A case study of ground response due to diaphragm wall installation

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ABSTRACT

The purpose of this research is to investigate the ground response due to diaphragm wall construction using three-dimensional numerical modelling. In this study, the commercial finite difference method software, FLAC^{3D}, and the finite element upper and lower bound limit analysis methods are employed. In addition, a range of factors are investigated. They include the dimensions of the single panel, over-consolidation ration (*OCR*), soil stiffness (E/s_u), and the height of the bentonite slurry. The solutions from the numerical upper bound limit analysis method are used for comparison purposes. The results obtained indicate that the above factors do have influence on ground response in terms of its stability and displacements. The discussion in the paper can be utilised as the reference for practical designs.

Keywords: excavation, displacement, three-dimensional

1 INTRODUCTION

As the population of our major cities continues to grow, the available space for human inhabitancy is reduced. This is called urbanization. As a consequence, high rise buildings become more popular, as they are more efficient at using the available space. Such buildings generally need larger underground space for car parking, and therefore deep excavation, foundations and retaining system are used more frequently.

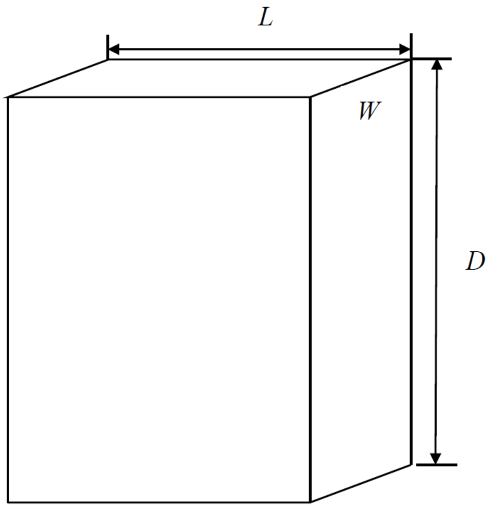
In recent years, the diaphragm wall method of construction has become popular for excavations in Taipei. The advantages include low vibration and noise, and high stiffness. Furthermore, diaphragm walls can provide better control of displacement and water drainage during the excavation, compared to other methods (Ou 2006). In general, single diaphragm wall panel construction can probably be divided into three stages, which are (1) Simultaneous trench excavation and bentonite pressure, (2) Place steel cages, (3) Cast the concrete panel. The first stage is often the most critical during the diaphragm wall construction as the unbalanced forces between the trench and soil mass are at their greatest.

In engineering practice, often the vertical and horizontal displacements caused by the diaphragm wall construction are not considered. It is because they are generally relatively small, compared with the main excavation. However, surface settlements induced by diaphragm wall construction have been reported to be as much as 30%~50% of final cumulative settlements (Cowland and Thorley 1985, Morton et al. 1980). The measured results from Taipei Rapid Transit system indicated that the surface settlement induced by diaphragm wall installation is significant. Its magnitude also agreed with previous observations. Consequenctly, the potential to damage adjacent buildings during underground construction is increased.

Based on the discussions above, the importance of understanding ground response caused by diaphragm wall installation can be seen. In order to understand the ground responses in the Taipei basin, the commercial finite difference method software, FLAC^{3D} (Itasca 2002), is employed in this study. A range of parameters and factors which will influence soil movement evaluation in simulations are investigated. The study aims to provide a better understanding of ground displacements and influence zones due to diaphragm wall constructions.

2 PREVIOUS STUDIES

The construction of a single diaphragm wall panel with the dimensions 1m×5m×28m (*W*×*L*×*D*), was investigated by Dibiagio and Myrvoll (1972) in Oslo. The variables *W*, *L* and *D* are used to define the dimensions of a single trench or panel in this paper, as shown in Figure 1. Before concreting, the trench stood for 31 days by applying bentonite pressures to the trench faces alone. The maximum surface settlement increased from 4mm to 8mm in this period. It was found that the maximum lateral displacement surrounding the trench was recorded as being 7 times the maximum vertical displacement which is significant. Therefore, they concluded that the phenomenon would be due to the suction forces between the excavating machine and soil. The increment of vertical displacements prior to casting concrete in the trench was also observed by Farmer and Attewell (1973). They reported that the ratio of maximum horizontal displacement to maximum vertical displacement is 40%.



L: The trench length, *W*: The trench width, and *D*: The trench depth

Figure 1. The dimensions of a single trench (or panel)

A detailed observation and measurement of a diaphragm wall construction was done by Poh and Wong (1998). One of the most important findings in their studies was that the height of bentonite slurry has a significant influence on the soil deformation. It was observed that the maximum vertical and horizontal displacements can increase by up to 50% when the bentonite slurry level is reduced by 1m. The ground movements induced by the trench installation in Taipei basin have been observed by Yang (2000) and Huang (2003). It was indicated that the diaphragm wall construction will lead to settlements for adjacent buildings. The influences on the spread footing foundations are more significant than those on the mat foundations.

Due to the great progress in computer power for the past two decades, three dimensional (3D) analyses are now possible and have become more commonplace. Based on the 3D numerical modelling, it was found by Ng and Yan (1998, 1999) that the maximum surface settlement occurred when the trench is excavated and only bentonite pressures applied on its surfaces. It demonstrated that the soil behaviour is critical at this stage. In addition, at a distance of one trench depth (1*D*) away, no significant vertical displacement is computed.

Gourvenec and Powrie (1999) indicated that the maximum soil lateral displacement will occur on the top of the trench (i.e. ground surface). This horizontal movement decreases with increasing depth. Currently, the study of Arai et al. (2008) is the only study that has investigated the whole process of installing a circular diaphragm wall, including 24 panels. It showed that the soil movements and lateral stresses are not axis-symmetric which changes with the panel construction sequence.

3 METHODOLOGY

As mentioned previously, the commercial software, FLAC^{3D}, is adopted to simulate the diaphragm wall construction. The Mohr-Coulomb failure criterion with elastic-perfectly plastic model is used. The configuration used in the numerical analysis is shown in Figure 2 where the panel dimensions are 1m×4m×40m (*W*×*L*×*D*). The dimensions will be used for all analyses, unless stated otherwise. In addition, the discussion in this paper focuses on the vertical surface movement. The mesh boundary has been investigated to make sure its effect on the computed settlement is extremely small (less than 1mm). The same simulation procedures as Ng and Yan (1999) are used which can be divided into three main stages, as following.

1. Excavate the trench and apply hydrostatic bentonite pressure on the trench faces simultaneously.
2. Cast the concrete panel by increasing the lateral pressure inside the panel from the bottom using a theoretical bilinear wet concrete pressure envelope proposed by Lings et al. (1994).
3. Cure the concrete panel by replacing the trench with elastic concrete elements and removing the applied bilinear concrete pressures on the trench faces simultaneously.

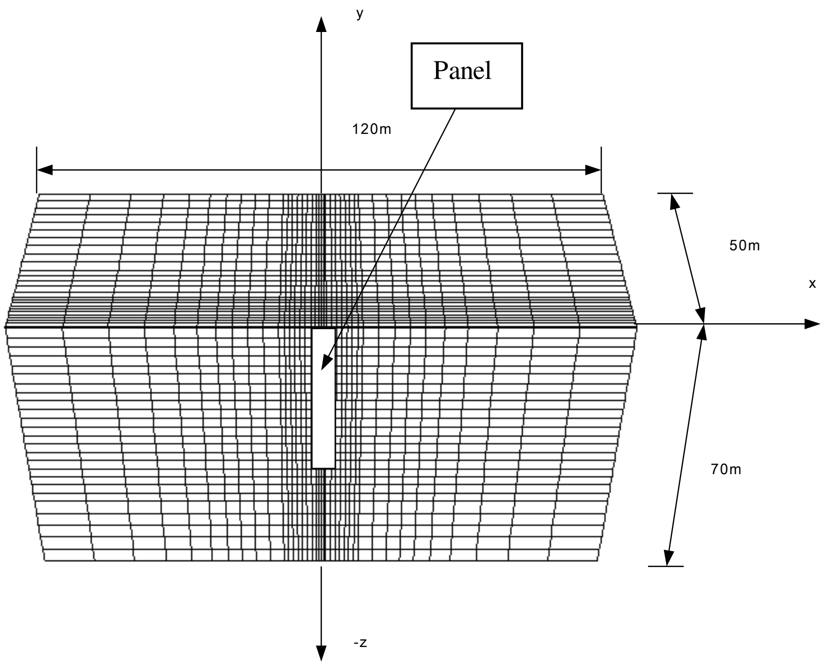


Figure 2. The mesh configuration

In addition, the finite element upper bound limit analysis method (Lyamin and Sloan 2002, Krabbenhoft et al. 2005) is employed to investigate the potential failure zone due to diaphragm wall installation.

The clay in Taipei close to the ground surface typically would be slightly overconsolidated (Hsiung 2002). Therefore, it is difficult to use just one curve of over-consolidation ratio (OCR) versus depth to represent the weak clays in Taipei basin. Figure 3 shows the surface settlements at the centre of trench on y-axis after single diaphragm wall installation. E/s_u = 650 and s_u/σ_v' = 0.33 (Ou 2006) are adopted. As shown in Figure 4, the OCR profiles in cases are approximations to the measured OCR in the field, except case 3. Case 3 is the only case which is purely normally consolidated clay. Referring to Figure 3, there is not much difference in settlement prediction if surface OCR is taken into account. However, the influence on the settlement prediction is by up to 80% when only normally consolidated clay is considered. As a consequence, it is essential to account for surface OCR in the following simulations.

To obtain reasonable prediction of ground movement, soil stiffness is an important issue to be considered. The computed vertical displacements for different E/s_u are displayed in Figure 5 where s_u/σ_v' = 0.33 is employed. As expected, the larger E/s_u will lead to smaller displacement prediction. It was found that using s_u/σ_v' = 0.33 and E/s_u = 500 agrees well with field measured data by Huang (2003). Therefore, they are utilised in the further analyses.

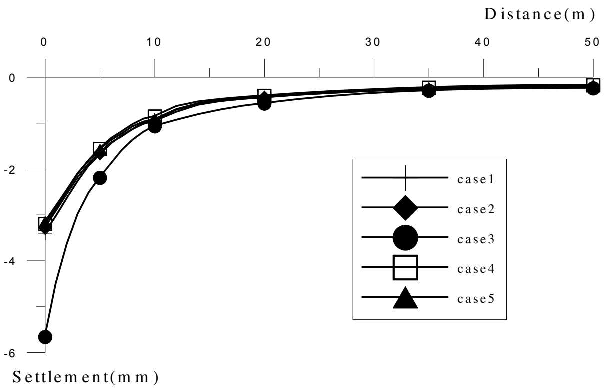


Figure 3. Surface settlement at the centre of panel on y-axis

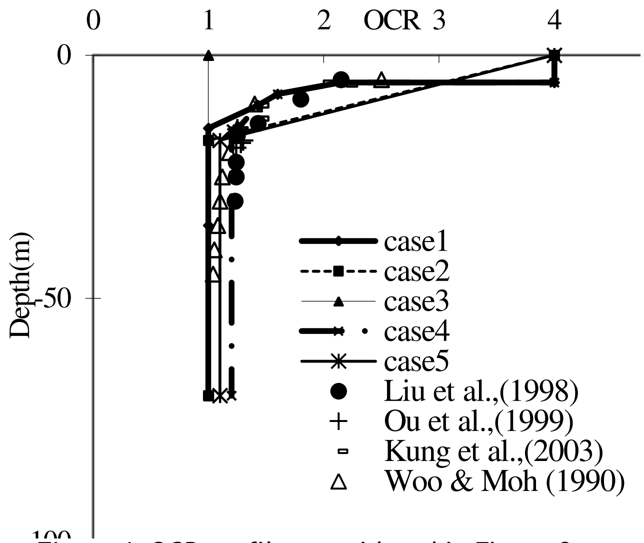


Figure 4. OCR profiles considered in Figure 3

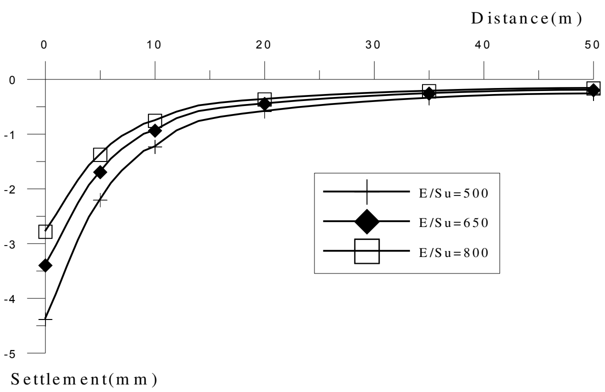


Figure 5. Surface settlement at the centre of panel on y-axis for various E/s_u

4 RESULTS AND DISCUSSIONS

Figure 6 presents the obtained results for different diaphragm wall panel lengths. The range of panel length is determined based on the reported dimensions in the studies of Yang (2000) and Huang (2003). It can be observed that the surface movement increases with increasing panel length. In addition, the magnitude was found to be insignificant when $L \leq 3$m. For $L \geq 4$m, the trends of the settlements are similar.

Recent investigations of Shyu (1995), Poh and Wong (1998), and Chang (1999) indicated that the bentonite slurry pressure will significantly influence the diaphragm wall trench stability and soil movements. The effects of bentonite slurry height are therefore investigated herein. The predicted soil vertical displacements are shown in Figure 7 where the betonite slurry is assumed to be below the ground surface of 0m, 1m, 2m and 2.5. As expected, the soil movement is larger when the slurry height is lower. Moreover, it should be noted that the maximum vertical displacement of betonite slurry height 2.5m below the ground surface is 2 times to that of betonite slurry height at ground surface which is significant. A comparison between bentonite at 0 m and -1m shows that the difference in surface settlement is 50%. This finding agrees well with the previous study of Poh and Wong (1998).

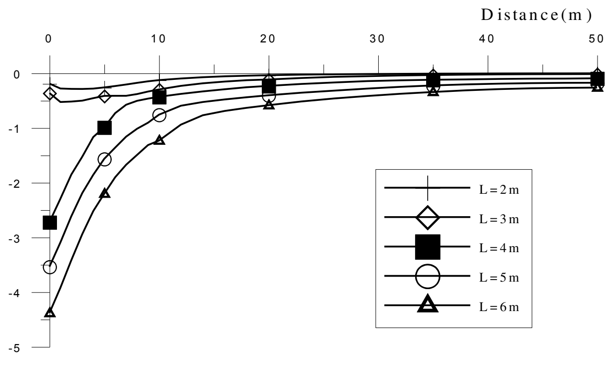


Figure 6. Surface settlement at the centre of trench on y-axis for different panel lengths

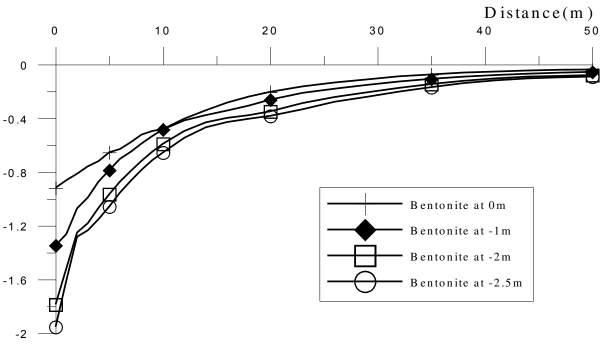


Figure 7. Surface settlement at the centre of trench on y-axis for different bentonite slurry height

An observation of Figure 3 to Figure 6 revealed that the ground surface settlement shape for diaphragm wall installation is spandrel. The settlement at a distance of 20m away from the panel changed more obviously. The settlement at a distance over 30m away from the panel is more gentle which can be seen as a straight line. The distance between 20m and 30m is the transition. If the distance is normalised by the trench depth (*D*), a normal distance of 0.5 times the trench depth (0.5*D*) can be seen as the primary influence zone due to single diaphragm wall construction. 0.5*D* ~ 0.75*D* is the transition zone and the settlement at a distance over 0.75*D* is less significant. The observed primary influence zone is larger than the investigations of Ng and Yan (1998). It would be due to the diaphragm dimension is larger and the clay is weaker.

In addition, the finite element upper bound limit analysis (Lyamin and Sloan 2002, Krabbenhoft et al. 2005) is used to investigate the potential failure zone for single trench. The plastic zone obtained from the numerical upper bound method is displayed in Figure 8 where *L/D* = 0.1. It was found that the bentonite slurry pressure does not play an important role to the potential failure surface. In Figure 7, it can be seen that the influence distance vertical to the trench is around 0.7*D* which is reasonably agreed with the observed transition zone (0.5*D* ~ 0.75*D*) in previous discussions. This finding would explain the relation between the primary settlement zone and the trench failure mechanism.

5 CONCLUSION

Based on the discussions above, the length of the single diaphragm wall panel, over-consolidation ration (*OCR*), soil stiffness (E/s_u), and the height of the bentonite slurry were found to have significant effects on settlement prediction for diaphragm wall installation simulations. An observation of numerical results indicated that the primary influence zone due to single diaphragm wall installation is between 0.5*D* and 0.75*D*. The magnitude agreed with the potential trench failure zone reasonably.

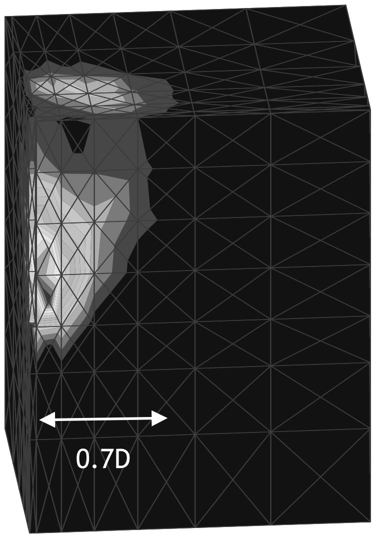


Figure 8. Numerical upper bound plastic zone

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