*Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)*


# Observed behaviours of deep excavations in sand

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ABSTRACT: In this paper, structural and ground behaviours of several excavations in Kaohsiung, Taiwan were described and examined. Based on behaviours observed from these excavations, it was found that the maximum lateral wall displacement ($\delta_{hmax}$) in relation to the maximum excavation depth ($H_e$) is approximately 0.034 to 0.3%. The ratio of maximum surface settlement ($\delta_{vmax}$) to $\delta_{hmax}$ varies from 0.5 to 0.7 for the excavation constructed by bottom-up method and from 1.3 to 1.8 for the excavation using a semi-top-down method. The zone at ground level affected by the excavation is up to 3 times the maximum excavation depth behind the diaphragm wall which retains the earth during construction. This finding is different from previous conclusions reported by Clough & O'Rourke. It is apparent that chemical churning pile does not effectively reduce influences of the excavation on adjacent buildings.

## 1 INTRODUCTION

Ground deformations induced by deep excavations in clays have been explored widely (Wong et al., 1997, Hsieh & Ou, 1998, Hsiung, 2002, Liu et al., 2005) but studies regarding observed behaviours of deep excavations in sand are comparatively limited (Burchell, 2000 and El-Nahhas, 2006). In this paper, case histories from excavations in Kaohsiung City, Taiwan provide an opportunity to explore structural and ground behaviours induced by excavations in sand. Empirical approaches for evaluating lateral wall movements and surface settlements were studied and discussed. Further, the effectiveness of chemical churning pile for house protection and prediction of prop load were also discussed in this study.

## 2 THE SITES

Several deep excavations for the Orange Line of the Kaohsiung Rapid Transit Systems (KRTS) have recently been carried out in an area where the ground conditions are relatively uniform. Among them, excavations of three underground stations, O6, O7 and O8 were selected for this study. The sites are located at the centre of Kaohsiung City, Taiwan and the maximum excavation depth varies from 19.6 m to 20.9 m. Lengths and widths of these excavations are in the range of 178 to 215 m and 22 to 24 m, respectively. All excavations are retained by 1.0 m thick reinforcement concrete diaphragm walls. Construction sequences of O6, O7 and O8 are listed in Tables 1 to 3. H-type steel sections were selected for horizontal props and the levels of props at these sites are also described in Tables 1 to 3. The horizontal spacing of props is similar at O6. O7 and O8 and is approximately 4.5 m. In addition, angle bracing and waling were constructed using H-type steel sections in order to strengthen the strut system.

Table 1. Construction sequence at O6.

| Construction activity | Period (day/month/year) |
|---|---|
| Excavate to 3.4 m below ground level | 24/10/03–27/10/03 |
| Install 1st level prop at 2.5 m below ground level | 02/11/03–06/11/03 |
| Excavate to 6.8 m below ground level | 08/11/03–12/11/03 |
| Install 2nd level prop at 5.9 m below ground level | 13/11/03–16/11/03 |
| Excavate to 10.0 m below ground level | 24/11/03–27/11/03 |
| Install 3rd level prop at 9.1 m below ground level | 04/12/03–07/12/03 |
| Excavate to 13.5 m below ground level | 14/12/03–16/12/03 |
| Install 4th level prop at 12.6 m below ground level | 28/12/03–31/12/03 |
| Excavate to 17.0 m below ground level | 06/01/04–08/01/04 |
| Install 5th level prop at 16.1 m below ground level | 09/01/04–12/01/04 |
| Excavate to 19.6 m below ground level | 25/01/04–02/03/04 |

The main soil stratum of these sites is similar and consists of medium to dense silty sand with several

Table 2. Construction sequence at O7.

| Construction activity | Period (day/month/year) |
|---|---|
| Excavate to 3.1 m below ground level | 09/12/03–13/12/03 |
| Install 1st level prop at 2.5 m below ground level | 26/12/03–03/01/04 |
| Excavate to 6.9 m below ground level | 08/01/04–17/02/04 |
| Install 2nd level prop at 6.3 m below ground level | 18/02/04–22/02/04 |
| Excavate to 10.7 m below ground level | 06/03/04–08/03/04 |
| Install 3rd level prop at 10.1 m below ground level | 09/03/04–14/03/04 |
| Excavate to 14.6 m below ground level | 15/04/04–18/04/04 |
| Install 4th level prop at 14.0 m below ground level | 19/04/04–21/04/04 |
| Excavate to 18.4 m below ground level | 22/04/04–26/04/04 |
| Install 5th level prop at 17.8 m below ground level | 27/04/04–29/04/04 |
| Excavate to 21.7 m below ground level | 31/05/04–31/05/04 |

Table 3. Construction sequence at O8.

| Construction activity | Period (day/month/year) |
|---|---|
| Excavate to 1.6 m below ground level | 27/02/04–02/03/04 |
| Install 1st level prop at 1.0 m below ground level | 03/03/04–07/03/04 |
| Excavate to 5.2 m below ground level | 18/03/04–22/03/04 |
| Install 2nd level prop at 4.6 m below ground level | 23/03/04–27/03/04 |
| Excavate to 8.3 m below ground level | 30/03/04–02/04/04 |
| Install 3rd level prop at 7.7 m below ground level | 03/04/03–07/04/04 |
| Excavate to 14.6 m below ground level | 08/04/04–10/04/04 |
| Construct concourse-level slab (0.8 m thick) at 14.2 m below ground level | 11/04/04–15/05/04 |
| Excavate to 17.0 m below ground level | 14/08/04–16/08/04 |
| Install 4th level prop at 16.4 m below ground level | 17/08/04–19/08/04 |
| Excavate to 19.0 m below ground level | 08/09/04–15/09/04 |
| Install 5th level prop at 18.4 m below ground level | 15/09/04–18/09/04 |
| Excavate to 20.9 m below ground level | 19/09/04–22/09/04 |

thin layers of clay. The SPT-N value of ground is from 5 to 30. The initial groundwater level was 3–6 m below ground level and it remained hydrostatic before commencement of excavation. Most excavations are surrounded by 4-storey to 7-storey buildings but some high-rise buildings (up to 12-stories) are also observed on site.

## 3 OBSERVATIONS

Monitoring instruments installed on site included inclinometers inside the diaphragm wall and soils,

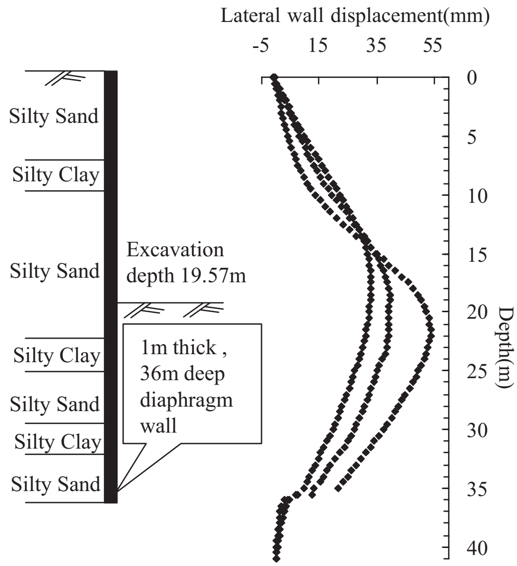


Figure 1. Lateral wall deformations and ground profile at O6.

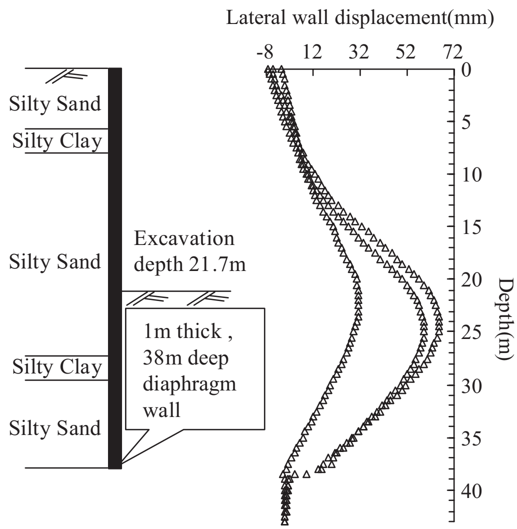


Figure 2. Lateral wall deformations and ground profile at O7.

observation wells, standpipe/electrical piezometers, vibration wire gauge on struts, tiltmeter and précision levelling on buildings.

Figures 1 to 3 show the lateral wall deformations observed from O6, O7 and O8 at the final excavation stage together with their ground profiles, respectively. It is evident that the maximum lateral wall movement varies from 32 to 64mm. The shape of lateral wall

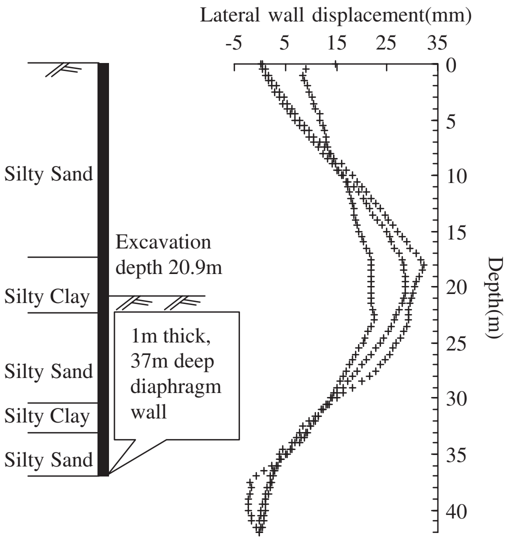


Figure 3. Lateral wall deformations and ground profile at O8.

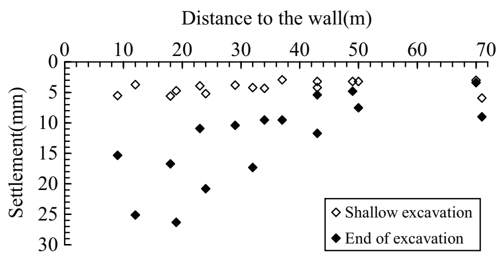


Figure 4. Surface settlement at O6.

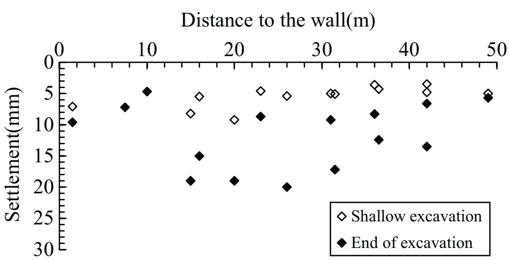


Figure 5. Surface settlement at O7.

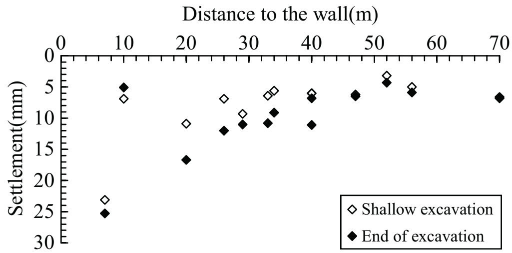


Figure 6. Surface settlement at O8.

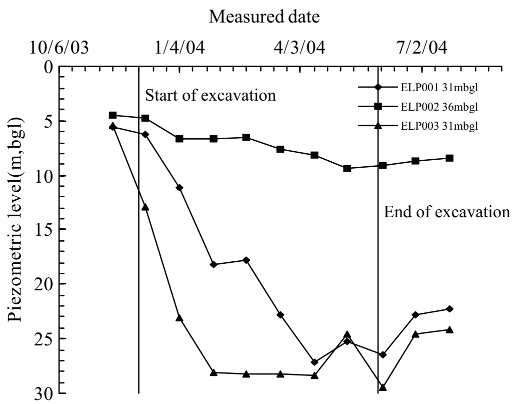


Figure 7. Piezometric levels inside the excavation at O7.

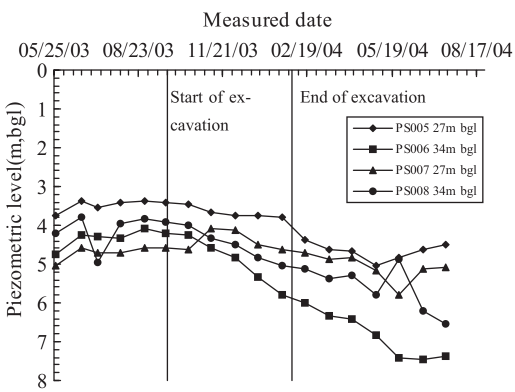


Figure 8. Piezometric levels outside the excavation at O6.

deformation is a cantilever at the shallow excavation level but tends to become prop-mode the deeper the excavation. The depth where the maximum lateral wall movement occurs is generally at the same depth of excavation.

Figures 4 to 6 present induced surface settlement and the observed maximum surface settlement is up to 20 to 28 mm at the completion of excavation. However, as shown in Figures 4 to 6, limited data was available for the area close to the excavation.

Since piezometers inside the excavation at O8 were all broken, only piezometric levels inside the excavation at O6 and O7 were measured, as indicated in Figure 7. The piezometric levels continue to decrease as excavation progresses. Figure 8 indicates

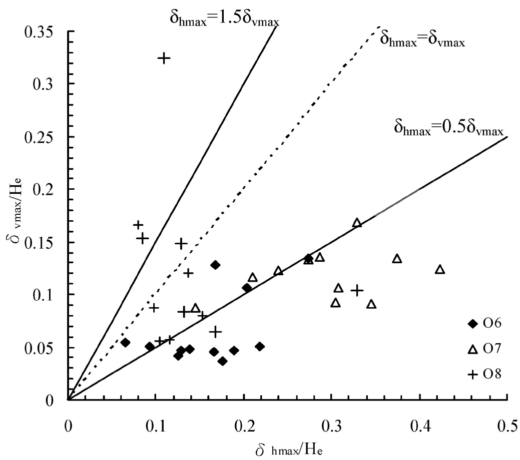


Figure 9. The relationship of $\delta_{vmax}$, $\delta_{hmax}$ and $H_e$

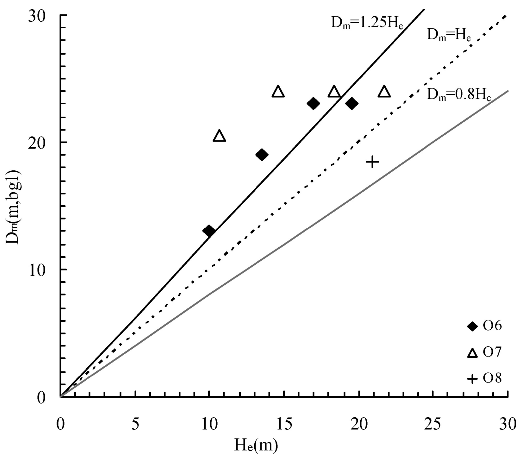


Figure 10. The relationship of the depth of the maximum lateral wall displacement ($D_m$) and excavation depth ($H_e$).

the piezometeric level outside the excavation. It is apparent that it is affected by a change of pore pressure inside the excavation therefore it shows a slight drop as excavation progresses.

The loads on struts were also measured and the maximum observed measured load is in the range of 220 to 320 tons.

## 4 DISCUSSIONS

### 4.1 *Maximum movements*

Figure 9 presents the relationship of maximum lateral wall movements and excavation depth at O6, O7 and O8. It is found that the maximum lateral wall displacement ($\delta_{hmax}$) in relation to the maximum excavation depth ($H_e$) is approximately 0.034 to 0.3%. The ratio of $\delta_{hmax}$ /$H_e$ is comparatively high at O7 and this could be accredited to less stiffness of the supporting system. Mana & Clough (1981) described the ratio of $\delta_{hmax}$ /$H_e$ mainly in the range of 0.4 to 2.0%. Ou et al. (1993) reported that the same ratio was approximately from 0.2 to 0.5% for excavations in Taipei. The ratio obtained from this study tends to be lower and it is considered that varying ground conditions could be the reason for the difference.

As shown in Figure 10, the depth where maximum lateral wall movement occurs is in a range of 0.86 to 1.26$H_e$. The maximum lateral wall movement is close to the excavation level.

The lateral wall movement at O8 is smaller than the others and it is assumed a semi-top-down construction method might provide a greater strut stiffness and reduce lateral wall movement in the excavation.

### 4.2 *Surface settlement troughs*

As shown in Figure 9, the maximum surface settlement ($\delta_{vmax}$) is approximately 0.05–0.13% of $H_e$. Wang (2003) suggested that $\delta_{vmax}$ induced by the excavation in Kaohsiung might reach 0.04% to 0.25% of $H_e$. Observations in this study appear to be consistent with Wang's conclusion.

Further, the relationship between $\delta_{vmax}$ and $\delta_{hmax}$ was explored and Figure 9 presents the distribution of the calculated ratio of $\delta_{vmax}$ to $\delta_{hmax}$. It appears that the ratio of $\delta_{vmax}/\delta_{hmax}$ falls in a range of 0.3 to 0.75 at O6 and O7 but tends to be greater at O8 (approximately from 1.3 to 1.8). Since different construction methods (bottom-up for O6 and O7 but semi- top-down for O8) were employed this is considered to be the main reason for the difference. As additional lateral wall movements at O6 and O7 were generated by the delayed installation of struts at several stages, this might reduce the ratio of $\delta_{vmax}$ to $\delta_{hmax}$. Some data from O6 and O7 were therefore ignored, hence it is suggested that the ratio of $\delta_{vmax}/\delta_{hmax}$ varies from 0.5 to 0.7 at O6 and O7. However, only limited data were collected for areas near the excavation (0 to 5 m from the excavation). This might affect the accuracy of the measurement of ground surface settlement.

Clough & O'Rourke (1990) suggested that the influence zone at surface level affected by the excavation in sand was two times the excavation depth for the ground behind the wall retaining the soil, but it tends to be greater (up to three times the excavation depth) at O6, O7 and O8. Pumping from deeper levels under ground is thought to be the reason for that.

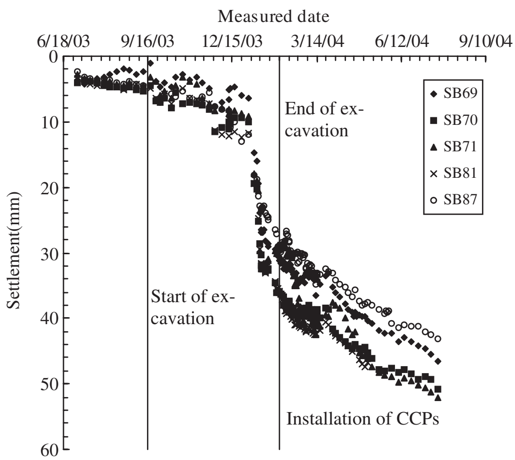


Figure 11. Building settlement at O6.

## 4.3 *Use of chemical churning pile*

Chemical churning piles (CCP) are commonly used in Taiwan in order to reduce the influence on buildings resulting from adjacent excavation. Materials used for CCP generally include cement and water. Woo & Moh (1990) reported that the movements of the building could be prevented if the tip of the chemical churning pile was installed deeper than the potential failure surface. CCPs were used at O6 in order to protect structures nearby. For the design of CCPs, piles have to penetrate at least 2 meters below the 45° active failure surface of the excavation (Maeda- Longda Joint Venture, 2003). CCPs were installed between the excavation and buildings, approximately 7.5–9.0 m from the excavation. The diameter of the pile is 0.35 m and the length of the pile varies from 12.0 to 14.5 m. During the construction, pressure used for jet-grouting was kept at 19.6 MPa. The rate of rotation and raising of the rod were 20 rpm and 4.0 min/m, respectively. Although CCPs were installed around O6, the buildings adjacent to O6 continued to settle after installation of CCPs, as shown in Figure 11. CCPs may only provide very limited influence on reducing continual settlement of buildings and this is consistent with observations that Hsiung (2002) reported. Insufficient CCPs stiffness could be a possible reason.

## 4.4 *Prop load*

Peck (1969) suggested that the prop load could be estimated associated with the apparent earth pressure method. Consideration of case histories from different projects, Twine & Roscoe (1997) revised the apparent earth pressure method. Figures 12 and 13 present the comparison of strut load from field measurement and apparent earth pressure suggested by Peck and Twine and Roscoe. It suggests that Peck's method obviously underestimates the actual load on the prop but the method suggested by Twine and Roscoe provides a

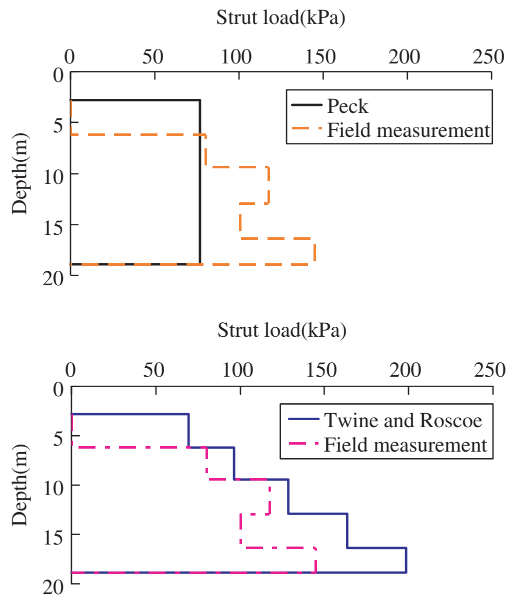


Figure 12. Comparison of prop load from field measurement and apparent earth pressure at O6.

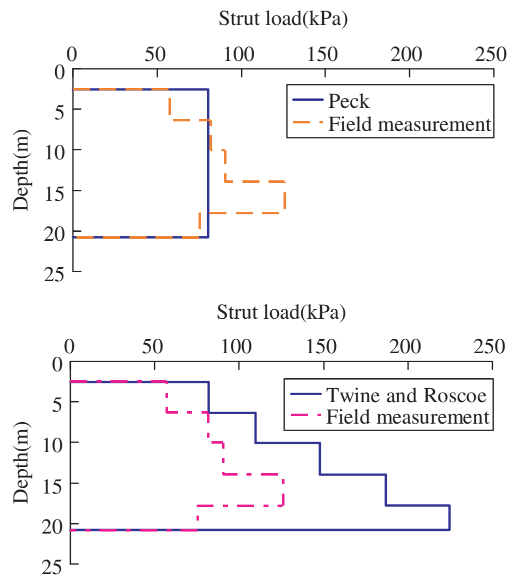


Figure 13. Comparison of prop load from field measurement and apparent earth pressure at O7.

more accurate prediction in practice. Such conclusion is similar to those by Ou et al. (1998) and Hsiung (2002).

## 5 CONCLUSIONS

This study provides an opportunity for exploration of ground behaviours induced by excavation in sand. Based on this study, conclusions can be made, as follows:

1. The lateral wall movement induced by excavations selected in this study is up to 0.3% of the excavation depth. Such displacement is less than those found from several related previous literatures. It is suspected the varying ground conditions could be a factor in the difference.
2. The maximum lateral wall displacement is 0.86 to 1.26 of the excavation depth. The depth where the maximum lateral wall movement occurs tends to be close to the excavation level
3. Associated with observations in this study, the ratio of $\delta_{vamx}$ to $\delta_{hmax}$ varies from 0.5 to 1.8 and the use of construction method (bottom-up and semi-top-down) might induce the obvious change in this ratio.
4. The influence zone caused by excavation can be up to three times the excavation depth.
5. The installation of CCPs does not provide an effective solution for reducing the settlement of buildings near the excavation. Insufficient CCPs stiffness might be a reason.
6. The apparent earth method suggested by Peck underestimates the prop load. The method suggested by Twine and Roscoe might provide a more acceptable result in practice.

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