Use of rigid support system to reduce movements in deep excavations

Utilisation du système support rigide pour réduire les mouvements dans les excavations profondes

Chang-Yu Ou, Aswin Lim
Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taiwan R.O.C, aswin_lim@yahoo.co.id

Pio-Go Hsieh
Department of Assets and Property Management, Hwa Hsia Institute of Technology, Taiwan R.O.C.

ABSTRACT: Three-dimensional finite element analyses were performed to examine the performance of the rigid support system to reduce movements in the top-down excavation. The rigid support system is an integrate system between diaphragm walls and a series of concrete walls which are perpendicular to the diaphragm wall. This series of concrete walls consist of buttress walls and/or combined with cross walls. Parametric studies were conducted to investigate some possible configurations of the concrete walls. The results showed that the concrete walls with combination of buttress walls and cross walls yielded the greatest performance in reducing movements. For a 20 meter depth top-down excavation without adopting the rigid support system, the maximum wall deflection and the ground surface settlement were 148 mm and 91 mm, respectively. When the U-shape rigid support system was introduced, the maximum wall deflection and ground surface settlement could be reduced to 29 mm and 19 mm, respectively. The movement reduction ratio was around 80%.

RÉSUMÉ : Pour examiner et évaluer les performances du system support rigide afin réduire les mouvements dans la l'exécution de l'excavation profonde par la méthode descendante , des séries d'analyses numériques en trois-dimensions élément finis ont été effectuées. Le system support rigide est un system intégré entre la paroi moulée et une série the de parois en béton qui sont perpendiculaires à la paroi moulée. Cette serie de parois en béton est constituée de des murs contreforts et/ou combinée avec des murs transversaux. Des études paramétriques ont été menées pour analyser certaines configurations possibles des murs en béton. Les résultats ont montrés qu'une combinaison des murs de béton et des murs contreforts et transversaux a affichée une excellente réduction des mouvements dans l'exécution des excavations profondes. Pour une excavation profonde avec la méthode descendante de 20 mètres de profondeur sans adopter le système support rigide, la flexion maximale de la paroi et l'affaissement superficiel du sol étaient respectivement de 148 mm et 91 mm et lorsque le système support rigide en forme de U a été adoptée, la flexion maximal de la paroi et le l'affaissement superficiel du sol pourraient être réduits respectivement à 29 mm et 19 mm. Le taux de réduction du mouvement était d'environ 80%.

KEYWORDS: Rigid support system, Buttress wall, Wall deflection, Ground settlement, Deep excavation.

1 INTRODUCTION.

Deep excavation is usually performed to construct a basement. In some cases, a deep excavation is located close to existing underground metro tunnels or adjacent buildings (Hou et al. 2009, Hsieh et al. 2015a, Chen et al. 2016). Hence, the design and construction of a deep excavation should be carefully executed because it may induce excessive wall deflections and ground surface settlements, especially if the ground condition is relatively soft (e.g. the Taipei Silty Clay, the Shanghai soft clay, or the Singapore Marine Clay). Obviously, those movements should be strictly controlled to avoid damages of adjacent buildings or the adjacent underground metro tunnels.

In addition to ground improvement techniques, some auxiliary measures that widely used to protect adjacent infrastructures are cross walls and buttress walls (Hsieh et al. 2015a, Hsieh et al. 2015b). The application of cross walls in a deep excavation can effectively reduce wall deflections to a very small amount as demonstrated by Ou et al. 2011, Hsieh et al. 2013, and Ou et al. 2013. The buttress wall is a concrete wall perpendicular to the diaphragm wall with the limited length. If the buttress wall is connected to the opposite diaphragm wall, then it is called the cross wall. According to Ou et al. 2006, the cross wall functions as a strut-like component, which, with high compressive strength, exists before excavation. In theory, movement of the retaining walls near the cross wall will be restrained during excavation, and the lateral displacement of retaining walls will decrease. Ground settlement outside the excavation will be reduced too, which therefore achieves the protection of adjacent buildings.

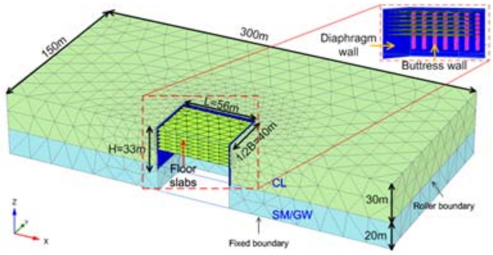


Figure 1. Three dimensional finite element mesh of a typical excavation for analysis.

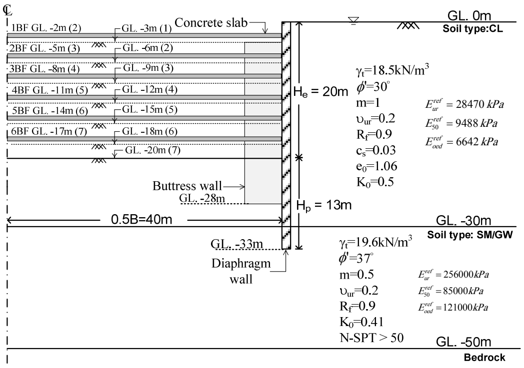
Based on the reported case histories above, buttress walls are located inside the excavation zone, starting from the ground level (GL) -3 m until the diaphragm wall toe. Moreover, buttress walls are mostly demolished together with excavation process and it is defined as the conventional buttress wall system. Lin and Woo (2007) reported the excavation of the Taipei 101 building in which some of buttress walls were located outside the excavation zone and they were maintained until the end of construction. Indeed, buttress walls that are located inside the excavation zone could also be maintained until the end of excavation. Thus, by making use of the top-down excavation method, buttress walls, cross walls, diaphragm walls and floor slabs could be connected together as the rigid support systems. However, no comprehensive study has been carried out to investigate the performance of such a rigid support systems.

In this article, a series of three-dimensional finite element analyses were conducted to investigate the performance and mechanism of the rigid support systems.

2 FINITE ELEMENT MODELLING

2 .1 *Excavation geometry and procedures*

Three-dimensional numerical analyses were conducted using the commercial software package, namely PLAXIS 3D (Brinkgreve et al., 2013). **Fig. 1** describes a typical excavation and three-dimensional finite element mesh used for analyses. The excavation geometry was assumed 56m in length (L), 80m in width (B), and 20m in height (H_e). By making use of symmetry, only half of excavation geometry (1/2B) was adopted for analyses. Ten-node tetrahedral elements were used to simulate soil volume, 6-node plate elements were used to model the diaphragm wall, the cross wall, the buttress wall and the concrete floor slab. Moreover, 12-node interface element were applied to model soil-plate element interaction behavior. Soil movements normal to the four vertical sides of the mesh were restrained while they were fixed in all directions at the bottom of geometry. In addition, the distance between the diaphragm wall and the outer boundary of mesh was ensured to be larger than $2H_e$ (final excavation depth) to minimize boundary effects.



Note: a number inside parenthesis indicates the excavation stage

Figure 2. Profile of subsurface soil and excavation sequences.

Fig. 2 depicts the profile of the excavation and subsurface soil conditions together with their physical properties and soil parameters. The subsurface soil conditions consist of a 30 m thick of the clay (CL) layer and followed by a 20 m thick of the silty-sand well graded gravel (SM/GW) layer. The soil stratum was a simplification of typical subsurface conditions in the Taipei area. The 20m depth of excavation was planned to be constructed in seven excavation stages. For this study, the thickness of diaphragm walls and concrete walls was determined to be 0.6 m and the arrangement of concrete walls were uniformly distributed along the longitudinal side of the diaphragm wall which was 8 m. The groundwater level inside the excavation was lowered to the excavation surface, while the groundwater level outside the excavation maintained at its original level.

2 .2 *Soil constitutive model and materials parameters.*

The Harding Soil model (Schanz et al. 1999), referred to as the HS model, was adopted to simulate the behavior of soils, including clay (CL) and gravel (GW) under the undrained and drained conditions, respectively. Of the HS parameters; the secant stiffness (E_{50}^{ref}) corresponding to the reference stress, p^{ref} , the tangent referential stiffness for primary oedometer loading (E_{oed}^{ref}), the unloading/reloading referential stiffness (E_{ur}^{ref}), and the power for stress-level dependency of stiffness (m); were calculated according to Lim et al. (2016) and Calvello and Finno (2004) for clay, and to Khoiri and Ou (2013) for gravel. The coefficient of the at-rest earth pressure for the SM/GW layer was calculated from Jaky's equation (Jaky, 1944) which was $K_0 = 1 - \sin\phi'$ and the coefficient of the at-rest earth pressure for the CL layer was estimated based on Ladd's equation (Ladd et al. 1977) which was $K_{o,oc} = (1-\sin\phi')(\mathrm{OCR})^{\sin\phi'}$. Basically, the model parameters for soil are typical value for Taipei Silty Clay and Gravel. The structural members, such as the diaphragm walls, the buttress walls, the cross walls, and the concrete slabs, were assumed to behave as linear-elastic. The stiffness of all the structural elements were reduced by 20% from the nominal value, considering that the stiffness of the concrete retaining wall reduces when large bending moment of the diaphragm wall causes the occurrence of the crack in the concrete (Lim et al., 2010). The buttress walls were casted using the low strength concrete (f_c' =14MPa) and the diaphragm wall and the concrete floor slab were casted using the concrete with f_c' =27.5MPa.

3 FEM ANALYSIS PROGRAMS

The simulation program of the rigid support systems is listed in **Table 1**. Three series of simulations were conducted to understand the performance and mechanism of the rigid support systems. The series one covered the analyses of the rigid support system which consists of the buttress walls only. The treatments of buttress walls consisted of two scenarios which were the case of maintained buttress walls and the case of demolished buttress walls (the conventional buttress wall system). It should be noted that analyses of the conventional buttress wall system were performed for the comparative study only. Moreover, the interface between buttress walls and surrounding soil was modeled as friction and frictionless behaviors. When the frictionless interface was modeled, the performance of the buttress walls rigid support system was fully controlled by the combined stiffness between buttress walls, floor slabs, and diaphragm walls. The objective of those analyses were to investigate the deformation control mechanism of the buttress walls rigid support system.

Table 1. List of simulation programs

Series	H_{bw} (m)	L_{bw} (m)	H_{cw} (m)	Treatment	Interface model
1: Buttress walls	25	2,4,6,8,10	0	Demolished & Maintained	Friction & Frictionless
2: Cross walls	0	0	1,2,3,4,5	Maintained	Friction
3: U-shape	20	1,2,3,4,5			

The series two was performed to investigate the effect of cross walls only to the movements induced by deep excavations. Meanwhile, the series three investigated the U-shape rigid support system in which the U-shape was a combination of buttress walls and cross walls system, as illustrated in **Fig 3**.

Furthermore, the performance of each analyses is assessed quantitatively by introducing two parameters, namely, the maximum deflection ratio (MDR), and the maximum settlement ratio (MSR). The MDR and the MSR are the reduction ratio of the maximum lateral wall deflection and the ground surface settlement when buttress walls were introduced, respectively. The MDR and the MSR are based on the maximum value of excavation induced-movements. The MDR, and MSR are defined as:

$$MDR = \frac{(\delta_{h\max 0} - \delta_{h\max i})}{\delta_{h\max 0}} \times 100\% \qquad (1)$$

$$MSR = \frac{(\delta_{\mathrm{v}\max 0} - \delta_{\mathrm{v}\max i})}{\delta_{\mathrm{v}\max 0}} \times 100\% \qquad (2)$$

where:

$\delta_{hmax,0}$ and $\delta_{hmax,i}$ are the maximum lateral wall deflection at the cross section without and with the rigid support system, respectively. $\delta_{vmax,0}$ and $\delta_{vmax,i}$ are the maximum ground surface settlement at the cross section without and with the rigid support system, respectively.

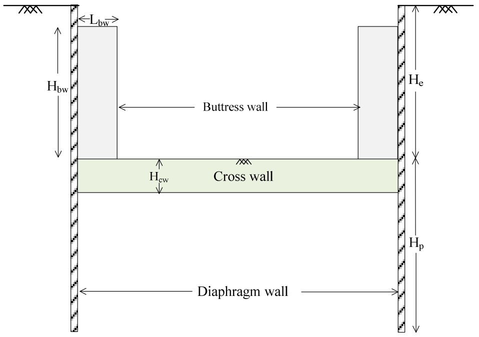
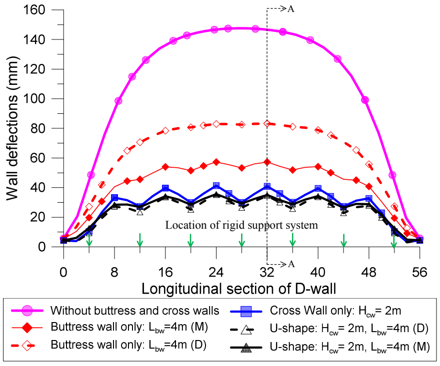


Figure 3. Profile of the U-shape rigid support system.

4 RESULTS AND DISCUSSION

The results of the 4 m length of buttress walls and the 2 m height of cross walls were selected to represent the other analyses results. It should be noted that the selections were able to represent general behaviors of the other analyses results. The typical plan view of diaphragm wall deflections at the final excavation level are shown in **Fig 4.** Obviously, the maintained buttress wall case yielded smaller wall deflections compared to the case of demolished buttress wall. However, for the case of the cross wall and the U-shape rigid support system, the wall deflections were close to each other and they became hard to be justified. Hence, the profile of wall deflections and ground surface settlements was plotted at cross-section A-A (**Fig 4**) and it was depicted in **Fig 5**. The cross section A-A was located between two buttress walls or cross walls.

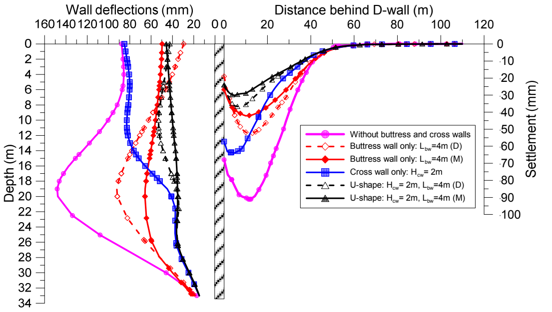


Note: M and D denote the buttress walls were maintained and demolished, respectively.

Figure 4. Plan view of typical diaphragm wall deflections.

As plotted in **Fig 5**, the case of the demolished buttress walls yielded a curvature line, whereas the case of the maintained buttress walls yielded almost a vertical straight line (a translational mode) from GL 0 m to GL -28 m in which the buttress wall was connected with the diaphragm wall. According to Fang and Ishibashi (1986), one of the characteristics of the rigid retaining wall is that the retaining wall deforms as a translational mode. Hence, the case of maintained buttress walls is defined as the rigid support system. Furthermore, the cross walls could well restrain the diaphragm wall deflection, especially at the location of the cross wall which was below the final excavation level. However, the diaphragm wall deflection above the final excavation level was still relatively large.

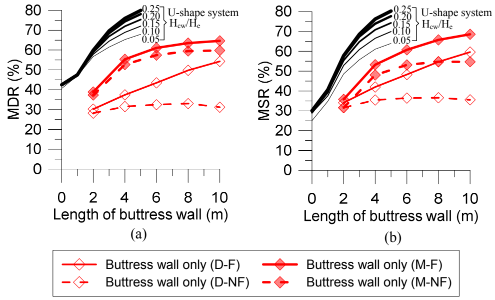
The combination of cross walls and buttress walls (the U-shape) could improve the overall performance of the support system. The U-shape support system have the advantages from the maintained buttress walls and the cross walls system, such as the wall deflection could well restrain above and below the final excavation level. The U-shape support system also yielded almost a vertical straight line of the wall deflection, thus it also could be categorized as the rigid support system. In addition, when the buttress walls of the U-shape support system were demolished along with excavation stages, the diaphragm wall deflection would slightly increase and become a curvature line. Furthermore, it was clearly seen that the trends of ground surface settlements were similar with the trends of wall deflections.



Note: M and D denote the buttress walls were maintained and demolished, respectively.

Figure 5. Comparison of wall deflections and ground settlements for various rigid support systems.

As mentioned earlier, all of analyses results were summarized and quantitatively assessed with the MDR and the MSR, as depicted in **Fig 6.a and 6.b**, respectively. For the buttress wall rigid support system, a 50% reduction of wall deflections and ground surface settlements was achieved by installing at least 4 m length of buttress walls. Meanwhile, it required 8 m length of buttress walls if the conventional buttress wall system, in which buttress walls were demolished along with excavation process, was adopted to achieve the same reduction as in the buttress wall rigid support system.



Note: M and D denote the buttress walls were maintained and demolished, respectively; F and NF indicate the friction buttress walls and non-friction buttress walls.

Figure 6. Reduction ratio of various rigid support systems: (a) maximum deflection ratio; (b) maximum settlement ratio

For the demolished buttress wall cases, the MDR of frictionless interface cases yielded a relatively constant value for different lengths of buttress walls, and those values were relative small if they were compared to the MDR of the friction interface cases. It indicates that the wall deflection control mechanism of the demolished buttress walls cases was mainly came from the frictional resistance between buttress walls and surrounding soil. This mechanism was also expressed by Hsieh et al. (2015b) and Lim et al. (2016).

For the maintained buttress walls cases, the MDR of frictionless interface cases yielded a quite large value, close to the MDR of friction interface cases. The difference was in the range of 5% to 10%, depends on the length of buttress walls. It implies that the contribution from the frictional resistance could only increase the performance of the integrated retaining system by 5% to 10%. In conclusion, the wall deflections control mechanism of the rigid support system was dominated by the combined stiffness between buttress walls and diaphragm walls.

As the result of the minor contribution from the frictional resistance between buttress walls and surrounding soils, for the design consideration, the limited length of buttress walls was suggested (i.e. L_{bw}< 4m). For the length of buttress walls was larger than 4 m, the MDR tends to reach a plateau. In other words, the MDR only increased 3% to 5% for each 2 m increment of the buttress wall length when the length of buttress walls was longer than 4 m.

The ground surface settlements control mechanism of the buttress wall rigid support system was governed by two factors including the combined stiffness of buttress walls and diaphragm walls, and the frictional resistance between buttress walls and surrounding soil. According to Lim et al. 2016, the frictional resistance of buttress walls at the excavation bottom could resist the soil heave at the excavation bottom. When the soil heave decreased, the ground surface settlement also decreased accordingly. Hence, the longer length of buttress walls provided the larger frictional resistance and yielded the greater MSR. The frictional resistance of could contribute 10% to 15% to the MSR.

For the U-shape rigid support system, the MDR and the MSR could be reduced to around 80% **(Fig 6.a & Fig 6.b)**, where the maximum wall deflection and ground surface settlement were 29 mm and 19 mm, respectively. It was reached when the height of cross walls and the length of buttress walls were 5 m. For achieving 50% movements reduction, the U-shape rigid support system only need at least 2 m length of buttress walls and at least 2 m height of cross walls. Overall, the performance of the U-shape rigid support system was better than the buttress wall rigid support system. The reason might be due to the effect of the cross walls that could limit the wall deflections at the location of the cross wall which was below the final excavation level. For design considerations, the 2 m height of cross walls seems suitable to be adopted because not only the higher cross wall could increase the construction cost but also the length of buttress wall could be adjusted to reach targeted wall deflections and ground surface settlements.

5 CONCLUSIONS

This study performed a series of 3D finite element analyses to investigate the performance and mechanism of the rigid retaining systems in order to limit deformations induced by deep excavation. The following conclusions can be drawn:

1. Two types of the rigid support systems were introduced such as the buttress walls rigid support system and the U-shape rigid support system. Indeed, the U-shape support system is the integration system between cross walls and buttress walls. The rigid support system was formed by maintaining buttress walls during the excavation stages.
2. By adopting the buttress wall rigid support system, the 50% reduction of wall deflections and ground surface settlements was achieved with the buttress wall length was at least 4 m. Meanwhile, it required at least 8 m length of buttress walls if the conventional buttress wall system, in which buttress walls were demolished along with the excavation sequences, was adopted as the auxiliary measure.
3. The wall deflections control mechanism of the buttress wall rigid support system mainly came from the combined stiffness between the diaphragm wall and the buttress wall. Meanwhile the ground surface settlement control mechanism of the buttress wall rigid support system was governed by two factors including the combined stiffness between the buttress wall and the diaphragm wall and the frictional resistance between the buttress wall and the surrounding soil.
4. In general, the performance of the U-shape rigid support system was better than the buttress wall rigid support system. The reason might be due to the effect of the cross walls that could limit the wall deflections at the location of the cross wall which was below the final excavation level. The MDR and the MSR could be reduced to around 80% when the height of cross walls and the length of buttress walls were 5 m. For achieving 50% movements reduction, the U-shape rigid support system only need at least 2 m length of buttress walls and at least 2 m height of cross walls.

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