Performance of cantilever buttressed diaphragm wall in a large-scale excavation in Kenny Hill Formation

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ABSTRACT

This paper presents an excavation case history in which a cantilever buttressed diaphragm wall was adopted instead of internal bracings or top-down construction method for an 11 m deep excavation in weathered residual soils of Kenny Hill formation. As the proposed support system is the first to be adopted in deep excavation and basement construction in Malaysia, this paper aims to present the construction methodology and its field performance. In addition, three-dimensional finite element analysis of the case history was also performed to evaluate the joint condition between the diaphragm wall and buttress wall. The results show that to obtain a realistic prediction of wall movement, the joint condition between the diaphragm wall and buttress wall should be appropriately accounted for in numerical modelling.

Keywords: deep excavation, buttress wall, Kenny Hill formation, finite element analysis

1 INTRODUCTION

Most deep excavation projects in the urban area require the use of a retaining wall together with a lateral support system to resist lateral earth pressure and to control ground movements. For the bottom-up construction method, the commonly adopted lateral support system is either internal steel strut bracings or tie-back anchors. As for the top-down construction method, basement floor slabs are used to support the retaining wall during excavation. However, for large-scale excavation where the plan dimensions of excavation geometry are large, it is challenging to ensure that the steel struts are appropriately installed, aligned and preloaded, and these would reduce the effectiveness of internal bracings. Conversely, the top-down construction method requires the plunge-in steel columns to be installed to support the slabs before excavation. These vertical supports may hinder and slow down the speed of earth removal when working underneath the slab with limited headroom. Given that for a large-scale excavation with total excavation depth of less than 12 m or less than 3 levels of basement floors, top-down construction method is a less attractive method based upon scheduling and financial concerns.

This paper presents an excavation case in which cantilever buttressed diaphragm wall is adopted instead of internal bracings or top-down construction method for an 11 m deep excavation in Kenny Hill formation.

As the proposed support system is the first to be adopted in deep excavation and basement construction in Malaysia, this paper aims to present the construction methodology and field performance of buttressed diaphragm wall. Three-dimensional finite element analysis of the case history was also performed to evaluate the joint condition between diaphragm wall and buttress wall to take into consideration that the diaphragm wall and the buttress wall are cast in a separate operation.

2 PROJECT OVERVIEW

The project site is located in Kuala Lumpur city centre. It is a residential development with a two-level underground basement. The geometry of the basement excavation is approximately 105 m x 160 m in plan with the total excavation depth of 11 m below existing ground level. Figure 1 shows the plan of the excavation site along with the position of the monitoring instruments.

Geological map of Kuala Lumpur, Malaysia (1993) indicates that the site is underlain by weathered residual soils of Kenny Hill Formation. The ground condition at the site consists of a silty sand layer (recent alluvium deposits) down to about 4.5 m, which in turn is underlain by residual soils of the Kenny Hill formation (Figure 2). Low SPT-N values were registered in the upper recent alluvium layer that mainly consists of loose silty sand material. As for residual soils of the Kenny Hill formation, the SPT-N value ranges from 10 to 120 blows/300mm and increases with depth. The groundwater table was observed at approximately 4.5 m below the ground surface. Figure 2 shows the profile of the excavation, diaphragm wall, buttress wall and subsoil profile.

The diaphragm wall of 22.5 m deep, and 0.6 m thick was supported by 0.6 m thick and 4 m length of low strength unreinforced concrete (15 MPa) buttress walls at 6.5 m centre to centre spacing. The buttress walls would be demolished after completion of the basement floor slabs.

The connection between the diaphragm wall and buttress wall was the T-section joint. The 0.6 m thick diaphragm wall was first excavated and cast, and buttress walls were installed after completion of the diaphragm wall. The adopted two-stage excavation and casting method were to avoid the problems related to the stability of T-shape trenches (Ou *et al*. 2006). To ensure proper contact between the diaphragm wall and buttress wall, a partition steel plate was installed on the excavation side of the diaphragm wall.

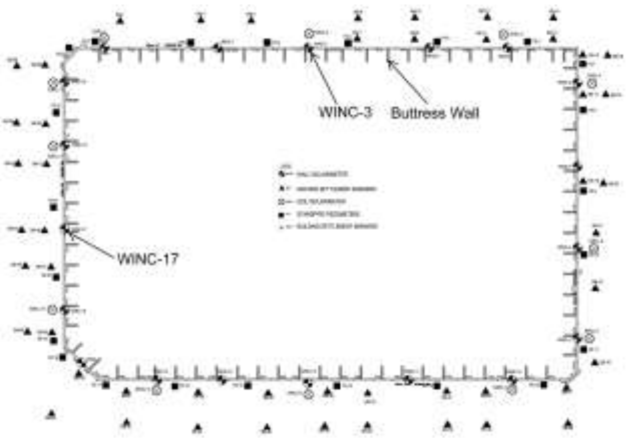

Fig. 1. Excavation and instrumentation plan

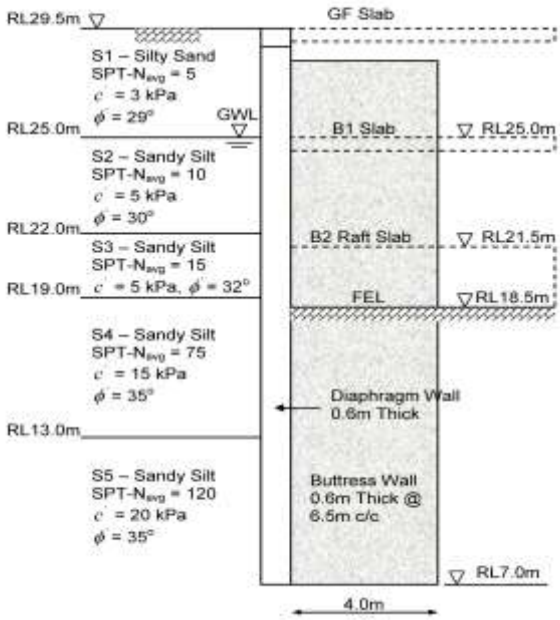

Fig. 2. The subsoil profile and sectional details

3 FIELD MONITORING RESULTS

This paper only focused on two inclinometer readings, i.e., WINC-3 and WINC-17, which were located at the centre of the long and short side of the diaphragm wall respectively. Figure 3 shows the measured wall deflection profiles of WINC-3 and WINC-17. The measured maximum horizontal wall deflection for both inclinometers is about 45 mm with the wall deflection to excavation depth ratio ($\delta_{h\max} / H_e$) of 0.41%. As can be observed from Figure 1, the pattern of the wall deflection is cantilever mode with a rotational movement at the wall toe. This is due to the toe of the buttressed diaphragm wall was founded in the hard layer with SPT-N value more than 100 blows/300mm.

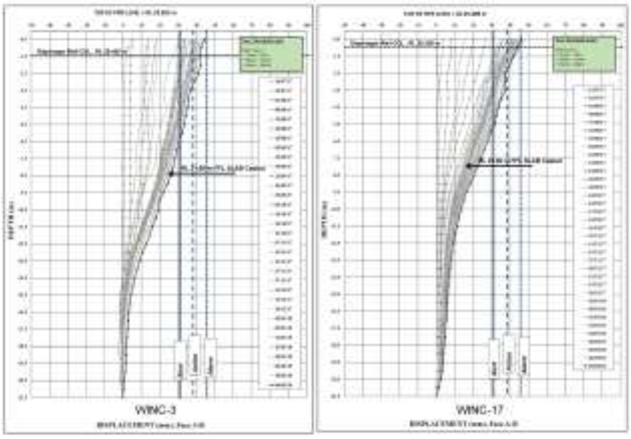

Fig. 3. Measured diaphragm wall deflections at WINC-3 and WINC-17

4 3D FINITE ELEMENT ANALYSIS

For numerical simulations carried out in this study, a commercially available 3D finite element program PLAXIS 3D was used. Figure 4 shows the 3D finite element mesh adopted in the numerical study. The four vertical side boundaries of the mesh are restrained from movement in the horizontal direction but are free to move vertically, and the bottom boundary of the mesh is entirely restrained from movement in both the horizontal and vertical directions. The mesh boundaries were set at 100 m from the diaphragm wall. This distance was approximately 9 times the maximum excavation depth (H_e), which exceeds the minimum distance to the mesh boundary of $3H_e$ as recommended by Lin *et al*. (2003).

Ten-node tetrahedral elements were used to model the soil volume. The stress-dependent stiffness model, the Hardening Soil (HS) model (Schanz *et al.*, 1999) was adopted to simulate the soil behaviour under drained condition. Table 1 summarises the input parameters for the soils modelled. The soil stiffness parameters of the HS model were based on empirical correlation as reported by Law *et al*. (2014).

Six-node plate elements were used to model the diaphragm wall and the buttress wall. Also, 12-node interface elements were applied to model the soil-wall interaction behaviour with an interface reduction factor, R_{inter} of 0.8 was adopted to model the interaction between soils and structural elements. The structural elements, such as the diaphragm wall and buttress wall are assumed to behave as linear elastic material. The analyses assumed that the diaphragm wall and buttress wall are "wished-in-place" and hence, do not consider local changes in stresses or soil properties associated with trench excavation and concreting process. Table 2 summarises the input parameters for the structural elements modelled.

For joints between the diaphragm wall and buttress wall, both rigid and free connections were considered in the numerical study to investigate the influence of joints condition on buttressed diaphragm wall behaviour. The rigid connection represents the joints between the diaphragm wall and buttress wall are intact. Whereas, the free connection represents the poor joint condition as a result of construction defects (slime trapped between diaphragm wall and buttress wall) and yielded the independent movements between diaphragm wall and buttress wall (Lim *et al*. 2018).

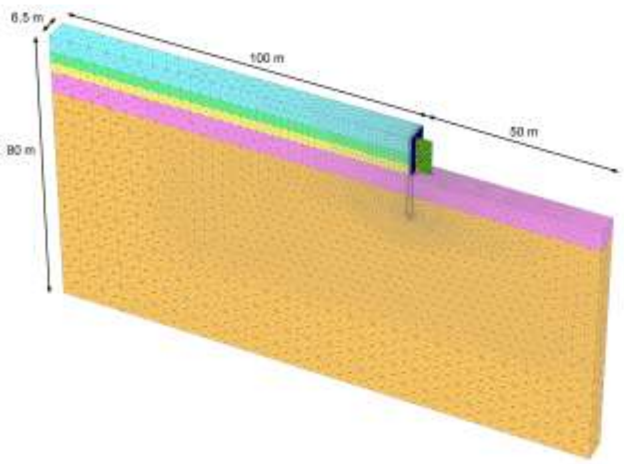

Fig. 4. 3D finite element mesh

Table 1. Effective shear strength and stiffness parameters.

Soil Profile	c' (kPa)	ϕ' (°)	ψ (°)	$E_{50}^{ref*} = E_{oed}^{ref}$ (MPa)	E_{ur}^{ref} (MPa)
S1	3	29	0	10	30
S2	5	30	0	20	60
S3	5	32	0	30	90
S4	15	35	0	150	450
S5	20	35	0	240	720

Table 2. Structural Elements Input Parameters

Structures	Concrete Grade (MPa)	Wall Thickness (m)	$E_1 = E_2$ (kN/m^2)
Diaphragm wall	35	0.6	28 x 10^6
Buttress wall	15	0.6	18 x 10^6

5 3D ANALYSIS RESULTS AND DISCUSSION

Figure 5 compares the measured and predicted horizontal wall deflection at the final excavation level. As seen in Figure 5, modelling the joints between the diaphragm wall and buttress wall as rigid connection yielded less wall movement compared to the free connection (35 mm versus 52 mm). The measured wall deflection is in between the two joints cases considered in the numerical study. The results indicate that the diaphragm wall and buttress wall do not behave as an integrated retaining system. Site inspection of the joints condition between diaphragm walls and buttress walls during the excavation has shown that the joints were intact with the buttress walls fully abutting to diaphragm wall without any slime trapped in between.

The above findings clearly indicate that the buttressed diaphragm wall behaviour is mainly governed by interface behaviour between steel plate and concrete. As the excavation progress, both the diaphragm walls and buttress walls would move toward the excavation side with cantilever mode of deflection profile. However, the buttress wall would tend to deflect less compared to the diaphragm wall due to the high bending stiffness of the buttress wall. This would cause differential movement and shearing force developed at the interface between diaphragm wall and buttress wall. Figure 6 compares the vertical movement of the buttressed diaphragm wall for rigid and free connections. As can be observed from Figure 6, for a rigid connection the diaphragm wall and buttress wall move together. On the other hand, for free connection, the diaphragm wall and buttress wall move independently to each other.

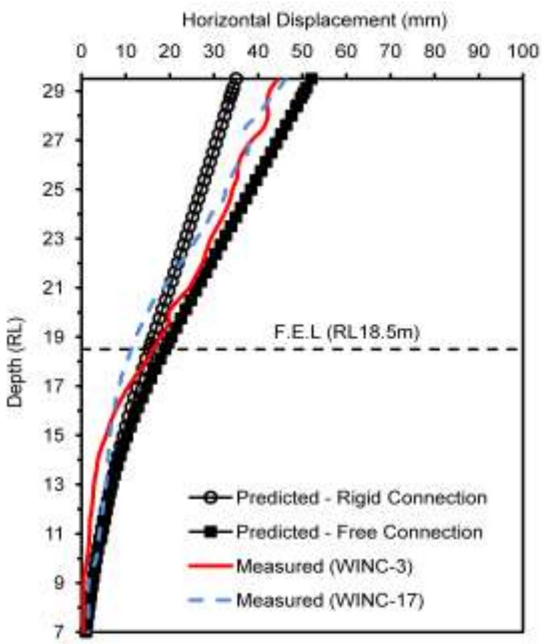

Fig. 5. Comparison of measured and predicted horizontal wall deflection

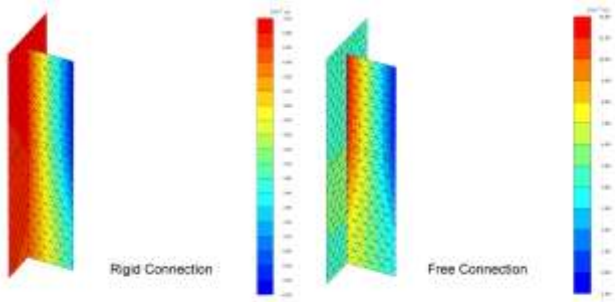

Fig. 6. Comparison of vertical movement between diaphragm wall and buttress wall or rigid and free connections

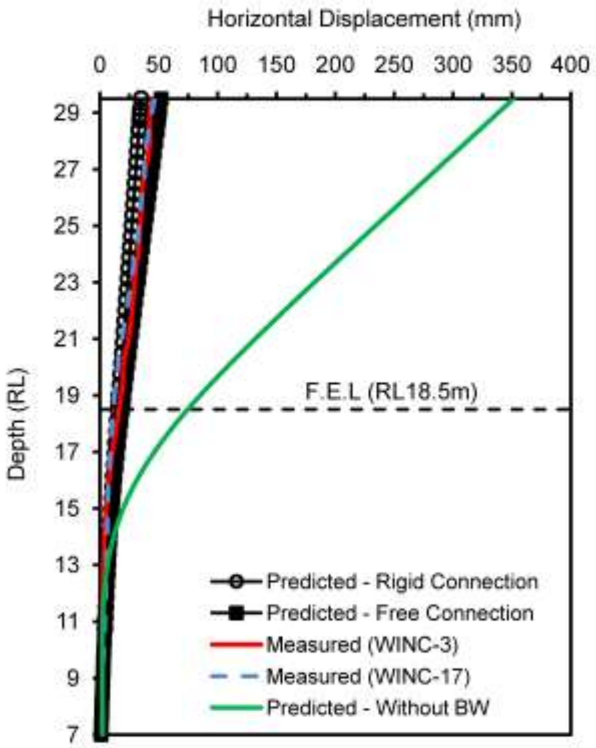

Fig. 6. Comparison of wall movement with and without buttress wall

As can be seen from Figure 5, the connection between the diaphragm wall and buttress wall is neither rigid nor free. From the field measurement data and numerical study, it is evident that the reduction of wall deflection was due to the frictional resistance developed at the interface (joints) between diaphragm wall and buttress wall, and the degree of mobilization needs to be further quantified and is beyond the scope of this paper. However, in the design, it is recommended that the joint between the diaphragm wall and buttress wall should be modeled as a free connection if the above-described installation method is to be adopted.

Figure 7 compares the predicted wall deflection with and without installation of buttress wall. As shown in Figure 7, the diaphragm would have moved 350 mm without the buttress wall. In other words, the buttress wall has effectively reduced the excavation-induced wall deflection by 85%. The deformation control mechanism of buttressed diaphragm wall was dominated by bending rigidity of buttress walls coupled with frictional resistance between buttress walls and surrounding soil (Hsieh *et al*. 2016). However, the latter plays a relatively minor role in controlling the excavation-induced wall deflection (Lim *et al*. 2018).

6 CONCLUSIONS

This paper presents the successful use of strut-free buttressed diaphragm wall as the retaining system of a large-scale deep excavation project. A numerical study was also conducted to investigate the effect of joints between the diaphragm wall and buttress wall on its deformation behaviour. For the situations discussed in this paper, the following conclusions can be drawn:

a) The application of buttress walls has effectively controlled the excavation-induced wall deflection within an acceptable limit, and substantial time and cost saving have been achieved in this case history.
b) The deformation control mechanism of cantilever buttressed diaphragm wall mainly derived from the combined bending stiffness of diaphragm wall and buttress wall. The frictional resistance between buttress walls and surrounding soil plays a relatively minor role in limiting the wall deformation.
c) The condition of joints between the diaphragm wall and buttress wall plays a significant role in the cantilever buttressed diaphragm wall behaviour.
d) The important lesson learned from this case history was that joints between the diaphragm wall and buttress wall should be connected properly. Otherwise, the integrated retaining system could not be formed.

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