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Influences of use of pile-type cross-walls on deep excavations

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ABSTRACT: Deep excavations in soft ground may induce unfavourable ground and structural movements but cross-walls formed by jet-grouted piles can be used to reduce these movements. However, it is not easy to evaluate the efficiency or the optimal arrangement of such cross-walls in limiting the ground and structural movements induced by the excavation. Based on parametric studies, it is suggested that installation of 6 m centre-to-centre distance cross-walls formed by 1 m diameter soil-cement piles can reduce excavation-induced displacements by up to 40%–50%. Also, increasing the pile diameters to a size greater than 1.4 m or increasing the depth of emplacement by more than 5 m may not contribute significantly to limiting the movements of diaphragm walls.

1 INTRODUCTION

In order to meet the need for developing urban areas of Taipei, deep excavation has often been utilised for the construction of underground space. Since the ground in Taipei is soft, deep excavation may also induce unfavourable structural and ground movements and thus cause damage to underground structures and adjacent structures. In this paper, the movements caused by an excavation in western Taipei are predicted. It has been seen that some buildings are located immediately next to the site. The additional movements contributed by the excavation may not be appropriate for these buildings so a pile-type cross-wall inside the excavation is proposed to reduce the induced deformations. The presented paper also contains a parametric study which was carried out to evaluate the effects of using a pile-type cross-wall on an excavation in soft ground.

2 THE SITE

The site is located in western Taipei and a cross section of the excavation is presented in Figure 1. The 1.1 m thick, 40 m deep diaphragm walls are installed to retain this 19.2 m deep excavation. The length and width of this excavation are approximately 330 m and 20 m, respectively. It is noticed that several four to seven-floor buildings are located at 1 to 20 m distance from the site.

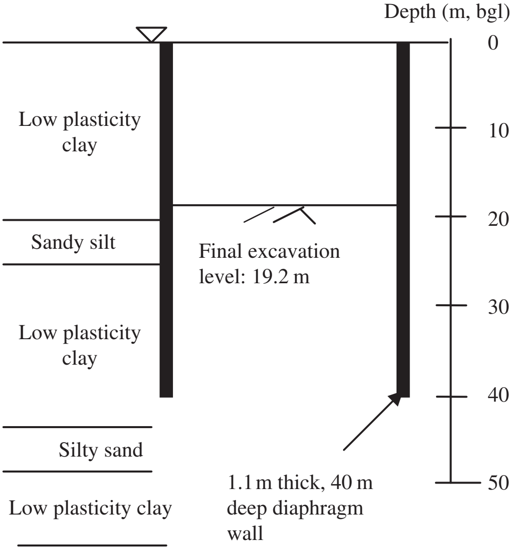

Figure 1. A cross section of the excavation.

The soil stratum mainly consists of very thick low plasticity, slightly over-consolidated clay with two very thin layers of silt and sand above gravel at a depth of 67.5 m, as indicated in Figure 1. The undrained shear strength at the base of the final excavation was generally 50 to 70 kPa, and the angle of shear resistance measured in consolidated undrained traxial tests was 30° to 34°. Finally, the groundwater table is approximately 2 to 4 m below ground level.

3 PRELIMINARY PREDICTION OF MOVEMENTS

Hsiung et al. (2003) delivered a "Wished in Place (WIP)" analysis to predict the lateral wall movement and ground surface settlement induced by the excavation and influences caused by wall installation were ignored. Figures 2 and 3 present predicted movements at a excavation depths of 2.8 m, 10.0 m and 19.2 m. It is shown that maximum lateral wall movement (δ_{hmax}) is expected to be 8 mm at an excavation level of 2.8 m bgl and 55 mm at the end. Further, only 2 mm of maximum surface settlement (δ_{vmax}) was predicted in shallow excavation, increasing to 25 mm at the final excavation stage. It is noticed that the influences of both wall installation and soil improvement are excluded from this study.

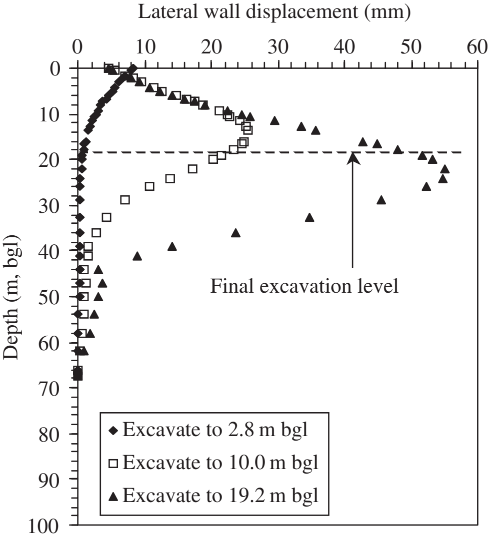

Figure 2. Predicted lateral wall deformation.

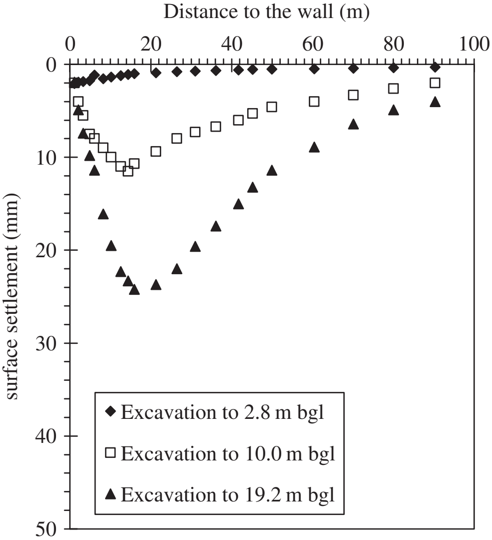

Figure 3. Predicted surface settlement.

4 PARAMETRIC STUDY OF PILE-TYPE CROSS WALL

As described above, some buildings are found at only a meter's distance from the excavation, so excessive movements on them may not be acceptable. Therefore, the method of using a pile-type cross-wall is considered. By this method, soil-cement piles are formed in the ground at the specific spacing and depth and it is anticipated that an additional internal strut be constructed as well, to increase the strength of soil inside the excavation (Woo, 1996). Figures 4 and 5 indicate the layout and depth of the pile-type cross-wall installed on site and the diameter of the soil-cement pile is 1 m. As shown in Figure 4, a double-line cross-wall is used on site. A finite difference analysis using FLAC was conducted to predict the vertical and horizontal movements caused by the excavation. This is

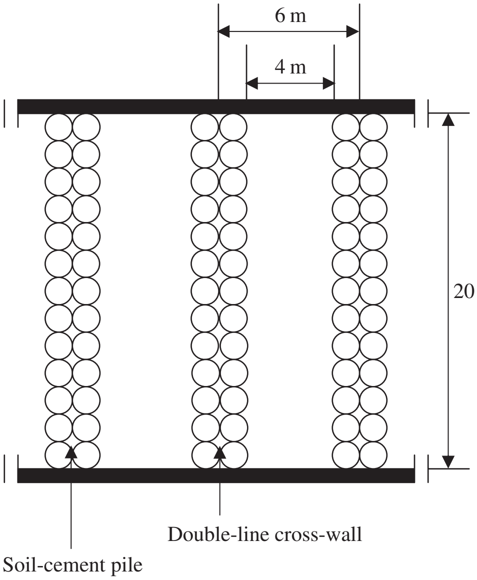

Figure 4. The layout of pile-type cross-wall.

also a "Wished in Place" analysis. To simulate the behaviour of the improved ground inside the excavation, three possible approaches, namely, the equivalent stiffness method, the horizontal-beam method and the vertical-beam method have been considered.

In this regard, for the equivalent stiffness method, the equivalent stiffness of the improved soil inside the excavation (E_{eq}) can be defined by:

$$E_{eq} = E_{cement} \times I_r + E_{soil} \times I_r \tag{1}$$

where E_{cement} and E_{soil} are the elastic modulus of cement and soil, respectively. I_r is the "soil improvement ratio", as will be explained in Equation 3.

The vertical-beam method uses several vertical beam elements to simulate the improved soil inside the excavation, as shown in Figure 6. In contrast, horizontal beam elements are utilised for the horizontal- beam method, as presented in Figure 7. Though both the equivalent method and vertical-beam method could give better predicted results, Lin (2003) suggested that the vertical-beam method should be selected since the mechanism of the vertical-beam method is adaptable to the conditions on site and thus this method was chosen in the present study.

The cross-wall was formed by high-pressure jetted soil-cement piles. In order to simulate the pressure on the wall, Hsieh et al. (2003) suggested that additional horizontal pressure should be added before the start of excavation. Based on field observations from two excavations in Taipei similar to the site used in this study, Lin et al. (2000) and Liao and Liu (1996) recommended that this additional pressure (σ_{hp}) should be put on the wall horizontally at 0 to 4 m above the final excavation level (see Figure 8) and σ_{hp} is defined by

$$\sigma_{hp} = 1.6 \times \sigma_{hini} \tag{2}$$

in which σ_{hini} is the initial horizontal pressure before the start of the excavation. The same simulation of preload of high-pressure jetting is included in this study.

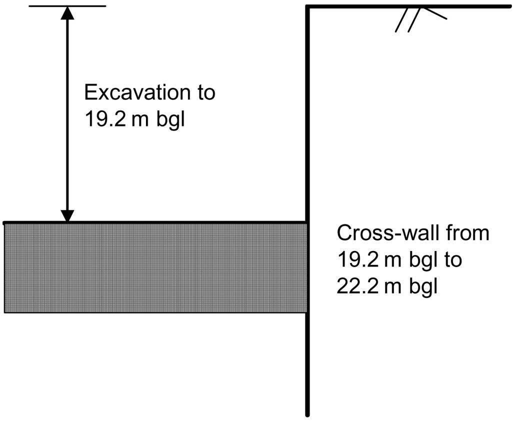

Figure 5. The depth of pile-type cross-wall.

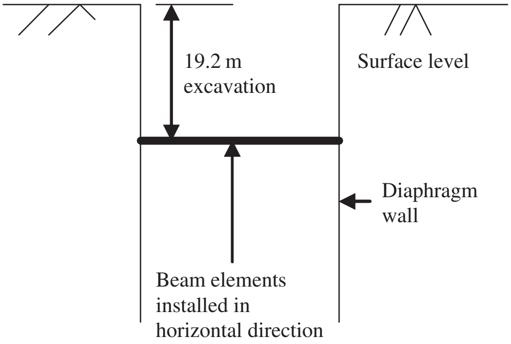

Figure 7. The horizontal method.

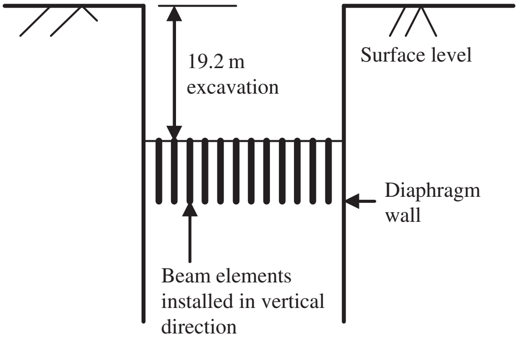

Figure 6. The vertical method.

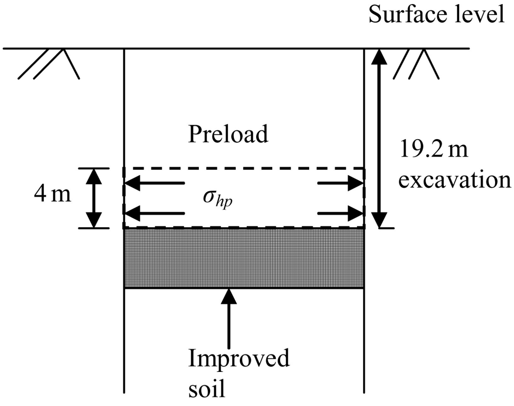

Figure 8. Preload simulation.

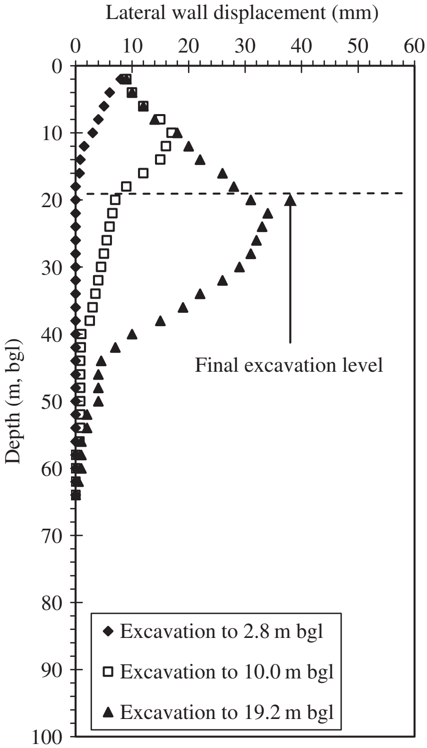

Figure 9. Predicted lateral wall deformation (with cross-wall).

For the boundaries utilised in the model, the grid points at the right vertical boundary were free to move in the y-direction but were fixed in the x-direction. The horizontal boundary was set at the same depth at the gravel layer (67.5 m bgl) and all grid points here are unable to move in both the x- and y-directions. The left vertical boundary is the axis of symmetry at the centreline of the excavation. All grid points at this boundary could move in the y-direction but not in the x-direction. Based on the suggestion of Hsiung (2002), the analyses used a mesh with a boundary of about 12 times the depth of the excavation.

Figure 9 and Figure 10 present the predicted lateral wall displacement and ground surface settlement at an excavation depth of 2.8 m, 10.0 m and 19.7 m. It is seen that the maximum lateral displacement reaches 8 mm at the stage of 2.8 m of excavation depth and increases to 34 mm at the end. The predicted lateral wall deformation shows the cantilever-mode at the shallow excavation stage, which becomes a prop-mode at the final excavation stage. In addition, the 2 mm of surface settlement was estimated at 2.8 m of the excavation depth; this increases to 16 mm at the final excavation level.

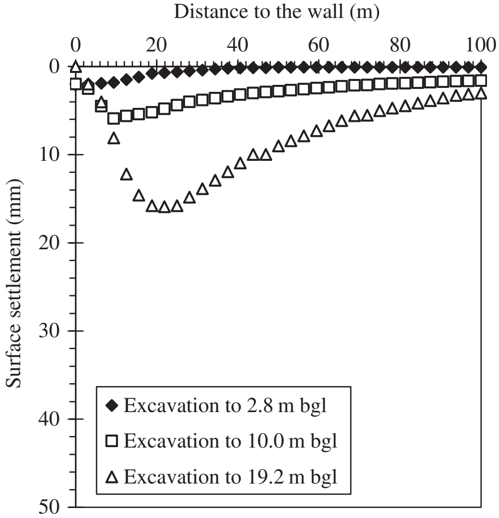

Figure 10. Predicted surface settlement (with cross-wall).

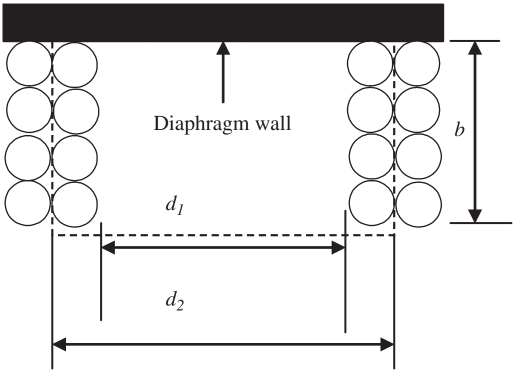

Figure 11. Definition of I_r.

A ratio called the "soil improvement ratio (I^r)" can be used to represent how much earth inside the excavation is replaced by cement. In general, I^r can be defined by

$$I_r = \frac{\frac{\pi}{4} \times (d_2 - d_1)^2 \times 8}{d_2 \times b} \tag{3}$$

where d_1, d_2 and b are defined by Figure 11 and the diameter of the soil-cement pile (d) is

$$d = 2 \times (d_2 - d_1) \tag{4}$$

For the simulation stated above, I_r is equal to 26%.

Figure 12 presents the relationship between I_r and the ratio of predicted maximum lateral wall displacement (δ_{hmax}) to maximum excavation depth (D) based

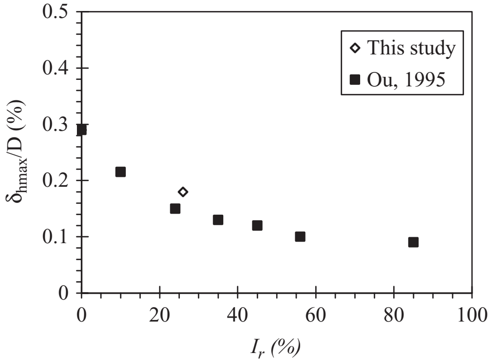

Figure 12. The relationship between I_r and the ratio of the predicted maximum lateral wall displacement (δ_{hmax}) to the maximum excavation depth (D).

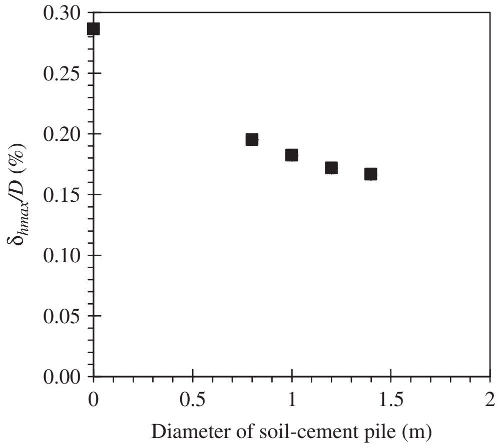

Figure 13. The influence of variation of the diameter of the soil-cement pile on δ_{hmax}.

on the outcome of this study. The pile-type cross-wall using 26% of I_r may reduce δ_{hmax} up to 40%, as shown in Figure 12. Ou (1995) also delivered a study to explore the relationship between I_r and δ_{hmax} to D but it seems that a slightly lower ratio of δ_{hmax}/D may be the case if the same I_r is applied, as shown in Figure 12.

Further, changing the diameter of the soil-cement pile (D_s) tends to affect the relationship between D_s and δ_{hmax}/D in this study. Figure 13 indicates that the δ_{hmax}/D can be reduced from 32 to 42% by varying D_s of 0.8 to 1.4 m. In addition, increasing D_s to 1.4 m may not dramatically reduce the wall deformation. In the end, an exercise was carried out in order to evaluate the influence of the installed depth of soil-cement pile on δ_{hmax}. It is assumed that all cross-wall grouting started from the final excavation level but was of five different lengths (0.8, 1.0, 3.0, 5.0 and 7.0 m). Figure 14 shows the predicted results and it is seen that the use of longer soil-cement piles may reduce δ_{hmax} effectively but having the pile length greater than 5 m may not have significantly contributed to restraining δ_{hmax}.

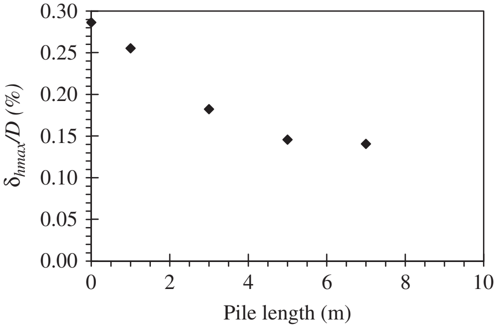

Figure 14. The influence of the variation of the pile length on the δ_{hmax}/D.

5 DISCUSSION

Considering the predicted results in this study, the use of 1 m of diameter, 6 m of centre-to-centre distance pile-type cross-wall (refer to Figure 12) may reduce δ_{hmax} up to 40%. The same prediction also forecasts that 50% of δ_{vmax} may be reduced. The efficiency of the use of pile-type cross-wall is confirmed herein.

Based on the observations in Taipei, Hsieh and Ou (1998) suggested that a ratio of δ_{vmax} to D for an excavation without any soil improvement should reach 0.26% but only 0.13% is predicted here. As anisotropy of soil has not been covered and the strain-stiffness relationship of clays in Taipei has not been confirmed in the analysis, these might be the reasons for the under-estimation of δ_{vmax}.

Comparing the predicted δ_{hmax} shown in Figure 2 with that in Figure 9, it is the same at the stage where the excavation level is 2.8 m but has a 40% difference at the stage where the excavation level is 19.2 m. Similar observations of δ_{vmax} have been found from comparing Figure 3 with Figure 10. It is anticipated that the difference was produced by the installed depth of the soil-cement pile since these piles were only installed at depths of 19.2 to 22.2 m below ground level and thus they affect δ_{hmax} and δ_{vmax} more at the later stages of excavation rather than the earlier stages.

Wu et al. (1997) concluded that the depth of between 0.8 and 1.2 of the maximum excavation depth may exhibit maximum lateral wall displacement but the cross-wall inside the excavation may raise it (Hsiung, 2002). The maximum lateral wall displacement was found at the depth of 22 m below ground level, which is satisfied at the depth suggested by Wu et al. suggested. The reason is that the ground beneath the final excavation level is not fully replaced and thus it is not stiff enough to raise the level at which there is the maximum wall deformation.

Having more than 5 m of length of soil-cement piles may not significantly reduce the δ_{hmax} but this does reduce the occurrence of lateral wall deformation below the final excavation level.

It seems that increasing D_s to 1.4 m may not be able to reduce the wall deformation dramatically. From the practical aspect, it is noticed that a pile-type cross-wall scheme with smaller soil-cement piles may have more overlap and the quality of the overlap is important to its performance. Conversely, larger soil-cement piles can reduce the amount of overlap but adequate pieces of equipment and operation parameters have to be used to maintain the quality of these soil-cement piles. The numerical analysis may help to provide an optimised design of layout, depth and size of soil-cement piles of the cross-wall, but the influence of the overlap, the equipment and the operation parameters on the ground behaviour are not included. Thus, it is still suggested that the design of a pile-type cross-wall should be finalised in association with the results of both numerical analysis and field trial tests.

6 CONCLUSIONS

Some conclusions may be drawn from this study, as follows:

The prediction shows that 55 mm of the lateral wall deformation and 25 mm of the ground surface settlement may be reached at the end of the excavation but that the use of a pile-type cross-wall may reduce 40%–50% of these deformations.

It may not dramatically reduce the wall deformation to increase D_s to 1.4 m in accordance with predicted results. In addition, the use of longer soil-cement piles may reduce δ_{hmax} effectively but a pile length greater than 5 m may not significantly contribute to limiting δ_{hmax}.

As the soil beneath the final excavation level has not been fully replaced, it has been found that both the shape of the wall deformation and the depth exhibiting maximum lateral deformation have not been changed by the installation of these soil-cement piles.

Considering the depth at which the soil-cement piles were installed, the pile-type cross-wall has a greater influence on the deformations generated at the earlier stages of the excavation rather than the later ones.

Since the influences from overlap, equipments and operation parameters on the ground behaviour could not be included in the numerical simulation, it is still suggested that the design of pile-type cross-wall should be finalised in association with the results of both numerical analysis and field trial tests.

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