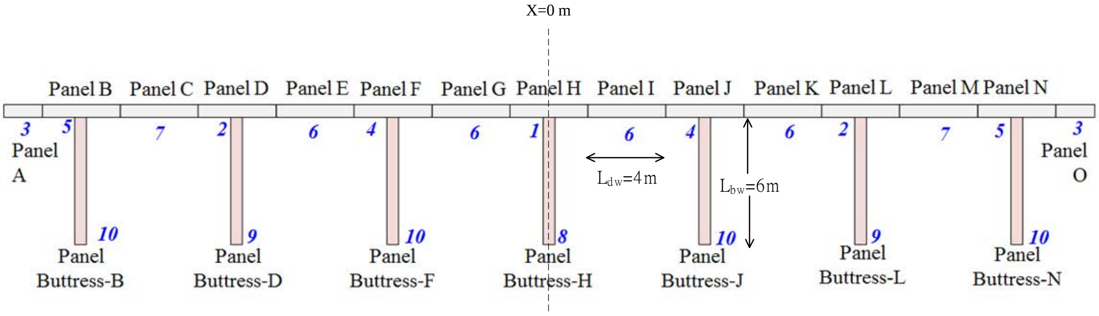
Figure 1 Finite element model for the WIM model analysis

Table 1 Soil Input Parameters for Analyses

Soil layer	Depth (m)	γ_t (kN/m^3)	ϕ' (deg)	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)	E_{ur}^{ref} (kPa)	m
CL(1)	0 - 2	18.25	30	7033	4923	21100	1
	2 - 4	18.25	30	6826	4779	20479	1
	4 - 5.6	18.25	30	6631	4642	19894	1
CL(2)	5.6 - 45	18.5	30	9488	6642	28470	1
GM	45 - 65	19.6	37	85000	121000	256000	0.5

Note: R_f = 0.9; υ_{ur} = 0.2

The plane section of the considered diaphragm wall consists of fifteen diaphragm wall panels and seven buttress wall panels with a selected length of 4 m and 6 m, respectively, as shown in **Fig 2**. The thickness of the diaphragm and buttress walls was assumed 0.6 m. A number nearby each panel indicates the construction stage, for example, the panel H was first constructed (stage 1), followed by the panel D and the panel L (stage 2), then the panel A and the panel O (stage 3), and so forth. After all of the diaphragm wall panels were completed, then the panel buttress-H was constructed (stage 8), followed with the panel buttress-D and the panel buttress-L (stage 9), and closed by the panel buttress-B, the panel buttress-F, the panel buttress-J and the panel buttress-N (stage 10).



Note: a number nearby each panel indicates the construction stage.

Figure 2 Construction stages of the diaphragm wall and buttress wall panels

For each stage, three additional steps should be conducted to model the WIM method such as:

(1). The excavation under slurry support was modeled by deactivating the respective finite elements inside the trench and applying the distributed loads on the surface of the trench walls. The magnitude of the loads corresponds to the hydrostatic slurry pressure with a bulk unit weight of γ_b=10.3 kN/m^3.

(2). On the subsequent process of concrete pouring, the distributed loads were increased from the slurry to the fresh concrete pressure (σ_c). The pouring process was modeled following the bilinear approximation by Lings et al. (1994), which adopts a hydrostatic pressure distribution up to a critical depth (h_{crit}) of 20–30% of the panel depth. Below h_{crit}, the pressure gradient corresponds to bulk unit weight γ_b of the bentonite slurry:

$$\sigma_c = \begin{cases} \gamma_c \times z, z \le h_{crit} \\ \gamma_b \times z + (\gamma_c - \gamma_b) \times h_{crit}, z > h_{crit} \end{cases} \quad (1)$$

where γ_c is the bulk unit weight of the concrete, γ_b the bulk unit weight of the slurry, z the depth below surface ground level.

(3). The finite elements representing the fresh concrete were activated inside the trench, and the distributed loads are removed. The increased stiffness of the concrete due to aging is considered by a suitable evolution of Young's modulus, E, and the Poisson ratio, υ, in the course of 28 days.

3. RESULTS AND DISCUSSIONS

Fig 3 shows the contour of ground surface settlements induced by the diaphragm and buttress walls installation. As shown in **Fig 3**, the installation of buttress walls inside the excavation zone did not yield significant ground surface settlement outside the excavation zone. However, it could generate the ground surface settlement inside the excavation zone. Furthermore, buttress walls also modeled outside the excavation zone. **Fig 4** shows the contour of ground surface settlements induced by the diaphragm and outer buttress walls installation. As shown in **Fig 4**, based on the maximum settlement point of view, the installation of outer buttress walls yielded insignificant additional ground surface settlements outside the excavation zone. But, the construction of outer buttress walls widened the settlement zone.

Table 2 summarizes the maximum ground surface settlement induced by the diaphragm and buttress walls installation inside and outside the excavation zone. The maximum ground surface settlement occurred at the center of the diaphragm wall section (x=0). The maximum ground surface settlement induced by diaphragm wall installation was 16 mm. It was apparent that the installation of seven inner and outer buttress walls only increased 1.1 mm and 0.6 mm of ground surface settlements, respectively, and they were minimal. The inner buttress wall trench excavation only induced ground surface settlement in the excavated zone but it was not necessary to be considered because the soil would be excavated soon after the retaining wall system was constructed. Moreover, the outer buttress wall trench excavation widened the ground settlement zone but the additional ground surface settlement induced by the outer buttress walls trench excavation was insignificant. Thus, it could be concluded that the installation of buttress walls has no significant effect on the additional ground surface settlement induced by the buttress walls trench excavation because the diaphragm wall was completed first before the construction of the buttress wall.

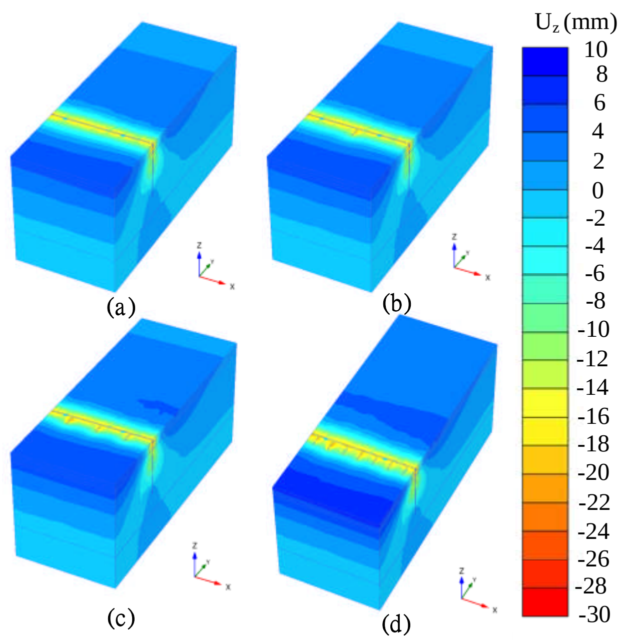


Figure 3 The contour of ground surface settlements induced by: (a) diaphragm wall installation, (b) diaphragm wall with single buttress wall installation, (c) diaphragm wall with three buttress walls installation, (d) diaphragm wall with seven buttress walls installation

Furthermore, the ground surface settlements at each cross section of the diaphragm wall with inner and outer buttress walls were plotted in **Fig 5** and **Fig 6**, respectively. The ground surface settlement (δ_{vw}) and the distance behind the diaphragm wall (d) are normalized with the depth of the trench (H_t). The main influence range of settlement was 0.3 to 0.5H_t from the diaphragm wall trench panel, and small settlement occurred beyond 1.0H_t from the panel. This observed settlement characteristic was also reported by Ou and Yang (2000) in which they monitored the settlement induced by the construction of the diaphragm walls for the excavations in the Taipei Rapid Transit System. In addition, at some cross-sections, small amount of ground surface heave was detected from the computation results, especially at the location between 0.5 to 1.0 d/H_t. According to author experiences, it seems that the ground heave was unlikely to be occurred in the field. The possible reason might due to the limitation of HS model. Moreover, the WIM method yielded the δ_{vw} was 0.05% Ht while Ou and Yang (2000) reported the δ_{vw} was in the range of 0.05% to 0.13% H_t, depends on the progress of completed diaphragm panels. Although the computed δ_{vm} might underestimate the field condition, at least the installation effect of buttress walls could be well captured.

Table 2 Summary of the Maximum Ground Surface Settlement Induced by the Diaphragm and Buttress Walls Installation

Description	Settlement behind the D-wall (mm)						
	x= 0 m	x= 4 m	x= 8 m	x= 12 m	x= 16 m	x= 20 m	x= 24 m
D-wall only	16.0	11.3	14.8	11.8	12.4	11.8	15.5
D-wall + 1 Inner B-wall	16.5	11.4	15.0	11.9	12.5	11.9	15.5
D-wall + 3 Inner B-walls	16.6	11.3	15.3	12.2	12.9	12.3	15.8
D-wall + 7 Inner B-walls	17.1	11.8	15.9	12.8	13.4	12.7	16.3
D-wall + 1 Outer B-wall	16.2	13.5	15.2	11.4	13.7	11.3	15.3
D-wall + 3 Outer B-walls	16.3	13.3	15.5	11.8	14.3	11.9	15.6
D-wall + 7 Outer B-walls	16.6	13.6	16.0	12.10	14.7	12.1	16.5

Note: x indicates the distance away from the center section of the diaphragm wall

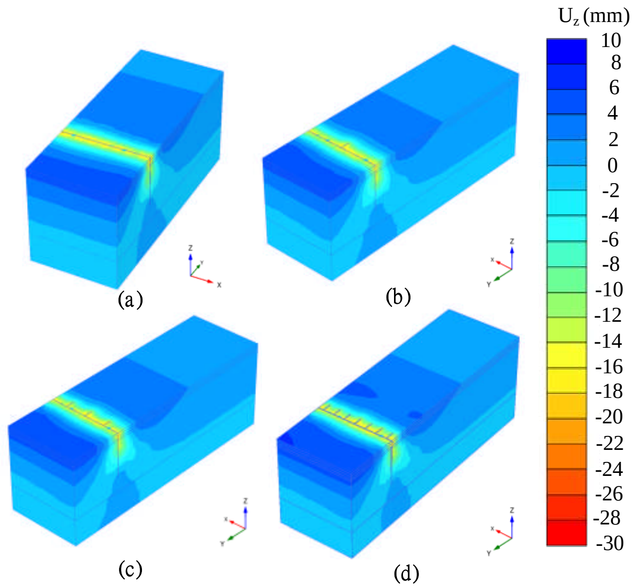


Figure 4 The contour of ground surface settlements induced by: (a) diaphragm wall installation, (b) diaphragm wall with single outer buttress wall installation, (c) diaphragm wall with three outer buttress walls installation, (d) diaphragm wall with seven outer buttress walls installation

4. CONCLUSION

As discussed above, the Wall-Installation-Modelling method would substantially increase the complexity and the running time of the analysis. Hence, for simplification, the widely used Wish-In-Place method (Hsieh et al. 2016, Dong et al. 2016, Goh et al. 2017) was adequate for the simulation of diaphragm wall and buttress wall with the consideration of the weight of the concrete from the diaphragm wall and buttress wall over the existing soil.

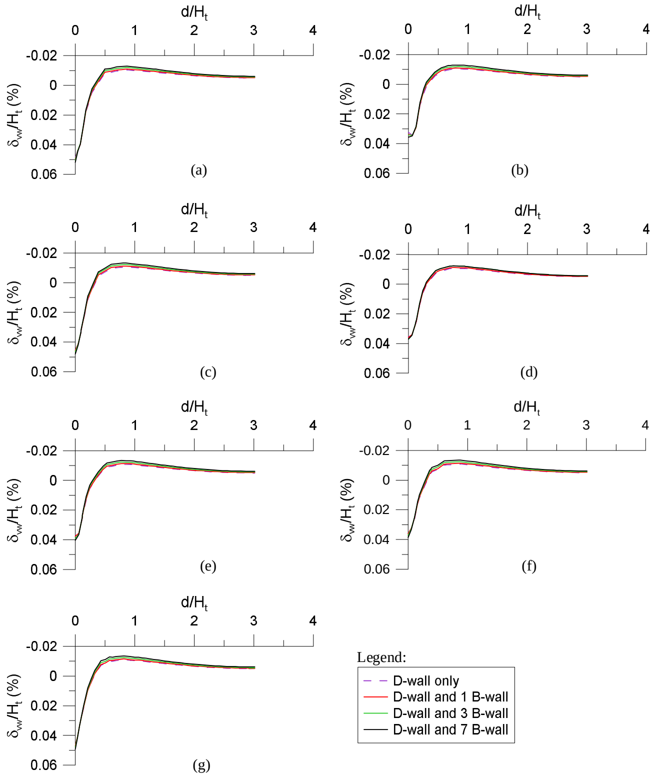


Figure 5 Profile of ground surface settlements at each cross section of the diaphragm wall and inner buttress walls: (a) x = 0 m, (b) x = 4 m, (c) x = 8 m, (d) x = 12 m, (e) x = 16 m, (f) x = 20 m, (g) x = 24 m

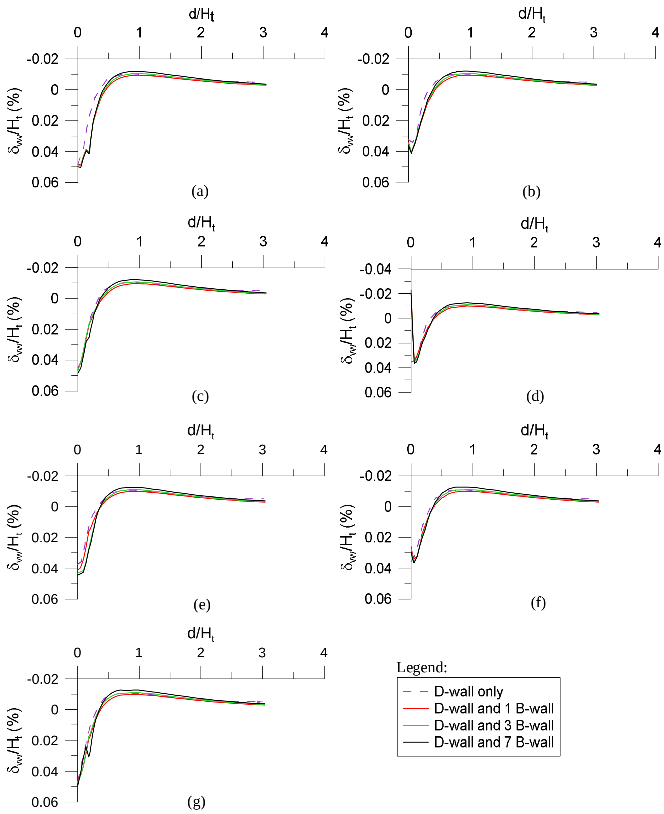


Figure 6 Profile of ground surface settlements at each cross section of the diaphragm wall and outer buttress walls: (a) x = 0 m, (b) x = 4 m, (c) x = 8 m, (d) x = 12 m, (e) x = 16 m, (f) x = 20 m, (g) x = 24 m

5. ACKNOWLEDGMENTS

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