A study of the efficiency of excavations with the installation of buttress walls in reducing the wall deflection

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ABSTRACT

Buttress walls are a common construction method in Taiwan for protection of adjacent buildings during excavation, but their mechanism in restraining movements was not fully understood. This study performs three-dimensional finite element analyses of two excavation cases with buttress walls to establish the numerical analysis model. Then a series of parametric study were performed by varying the length of buttress walls. Results show that the main restraining effect for rectangular shape buttress walls comes from the frictional resistance between the buttress walls and adjacent soil while the buttress walls were demolished along with the removal of soil. The efficiency of reducing wall deflection will increase with length of rectangular shape buttress wall. If the rectangular shape buttress wall length was less than 2.0 m, the buttress wall was unable to restrain the wall deflection. The restraining effect for T-shape buttress walls comes from the frictional resistance between the buttress walls and adjacent soil and bearing resistance from the flange. Increase of the web length has a slightly better effect in reducing the wall deflection than that of the flange length for T-shape buttress wall.

Keywords: excavation, buttress walls, case histories, three-dimensional finite element analysis, parametric study

1 INTRODUCTION

Wall deflection and ground movement normally occur as a result of excavation. Excessive ground movement frequently damages adjacent properties in urban areas. To avoid the damage of adjacent buildings during excavation, it is necessary to adopt auxiliary measures to limit the lateral wall deflection or ground settlement. Buttress walls have gradually adopted as an auxiliary measures for the protection of adjacent buildings during deep excavation in Taiwan.

Buttress walls are concrete walls, constructed perpendicular to the diaphragm wall prior to excavation, as shown in Fig. 1. A few studies on buttress walls have been found in the literature (Hwang et al. 2007, Ou et al. 2008, Chen et al. 2011) and indicated that the buttress walls have a certain effect in reducing the lateral wall deflection. However, the mechanism of buttress walls in reducing the deformation of diaphragm wall remains resolved.

In this paper, two excavation cases with buttress walls, one T-shape buttress walls in clay and another rectangular shape, referred to as R-shape, buttress walls in predominating sandy soil, were analyzed using the three-dimensional finite element method. These buttress walls were constructed directly after the completion of the main diaphragm walls. Because the buttress walls were dismantled during the process of excavation, no reinforcement steel bars exist in the buttress walls above the final excavation depth but temperature steel bars were arranged in the buttress...
walls below the final excavation depth. A numerical analysis model was established by comparing the monitored and computed wall deflections. Characteristics of wall deflection and development of lateral resistance from buttress walls were further studied using parametric study by varying the length of buttress walls in these two cases.

2 CASE STUDIES

2.1 Case 1

Case 1 was a 44m by 42 m excavation located in Taipei. The diaphragm wall was 21 m in depth and 0.6 m in thickness. In order to protect a gas station near the excavation, three T-shape buttress walls, with the thickness ($t_{bw}$) of 0.6m, the flange length ($L_f$) of 2.5 m and web length ($L_w$) of 5 m, were constructed from the 2.0 m below the ground surface level (GL) to GL -22.0 m against the diaphragm wall as shown in Figs. 2 and 3. Four excavation stages were executed to reach the final depth of 8.6 m. Three levels of struts were employed to support the diaphragm wall. Fig. 3 shows the construction sequence of excavation and the profile of the subsurface soil. The buttress walls were demolished along with excavation process. Two inclinometers, including SI-4 and SI-6, were installed to observe wall deflection during excavation, as shown in Fig. 2. A three-dimensional finite element computer program, PLAXIS 3D (2013), was used as a basic analysis tool. The Harding Soil model (Schanz et al. 1999), referred to as the HS model, was adopted to simulate the behavior of soils, including silty clay and silty sand under the undrained and drained conditions, respectively.

Of the HS parameters; the secant stiffness ($E_{sec}^{ref}$) corresponding to the reference stress, $p^{ref}$, the tangent referential stiffness for primary oedometer loading ($E_{tang}^{ref}$), the unloading/reloading referential stiffness ($E_{ur}^{ref}$), and the power for stress-level dependency of stiffness (m); were decided according to Lim et al. (2010) and Calvello and Finno (2004) for silty clay, and to Khoiri and Ou (2013) for silty sand.

The coefficient of the at-rest earth pressure ($K_0$) for silty sand, can be obtained by the equation $K_0 = 1 - \sin \phi'$ (Jaky 1944). The $K_0$ value for silty clay can be obtained according to Ou (2006).

The structural members such as diaphragm walls, buttress walls and concrete floor slabs employed in the top-down construction method were with plate elements and simulated as linear elastic material. The temporary struts were with axial elements and also simulated as linear elastic material. Their parameters can be obtained according to Ou (2006).

The vertical boundary of the finite element mesh was set at 26 m where hard rock exists. The horizontal boundaries were located at the distance two times the final excavation depth from the diaphragm wall.

Fig. 4 plots a comparison of the computed wall deflection and monitoring data at SI-4, near the location of a buttress wall. It can be observed that the computed wall deflections were in general close to the monitored values but slightly overestimated at the last two stages. For evaluation the effectiveness of buttress walls in reducing the wall deflection, analysis of the excavation with assumption of no buttress walls were performed and the results are also shown in Fig. 4. It can be found that the wall deflections were reduced significantly due to installation of buttress walls. The computed maximum wall deflections with buttress wall and without buttress walls were 76.1 mm and 41.5 mm, respectively. The ratio of reduction in the maximum wall deflection ($MR$) for wall deflection was 45.5%. Installation of buttress walls can reduce the maximum wall deflection significantly.
2.2 Case 2

Case 2 was a 64m by 43 m excavation located in Taipei, as shown in Fig. 5. The diaphragm wall was 43 m in depth and 1.3 m in thickness, penetrating 3.5 m into gravel layer. Three types of R-shape buttress walls with different $tbw$ and length ($L$) were constructed from GL+0 m to GL -35.0 m as shown in Fig. 6 and their allocations were shown in Fig. 5. The basement was constructed with top-down construction method up to 26.45 m in depth. Fig. 6 shows the construction sequence of excavation and the profile of the subsurface soil. The buttress walls were demolished along with excavation process. To monitor the wall deflection, 7 inclinometers as shown in Fig. 5 were installed penetrating 5 m into gravel layer. Among them, inclinometer SI-1, SI-3 and SI-4 were damaged so their data were excluded in this study.

In finite element analysis, the input parameters of soils and structures are decided similar to Case 1. The vertical boundary of mesh was set at 54.9 m, considering that hard rock would not deform during excavation. The horizontal boundaries were located at the distance two times the final excavation depth from the diaphragm wall.

Fig. 7 shows a comparison of monitored and computed wall deflection at stage 8. For evaluation of the effectiveness of installation of buttress walls, analysis of the excavation with the assumption of no buttress walls installed was also performed and the results are shown in the same figure. The computed wall deflections generally agreed with the monitored data for SI-2, SI-5, SI-6 and SI-7 at all excavation stages and the comparison at stage 8 is shown in Fig. 7. The analysis validates the constitutive model adopted and analysis procedure in this study. Fig. 7 also shows that the wall deflections at SI-2, SI-5, SI-6 and SI-7 were slightly smaller than those without buttress walls. Their $MR$ values were equal to 17.5%, 26.9%, 17.0% and 23.9%, respectively. Installation of buttress walls had effects in reducing the wall deflection.

3 PARAMETRIC STUDIES

A series of three-dimensional finite element analyses were performed where the excavation geometry and construction sequence of Case 1 and Case 2, respectively, were used as a basis, and combined with different length of buttress walls. The wall deflection and shear stress along the side surface of the buttress wall at point A in Fig. 2 and S15 in Fig. 5, both locating about central section of the excavation, were employed for studying the reduction in wall deflection.

3.1 Mechanism of buttress walls

Two scenarios were assumed. One was exactly the same as Case 1 project. The other was similar to Case 2.
but with R-shape buttress walls with \( L_r = 5.6 \) m. In each scenario, the analyses were performed with consideration of frictional resistance between the buttress walls and the adjacent soil by setting the interface properties \( R_{int} = 1.0 \), with the assumption of no frictional resistance by setting \( R_{int} = 0.01 \) and with the assumption of no buttress walls.

3.2 Effect of R-shape buttress walls length

As studied in the preceding section, the main restraining effect for R-shape buttress walls comes from the frictional resistance between the buttress walls and adjacent soil because the buttress walls were demolished along with the removal of soil.

Fig. 9 shows the variation of the computed wall deflections for Case 2 with buttress walls where \( L_r = 5\)m, 10m, 20m and without buttress walls, respectively. The amount of wall deflection certainly decreased with the increasing length of buttress walls.

Fig. 10 illustrates the distribution of shear stress and relative shear stress (\( \tau_{rel} \), defined as the ratio of shear stress to maximum shear stress of an interface element for a given effective normal stress) on the surface of resistance of the flange. Therefore, the restraining effect for T-shape buttress walls comes from the frictional resistance between the buttress walls and adjacent soil and bearing resistance from the flange.
and along the buttress wall. As shown in Fig. 10, the induced shear stress occurred at the diaphragm wall with the minimum value and increased with the increasing distance from the diaphragm wall. The $\tau_{rel}$ was mostly close to 1.0, especially for $L_r = 5\text{m}$ and 10\text{m}. Therefore, to further restrain the wall deflection, the length of buttress wall needs to be increased in order to provide larger frictional resistance.

Fig.10 also exhibits a relative small driving stress and $\tau_{rel}$ occurring within the first 2 m from the diaphragm wall, no matter how long the buttress was. This phenomenon can be explained by the fact that the movement of the buttress wall at any location was all the same, almost the same as the movement of the diaphragm wall because it had a very high axial rigidity. The soil in front of the diaphragm wall, say, 2.0 m from the diaphragm wall, directly pushed by the diaphragm wall, should have almost the same amount of movement of the diaphragm wall or buttress wall. Therefore, the relative displacement between the buttress wall and the soil within the first 2.0 m from the diaphragm wall was very small but it increased gradually with the increasing distance from the diaphragm wall. The relative shear stress was therefore very small near the diaphragm wall and it increased with the increasing distance from the diaphragm wall. It was clear that if the buttress wall length was less than 2.0 m, the buttress wall was unable to restrain the wall deflection although the combined stiffness from the contribution of the diaphragm wall and buttress wall seems increased.

![Fig. 10: Distribution of shear stress and relative shear stress of different lengths of R-shape buttress wall in Case 2 (a) shear stress (b) relative shear stress.](image)

### 3.3 Effect of T-shape buttress walls length

As studied in the preceding section, the restraining effect for T-shape buttress walls comes from the frictional resistance between the buttress walls and adjacent soil and bearing resistance from the flange.

Fig. 11 shows the computed wall deflections for the three combinations and case of without buttress walls in Case 1. Compared with the wall deflection for $L_w = 5\text{m}$ and $L_f = 2.5\text{m}$, either increase of the web length up to 7.5\text{m} or flange length up to 5.0\text{m} can reduce the wall deflection.

![Fig. 11: Comparison of Computed wall deflections for different lengths of T-shape buttress wall in Case 1.](image)

Fig. 12 shows the distribution of shear stress and relative shear stress on the surface of the web of the T-shape buttress wall, with three combinations of web and flange lengths, respectively. As shown in this figure, the shear stress and relative shear stress was smaller near the diaphragm wall, similar to the R-shape buttress wall, and that near the flange was also small due to the restraint by the flange. The phenomenon seems to be more obvious as the flange length increased as comparing the relative shear stress in the case of $L_w = 5\text{m}$ and $L_f = 2.5\text{m}$ with that of $L_w = 5\text{m}$ and $L_f = 5\text{m}$.

Though the relative shear stress or frictional resistance on the web in the case of $L_w = 5\text{m}$ and $L_f = 5\text{m}$ decreased, the bearing resistance of the flange increased and the resulting overall efficiency increased, as demonstrated in Fig. 11.

As observed in Fig. 12, the relative shear stress on the web surface for the case of $L_w = 7.5\text{m}$ and $L_f = 2.5\text{m}$ was larger than that of the case of $L_w = 5\text{m}$ and $L_f = 2.5\text{m}$. The relative shear stress was less influenced by the diaphragm wall and flange when the web length increased. Therefore, increase of the web length can provide more frictional resistance and the wall deflection reduced as a result.

It is clear that either extension of the web length or increase of the flange length can reduce the wall deflection. Under a condition of identical length/area of buttress wall, increase of the web length has a slightly better effect in reducing the wall deflection than extension of the flange length as shown in Fig. 11 as the comparison of the case of $L_w = 7.5\text{m}$ and $L_f = 2.5\text{m}$ and the case of $L_w = 5.5\text{m}$ and $L_f = 5.5\text{m}$. The phenomenon can be explained by the fact that the frictional resistance can be mobilized at a very small
displacement while mobilization of the bearing resistance required a relatively large displacement. Extension of the flange length can increase the bearing resistance but not fully mobilized the resistance and it also reduced the frictional resistance of the web. The overall efficiency was therefore less than increase of the web length.

Fig. 12. Distribution of shear stress and relative shear stress of the web of T-shape buttress walls in Case 1 (a) shear stress (b) relative shear stress.

4 CONCLUSIONS

Based on the studies in this paper, the following conclusion can be drawn:
1. When rectangular shape buttress walls in excavations were demolished along with excavation of soil, the effect of reduction in the wall deflection mainly come from the frictional resistance between the side surfaces of buttress wall and adjacent soil.
2. The main mechanism of the R-shape buttress wall was due to the frictional resistance. The amount of reduction in wall deflection increased with the increasing length of the buttress wall.
3. When the length of buttress walls was short, for example, 2.0 m, the frictional resistance between the buttress walls and adjacent soil cannot be fully mobilized. Therefore, it would be unable to effectively reduce the wall deflection.
4. The restraining effect for T-shape buttress walls comes from the frictional resistance between the buttress walls and adjacent soil and bearing resistance from the flange.

5. Increase of the web length has a slightly better effect in reducing the wall deflection than that of the flange length for T-shape buttress wall.

ACKNOWLEDGEMENTS

The authors acknowledge the support provided by the Ministry of Science and Technology in Taiwan via grant No. MOST 103-2221-E-146 -004.

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