Observed Performance of Diaphragm Wall Construction

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ABSTRACT: This study presents the behavior of ground movement induced by the construction of diaphragm wall based on the results of full-scale field tests or panel tests in the construction of the Taipei mass rapid transit system. Two typical test results are presented to understand the general characteristics of ground movement induced by the construction of one wall panel and multiple wall panels. Moreover, the panel test results from the other contracts are also summarized. Results show that the ground settlements after the completion of the whole diaphragm wall construction were much larger than those measured from panel tests because ground movement during the "normal" construction was heavily affected by construction factors. Use of panel test results to evaluate ground settlements might result in a misleading conclusion. Use of the envelope, as established in this study, was a rational way to evaluate ground settlements at the present stage. Besides, the maximum ground settlement of panel tests occurred was about 0.05~0.07 times the trench depth (D) percent and the primary settlement influence zone fell within a normal distance of 0.6D from the panel. The maximum ground settlement after the completion of the whole diaphragm wall construction was about 0.13D(%). The ground settlement beyond 1.5D ~ 2D was found to be insignificant.

1. INTRODUCTION

Wall deflection and ground movement normally occur as a result of excavation. Excessive ground movement frequently damages adjacent buildings in urban areas. To eliminate or reduce the possibility of such building damages, the ground movement must be predicted prior to excavation to assess impacts to adjacent buildings or public facilities. Moreover, most of analyses regarding ground movement focus on those due to main excavation, for example, excavation of soil, dewatering, strut installation and demolish. Ground movement induced by the diaphragm wall construction is seldom taken into account. It is often assumed that the diaphragm wall is wished in place.

Since diaphragm wall construction also goes through a stage of trench excavation, it should generate some ground movements. According to the studies by Cowland and Thorley (1985) and Morton et al. (1980), the ground movement induced by the construction of diaphragm wall may account for 30 to 50% of the total settlement for some cases. Unable to take account of this factor may increase the possibility of damaging adjacent buildings during excavation.

Though the problems of ground movement induced by the construction of diaphragm wall have gradually drawn attention from engineers, there are just a few study results available and most of them are confined to that induced by the construction process of a single diaphragm wall panel, for example, Dibiagio and Myrvoll (1972), Farmer and Attewell (1973), Poh and Wong (1998), Ng et al. (1999). The main reason is due to the complexity of the construction process of diaphragm wall, even just for a single panel construction and not mention of multiple panel construction.

There are a few studies on the behavior of ground movements induced by the three wall panels and all of them were based on theoretical analysis. Ng et al. (1995) and Gourvenec and Powrie (1999) investigated the characteristics of lateral soil displacement induced by the construction of three panels using the three dimensional or its approximation method. Ng and Yan (1999) studied the accumulation of ground settlements from the construction of the first panel and the two adjacent panels by using three dimensional simulation of the construction of three panels. However, no comparison between the field measurements and analysis results was made in the above-mentioned studies because field measurements of ground movements for the three panel construction are almost non-existent.

Besides, the final ground settlement should be the accumulation of settlements from all of the panels nearby, not just three panels as noted above. No solid conclusion regarding how to evaluate the final settlement induced by the diaphragm wall construction has yet been made. Moreover, the roles of construction factors in the evaluation of the ground settlement still remain resolved.

Since ground movement induced by the diaphragm wall construction involves many unknown factors, the contractors in some areas are then required to conduct so-called panel tests, that is, the ground movement is monitored during the construction of diaphragm wall panel, instead of performing numerical analysis. However, whether the panel test is an appropriate way to evaluate the ground movement also remains resolved.

For this reason, this paper presents the behavior of ground movement induced by the construction of diaphragm wall adopted from the monitoring results of the construction of the Taipei preliminary MRT (Mass Rapid Transit) network system. Of them, CN253B contract is first presented to understand the behavior of ground movement induced by the construction of one panel wall and multiple panels. The ground movements from the panel test results in the CN255 contract and those after the construction of the whole diaphragm wall construction, i.e., before main excavation, are compared to understand the characteristics of ground movement before the commencement of main excavation. Since the basic characteristics of ground movement in the other contracts were similar to the above mentioned two contracts, the profiles of movement profiles are not discussed here. Only the magnitude of the final ground settlement are summarized and compared with those in the literature. Figure 1 displays the contracts in the construction of the Taipei preliminary MRT network system where the panel test results are adopted in this paper.

2. MECHANISM OF GROUND MOVEMENT INDUCED BY DISPHRAGM WALL CONSTRUCITON

Ground movement induced by the diaphragm wall construction is mainly from trench excavation and its behavior is not the same as that caused by main excavation. The reasons for the differences are the differences in excavation geometric shapes and strutting methods. The ratio of the depth of a trench panel to its width and that of the depth to length are both much larger than those in main excavations. What's more, there is the influence of fluid stabilizer, employed to counteract the lateral earth pressure and to ensure the stability of trench walls. Nevertheless, in spite of the differences in geometric shapes and construction techniques, the excavation of a trench panel is also a type of excavation, producing movements. The shape of ground surface settlement is basically similar to that induced by main excavation. Besides, because the wall is the combined whole of many connected diaphragm wall panels and trenches are excavated separately, also different from main excavation.

The first stage of the constructing of diaphragm walls is to divide the whole length into several panels according to the construction conditions. The construction procedure of each panel is as follows: the construction of guided walls, the excavation of trenches, placing steel cages and concrete casting, as shown in Figure 2. After excavating the trench, mud in the trench must be cleared from the trench. Concrete casting, the last stage of diaphragm wall panel construction, is to adopt the Tremie pipe to pour concrete into the trench and form a diaphragm wall panel.

The depth of a guided trench is generally about 2~3 m, sometimes 5 m. Before concreting guided walls, guided trenches, not strutted, are open ditches. The maximum settlement induced by excavation of the guided trench occurs at the verge of the trench. The settlement decreases with the distance from the trench. Considering that both measurement of and literature on this field are almost nonexistent and that no significant settlement occurs during this stage (Woo, 1992), this paper will not delve into the subject.

As studied by Ng et al. (1995), Ng et al. (1999) and Gourvenec and Powrie (1999), the stress condition of soil in the vicinity of trenches during diaphragm wall construction is rather complicated. Take the construction of a single panel of a diaphragm wall for example. To keep the trench wall from falling, it is necessary to fill the panel with fluid stabilizer during the excavation process of the trench panel. Under normal construction conditions, excavating a trench panel filled with stabilizer will cause the stress states of the soil around the trench panel to change from the original K_0 to the balanced state of the fluid pressure of stabilizer. However, the fluid pressure of stabilizer is normally not equal to the original earth and water pressures in the trench panel, but is usually smaller. The trench excavation will decrease the total lateral stress of the soil within a specific range around the trench, and thereby produce lateral movement of the soil in the vicinity of the trench. Ground settlement is thus produced. During concrete casting, the lateral pressure in the panel during this stage should be greater than the fluid pressure during the stage of excavation because the unit weight of the wet concrete is greater than that of stabilizer. Therefore, the lateral movement caused at the previous stage will be pushed back and decreases while the amount of ground settlement changes accordingly.

After completion of a single panel wall, the second panel or other panels, adjacent to the first panel, would be constructed accordingly. The construction will go through the same construction procedure as the first one, which will cause the additional ground movement on that already induced by the first panel construction. With the continuation of the rest of the construction of panels, the ground movement near the first panel should be accumulated theoretically.

3. GEOLOGICAL FORMATION AND THE TAIPEI MRT CONTRACT

Generally, the Taipei basin is formed by a thick alluvium formation, i.e. Sungshan formation, which lies above the gravel formation, so-called Chingmei gravel formation. The Sungshan formation is consisted of some soft clay layers and sand layers, which appear alternately. The thickness of the Sungshang formation increases from south to north, up to more than 100 m. Near the center of the basin is about 40 to 55 m in thickness. The layers of the Sungshan formation are designated as, from bottom to top, the Sungshang I, Sungshang II, Sungshang III, Sungshang IV, Sungshang V and the Sungshang VI, which corresponds to silty sand and silty clay alternately (Huang et al., 1987).

The Taipei preliminary MRT network comprises six lines, i.e., Muzha, Danshui, Xindian, Nangan, Banqiao and Zhonghe lines. Of them, the last three lines were constructed underground and the diaphragm wall was used as the earth retaining structure in the construction of train stations. To evaluate the effect of diaphragm wall construction on adjacent buildings, the contractors were required to carry out panel tests in each diaphragm wall construction contract, that is, at least, the ground settlement and lateral soil movement were monitored at each stage of construction of wall panels.

The contracts where panel test results are adopted in this study are as shown in Figure 1. The sites are certainly all located on the deposit with alternating layers of silty sand and silty clay, but with different thicknesses. Figure 2 shows the construction procedure of a typical diaphragm wall panel.

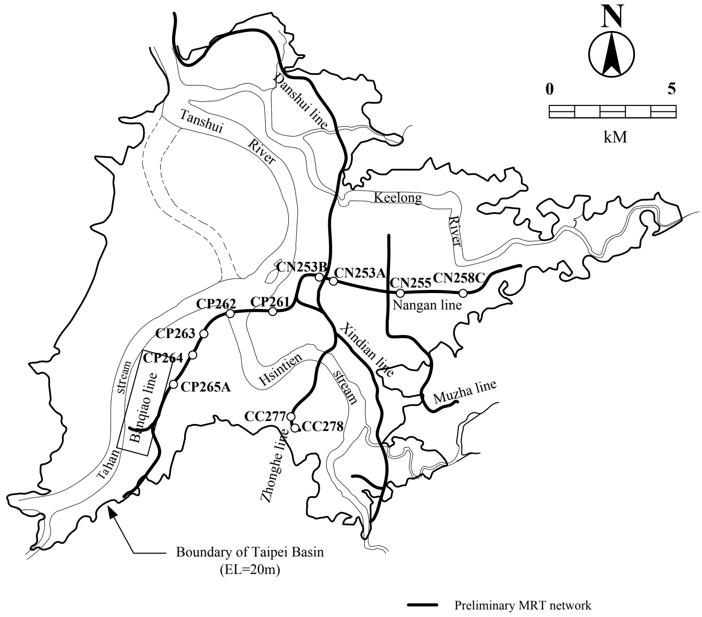

Figure 1 Location of the contracts adopted in the present study in the Taipei preliminary MRT network construction

4. PERFORMANCE OF THE DIAPHRAGM WALL CONSTRUCTION IN THE CN253B CONTRACT

Figure 3 shows the subsurface soil profile and their properties at the construction site of the CN253B contract. The dimensions of the test panel were 1.0 m thick, 3.4~5.5m long and 35.5 m deep. Figure 4 displays the sequence of the construction of the test panels and the arrangement of the settlement marks for the test panels. Besides, two inclinometers adjacent to the diaphragm wall were installed to monitor the lateral soil displacement during the test period. Inclinometer SIS31, located in the north side of the test panels, was 1.5 m from the diaphragm wall while inclinometer SIS32, in the south side, was 1.8 m from the wall. Both inclinometers were embedded to a depth of 50.5 m.

Figure 5 shows the lateral displacement of the soil adjacent to the first panel during the test period. As shown in the figure, the lateral displacements of the soil in the north side, i.e., at SIS31, generally had the same tendency as those in the south side, i.e., at SIS32. The inclinometers in clay were of the larger lateral displacements than those in sand. After the first bite, the soil moved toward the trench. However, due to unknown reasons, the soil displaced outward away from the trench after the second bite. After the third or central bite, i.e., the completion of trench excavation, the soil then moved toward the trench again and its magnitudes were greater than those after the first bite. However, the soil displaced toward the trench again right after concreting and moved outward away from the trench after 12 hours after concreting. The phenomenon is not consistent with the description as shown in Figure 2. The construction factors might play a main role for the lateral displacement of soil, especially those near the trench. More elucidation will be provided in the last part of this paper.

Figure 6 shows the corresponding ground settlements in the north side and in south side during the construction of the first test wall panel. Unlike the lateral displacements of the soil near the trench, the ground settled a lot after the completion of the second bite but settled little after the third bite or the completion of trench excavation. The soil settled slightly right after concreting. This may be due to the fact that concreting inevitable produced vibration, which in turns densified the soil nearby. Moreover, shrinkage of concrete due to hydration after12 hours after concreting was unable to induce further movement for the soil far away from the trench. This figure also shows that the ground settlements in the south side were larger than those in the north side. It is justified that major construction machines and vehicles for the excavation actively moved in the south side. The maximum ground settlements in the north and south sides were equal to 5 mm and 13 mm, respectively, which were separately equal to 0.014D(%) and 0.037D(%) where D denotes the depth of the trench.

Figures 7 and 8 separately show the variation of lateral displacement of the soil adjacent to the first panel and settlement of the soil perpendicular to the first panel with the construction sequence of the wall panels. As shown in Figure 7a, construction of the second panel, 11.9 m to SIS31 or SIS32 (center to center) caused a negligible change in lateral displacement for the soil adjacent to the first wall panel but it did induce a perceptible increase in ground settlement, for example, the 2.3 mm and 2.4 mm of increment at a distance of 4 m and 8 mm from the trench in the south side, respectively. Construction of the third wall panel, 7.6 m to SIS31 or SIS32 (center to center), engendered more conspicuous lateral soil displacements than those by the second wall panel (Figure 8c). The corresponding ground settlements appropriately increased, for example, 2.1 mm and 0.8 mm of increment at a distance of 4 m and 8 mm from the trench in the south side, respectively (Figure 8c).

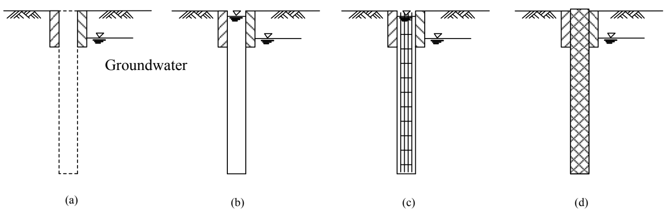

Figure 2 Construction procedure of a diaphragm wall panel
(a) construction of the guided wall
(b) excavation of the trench
(c) placement of reinforcements
(d) concrete casting

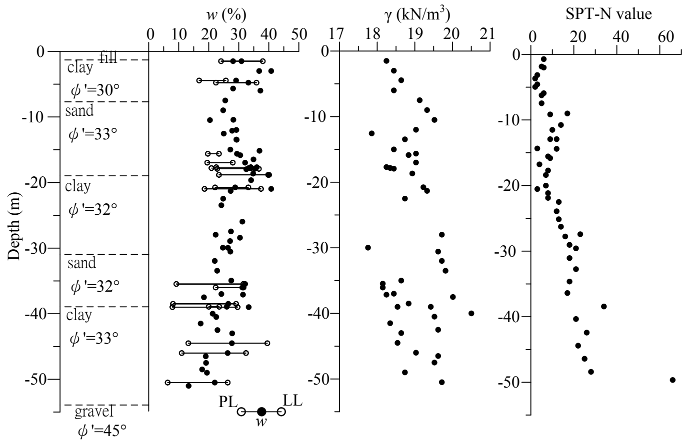

Figure 3 Subsurface soil profile at the CN253B construction site

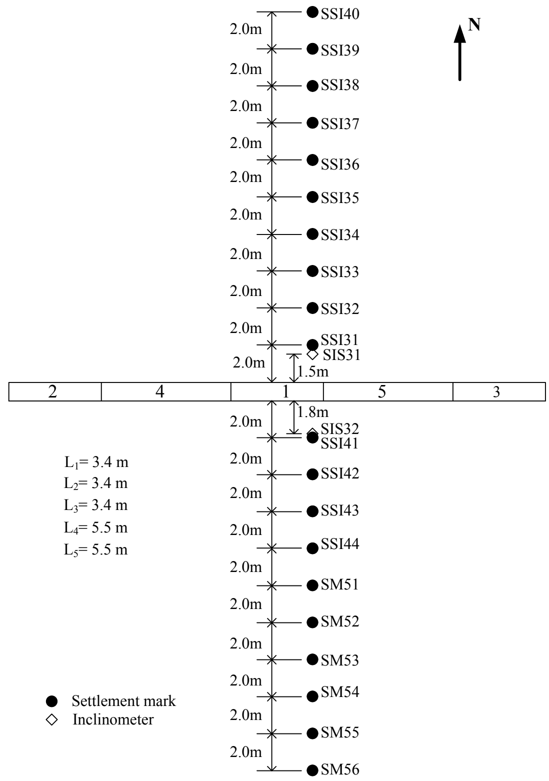

Figure 4 Layout of the panel test and monitoring items for the CN253B contract

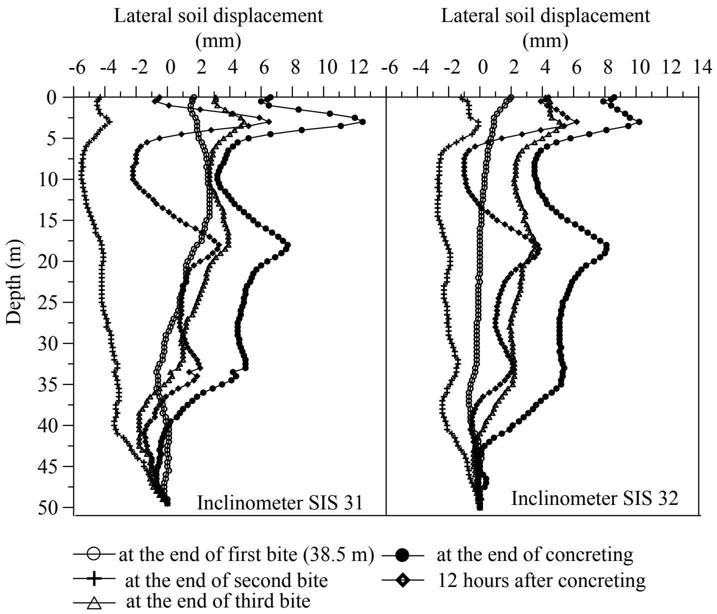

Figure 5 Lateral soil displacements due to the first panel construction for the CN253B contract

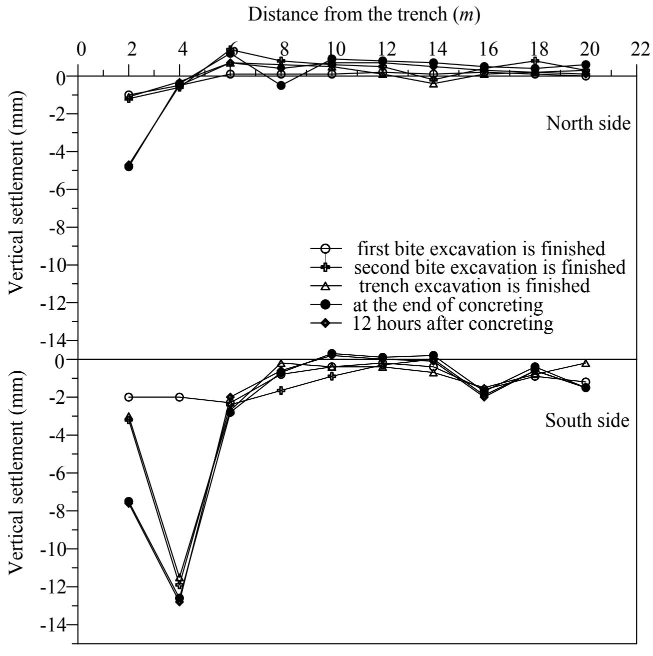

Figure 6 Ground settlements due to the first panel construction for the CN253B contract

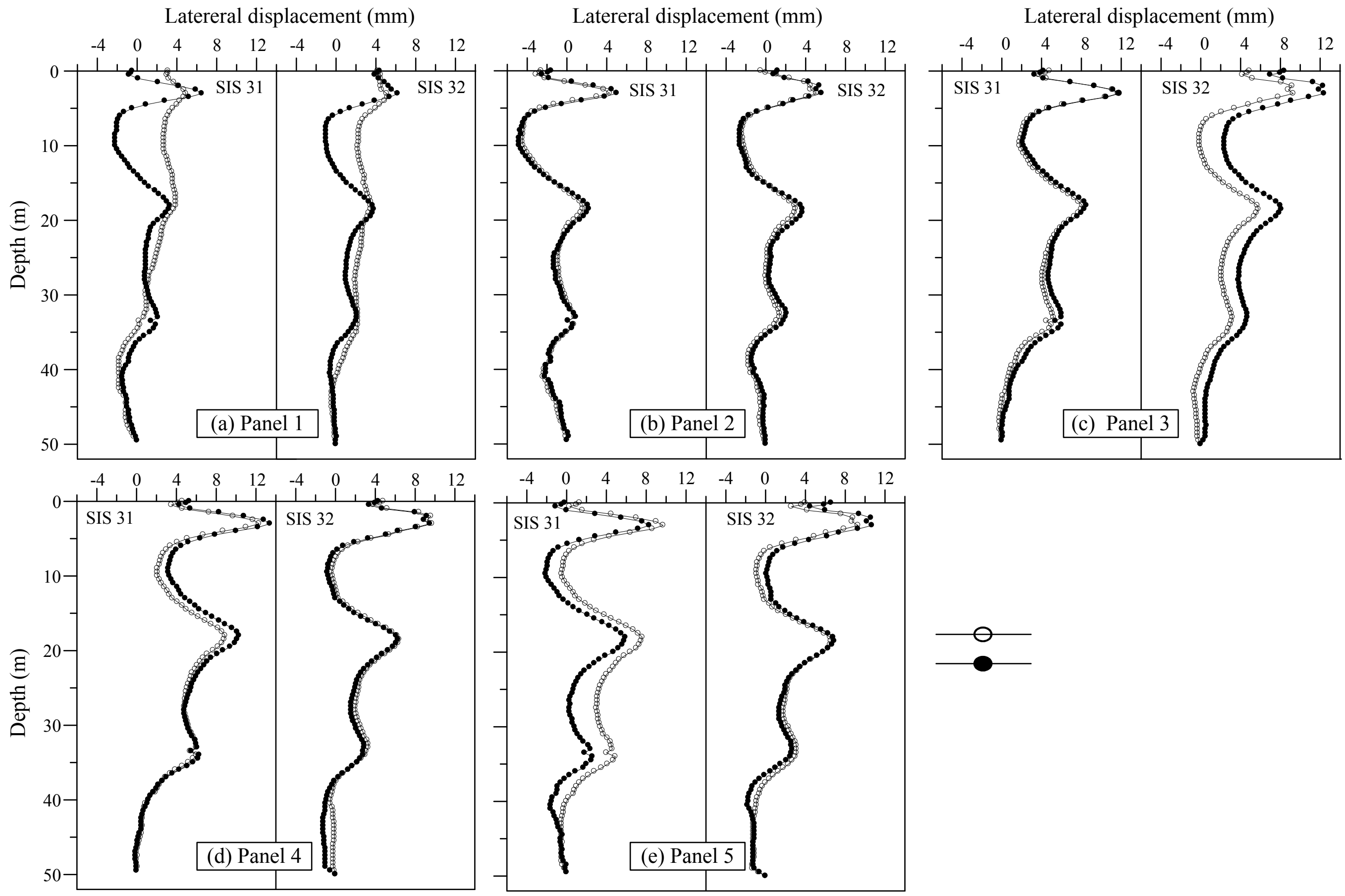

Figure 7 The lateral soil displacements induced by the construction sequence of multiple panels in the CN253B contract

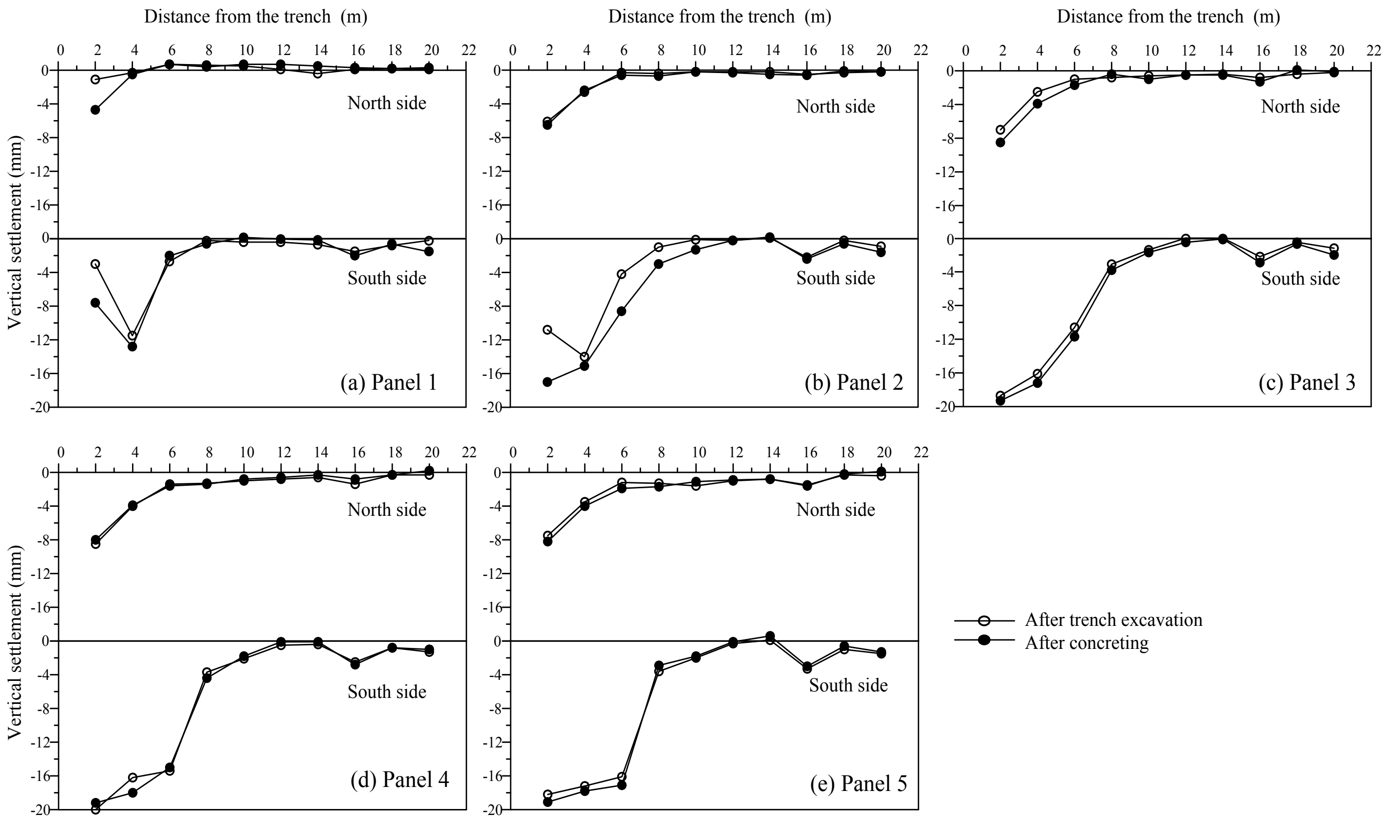

Figure 8 The ground movements induced by the construction sequence of multiple panelling in the CN253B contract

The reason why the lateral soil displacements disproportionately increased from the second panel to the third panel, as compared with the ground settlements, may be also attributed to the construction factors. The movement of the soil very close to the trench was especially sensitive to the operation of construction equipment. The shorter distance for the third panel to the inclinometers than the second wall panel, i.e., 7.6 m versus 11.9 m, may be another reason to cause such disproportional increase in lateral soil displacement.

As shown in Figures 7d and 7e, construction of the fourth panel did not cause significant changes in lateral soil displacement. Construction of the fifth panel even caused a slight decrease in lateral soil displacement. Moreover, construction of both the fourth and fifth panels caused the soil perpendicular to the first panel a minor increase in settlement. Theoretically, construction of the fourth and fifth wall panels, closer to the first wall panel than the second and the third wall panels, should have greater contribution in lateral soil displacement and ground settlement. The monitoring results did not exhibit the trend as we expect. Construction factors may be responsible for such a phenomenon.

As shown in Figure 8e, the accumulated maximum ground settlements in the north side and south side were separately equal to 8.2 mm and 19.1 mm, equivalent to 0.023D(%) and 0.054D(%), respectively. Amount of ground settlement due to multiple panel construction was not very different from that induced by the construction of the first panel. Such an observation was quite consistent with the numerical analysis results by Ng et al. (1995), which concluded that once an excavated panel has been concreted, the construction of adjacent panels has only a very minor influence on the final ground settlement at the center, behind the first constructed panel.

With panel tests, construction workers are often cautious in operation of equipment during the test period. However, the operation is not easily controlled as people conduct experiments in the laboratory. Construction factors like workmanship, biting rates of excavators, vibrations due to construction, time lag of concrete placement, weight of equipment etc. more or less affected test results. Thus, the test result is not always consistent with that shown in Figure 2.

5. PERFORMANCE OF THE DIAPHRAGM WALL CONSTRUCTION IN THE CN255 CONTRACT

The layout of the paneling for the CN255 contract, build for ventilation of the Nankang line, is shown in Figure 9. The dimensions of the test panel were 1.0 m thick, 41 m deep and 3.6~5.0 m long. The settlement marks, perpendicular to the test panel, are also shown in the figure. Figure 10 shows the subsurface soil profile along with the basic soil properties for each layer at the test site. As shown in the figure, the soft clay, with its water contents ranging from 30% to 40%, is the predominant soil, which affected the performance of the diaphragm wall construction.

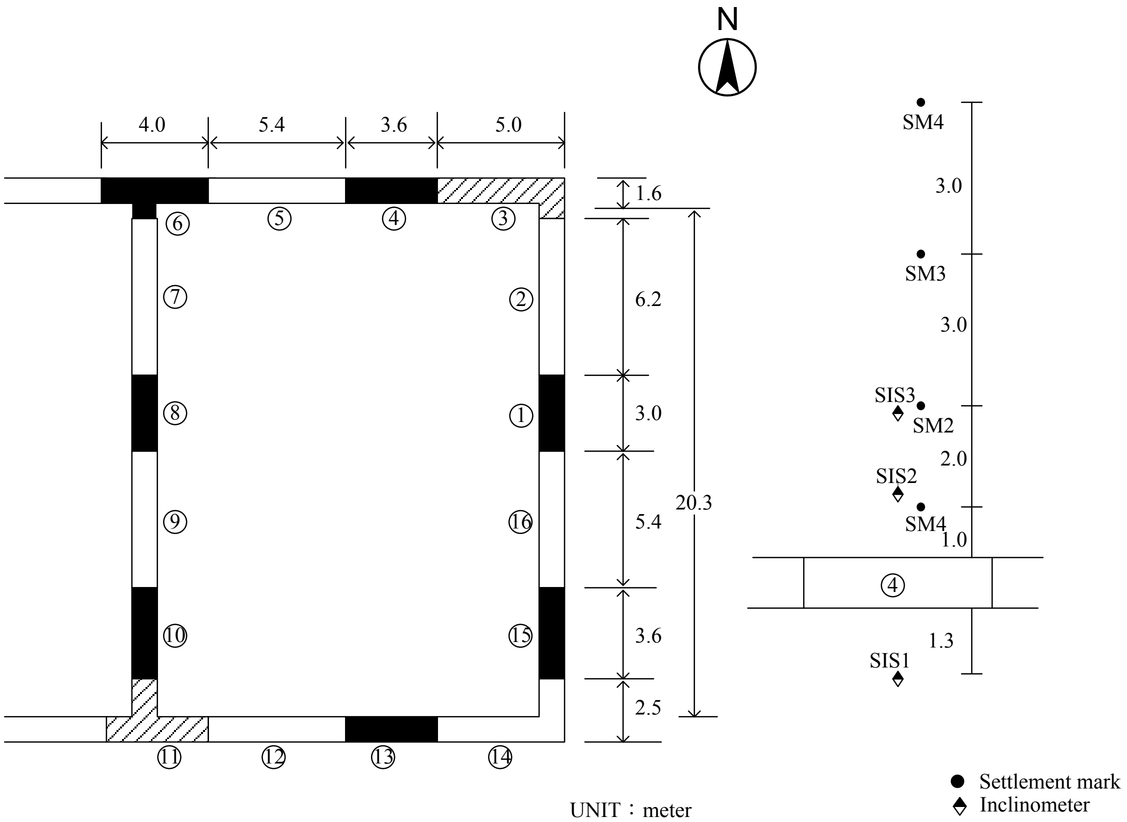

Figure 9 Paneling of the CN255 contract and its monitoring items

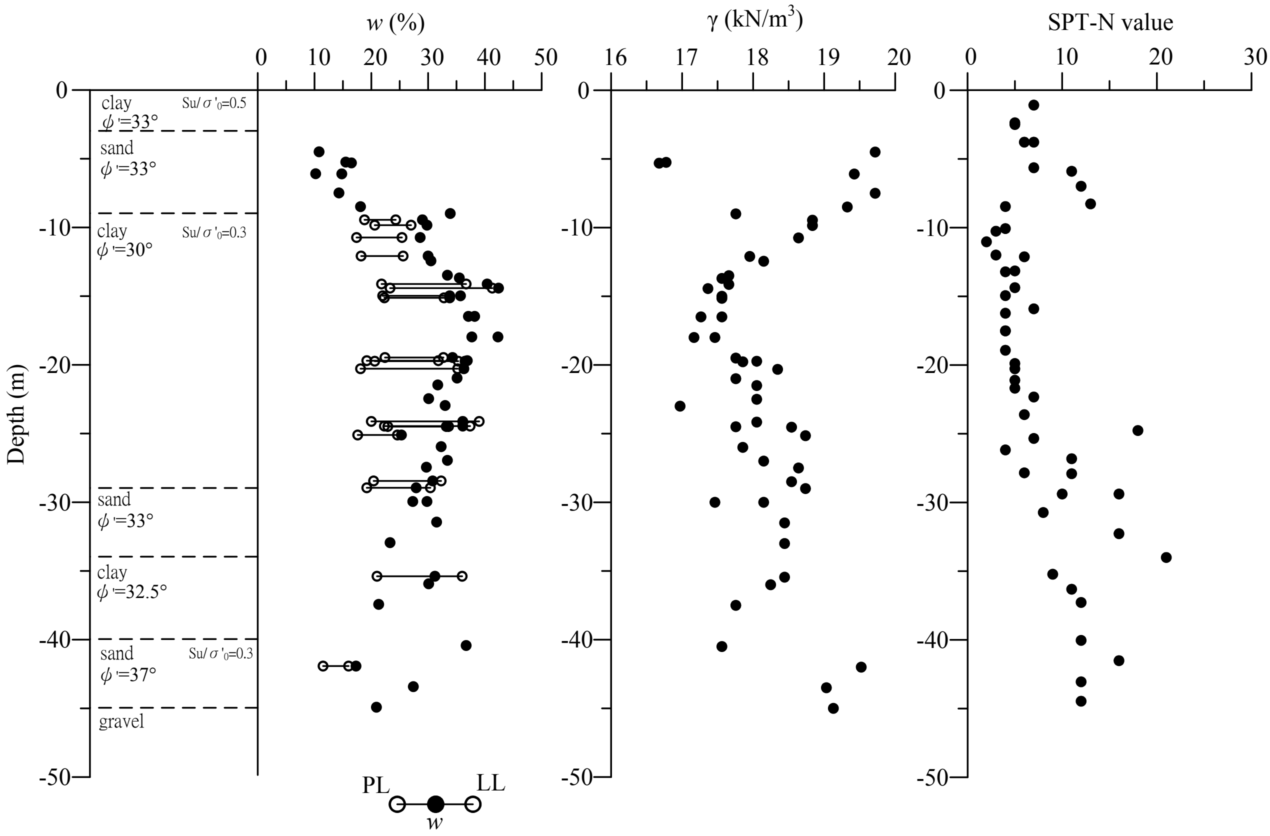

Figure 10 Subsurface soil profile at the CN255 construction site

Since the characteristics of lateral displacement of the soil adjacent to the test wall panel were basically the same as those noted in the CN253B contract, the behaviour of lateral soil displacement was not discussed here. Figure 11 shows that the ground settlement induced by each stage of wall construction. As shown in the figure, the maximum ground settlement was 16.5 mm, equal to 0.040D(%), which was close to that observed in the CN253B contract.

The ground settlements at the different locations surrounding the site after the completion of the whole diaphragm wall construction were also monitored, as shown in Figure 12. This figure indicates that the final ground settlements were much larger than those from the single panel test. This is because construction workers operated excavators, cranes, material handling or construction vehicles in a "normal" way rather than cautious or experimental attitude after the completion of panel tests. Besides, various construction equipment or vehicles moved back and forth at the construction site. Construction factors should heavily affect the monitoring result.

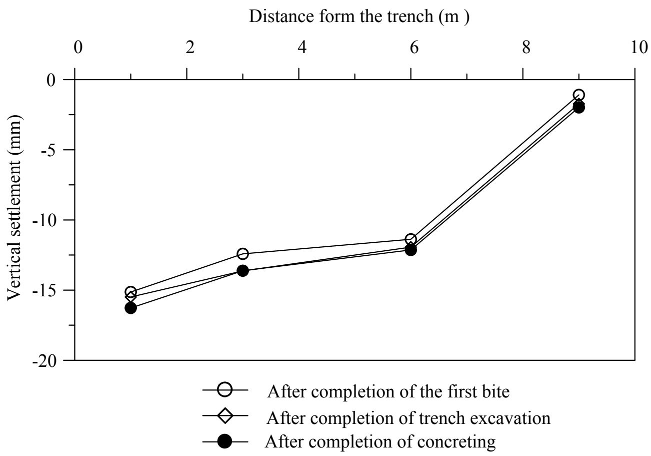

Figure 11 Ground settlements measured from the single panel test for the CN255 contract

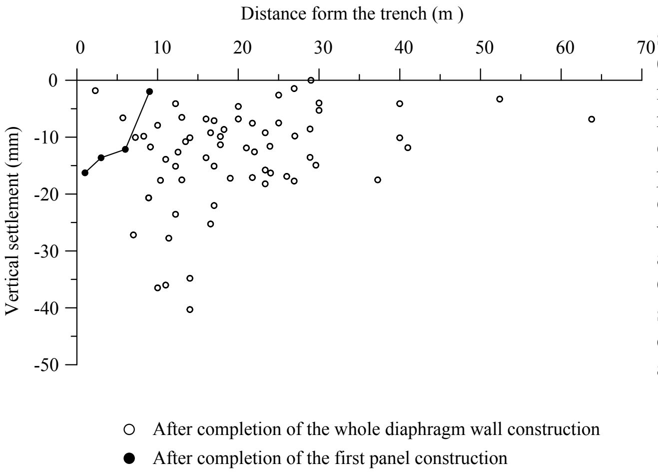

Figure 12 Ground settlements after the completion of whole diaphragm wall for the CN255 contract

2. ENVELOPE

Figure 13 shows the normalized ground settlements induced by single panels with respect to the depth of trench (D) from the above-mentioned contracts, i.e., CN253B and CN255, along with those from other contracts in the Taipei MRT construction as shown in Figure 1. The envelope of the ground settlements, with its normalized maximum value equal to 0.05%, was also displayed in the figure. The primary influence zone of settlements induced by the construction of single panels fell within a distance of 0.6D from the panel. The amount of the normalized maximum ground settlement were close to the results of the panel test in marine clay (Poh and Wong 1998), but greater than that computed by Ng and Yan (1999), who performed the three dimensional analysis for the test panel in stiff London clay.

Under the ideal condition, the settlement of the soil perpendicular to the first panel will be accumulated with the construction of the wall panels nearby the first panel. To investigate the influence of the multiple panel construction on the ground settlement, several contracts were also conducted with the multiple panel test in addition to CN253B (Figures 7 and 8). As shown in Figure 14, the ground settlement from the CP264, CP265A and CC277 contracts are also summarized. The envelope of the ground settlements, with its normalized maximum value equal to 0.07%, was also indicated in the figure. The influence zone of settlement was generally the same as that of a single panel, i.e., 0.6D from the panel. The amount of the normalized maximum ground settlement was greater than that obtained by Ng and Yan (1999), who simulated the sequence of construction of the three test panels in stiff London clay using the three dimensional finite element method. Comparing Figure 13 with Figure 14 or the envelopes displayed in Figure 15, we can find that the ground settlement induced by the construction of multiple panels was just slightly greater than that induced by the construction of single wall panel. As mentioned in the preceding section, the result were consistent with those presented in the literature (Ng et al. 1995, Ng and Yan 1998).

In addition to the CN255 contract, the ground settlement after the completion of the whole diaphragm wall construction for the CN258C contract was also monitored. The normalized ground settlement after the completion of the whole diaphragm wall construction based on the monitoring results of the CN255 and CN258C contracts is displayed in Figure 16 and its envelope is also indicated in Figure 15. It is found from Figures 15 or 16 that the envelope of ground settlements, with its maximum value equal to 0.13%, is much greater than those induced by a single wall panel construction and those induced by multiple wall panel construction. The ground settlement beyond 1.5D ~ 2D is found to be insignificant.

Clough and O'Rourke (1990) found that the maximum ground settlement induced by the construction of diaphragm walls is 0.15D(%), as shown in Figure 15, according to many in-situ monitoring results. The present study, deduced from the monitoring results in the Taipei MRT construction, was quite close to that established by Clough and O'Rourke (1990). The results from the present study as well as from Clough and O'Rourke's study all exhibited that the ground settlement after the completion of the whole diaphragm wall construction is significant and not as simple as those accumulated by the multiple wall panel construction. Cowland and Thorley (1985) also reported that the final ground settlement after the completion of the whole diaphragm wall construction can achieve 40%~50% of the total ground settlement after the completion of main excavation.

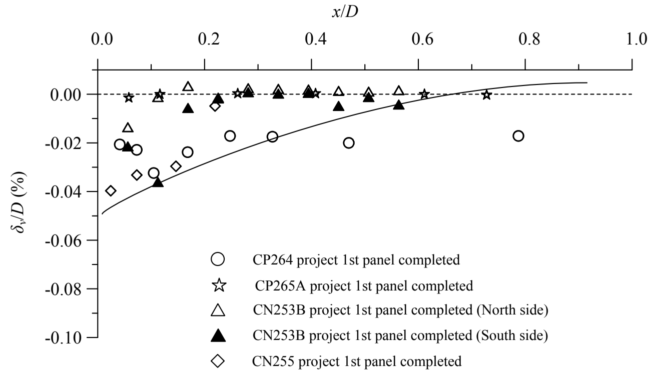

Figure 13 Normalized ground settlements due to the construction of single panels

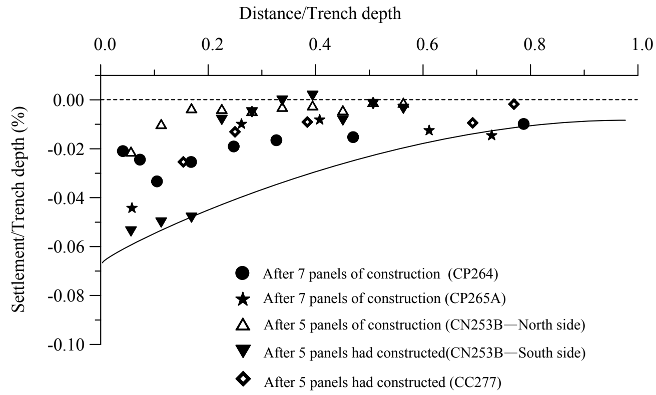

Figure 14 Normalized ground settlement due to the construction of multiple panels

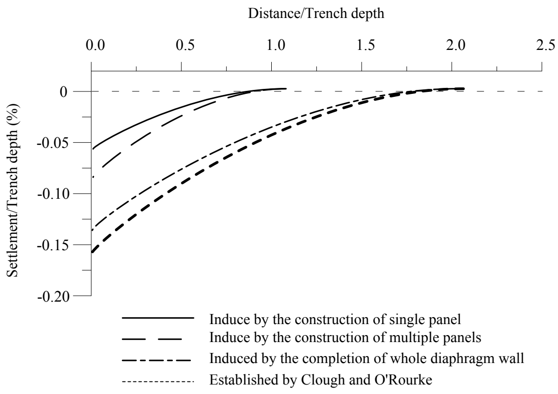

Figure 15 Envelope of ground settlements induced by the construction of diaphragm wall

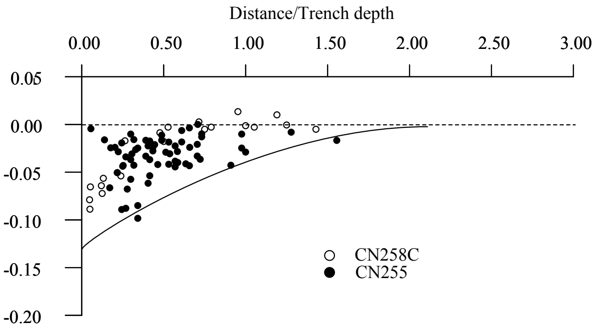

Figure 16 Ground settlements after the completion of the whole diaphragm wall

7. CONCLUSIONS

Theoretically, the lateral soil displacement or ground movement during the panel test should increase with the excavation area such as numbers of bites or panels. However, the monitoring results indicated that the lateral displacement of the soil near the trench did not necessarily increase with the number of bites or panels. Construction factors should be responsible for such a phenomenon because construction operations were not so well controlled as people conducting experiments in the laboratory. The ground settlement did increase with the numbers of panels but only to a certain extent.

After the completion of the whole diaphragm wall construction, the ground settlements were much larger than that induced by the construction of a single wall panel or multiple panels. This is because the construction workers operate excavators, cranes, material handling or construction vehicles in a “normal” way rather than in a cautious or experimental attitude. Besides, various construction equipment or vehicles moved back and forth at the construction site. Construction factors should heavily affect monitored results. Therefore, use of single panel test results, or even multiple panels test results, to estimate the potential ground settlement induced by the diaphragm wall construction but without consideration of construction factors, may result in a misleading conclusion.

On the other hand, the envelope of ground settlements are the synthesized results of excavation areas and construction factors necessarily involved during construction. Use of the envelope, as established in this study, was a rational way to evaluate the ground settlement induced by the construction of diaphragm wall at the present stage. Besides, the following conclusions can be drawn:

(1) With the single panel test, the maximum ground settlement induced by the construction of a single wall panel was about 0.05D% (D is the depth of a trench). The main influence range of settlement was 0.6D from the trench panel and little settlement occurred beyond 1.0D from the trench panel. The concrete casting did not cause significant settlement.

(2) With the multiple panel test, the maximum ground settlement was 0.07D% and its location and influence range were basically similar to those by single panel construction.

With the “normal” construction, the final ground settlement after the completion of the whole diaphragm wall was greater than that induced by the construction of a single test panel and that by the construction of multiple panels. The maximum ground settlement was about 0.13D%, which was close to that of Clough and O’Rourke’s envelope (0.15D%). Settlement became less observable beyond the distance of 1.5D~2D from the diaphragm wall.

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