Journal of GeoEngineering, Vol. 2, No. 2, pp. 61-71, August 2007

TOE MOVEMENTS OF DIAPHRAGM WALLS AND CORRECTION OF INCLINOMETER READINGS

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ABSTRACT

Inclinometer readings could be misleading if the toes of inclinometers are used as reference points for calculating wall deflections because the toes always move during excavation. Inclinometer readings obtained in three case histories in the Taipei Basin are studied and procedures for calibrating inclinometer readings to account for toe movements are proposed herein. A design chart is also provided for estimating toe movements in the T2 and TK2 Zones beforehand.

Key words: Diaphragm wall, deep excavation, instrumentation, wall deflection.

1. INTRODUCTION

As excavations go deeper and deeper, protection of adjacent structures becomes a serious concern. Because ground settlements, which are the major source of damages to adjacent structures, behind walls are closely associated with wall deflections, it is important to design walls and retaining systems to limit wall deflections. Although it is possible to compute wall deflections by using computer software, the results may be unreliable because of the limitations of the numerical schemes and also because of the difficulty in modeling complicated soil behavior. Therefore, judgment still has to be made on the reasonableness of the results obtained based on field observations.

Deflections of diaphragm walls are routinely monitored by using inclinometers which are amazingly accurate and can be considered as one of the most reliable geotechnical instruments. However, this does not mean that inclinometers always faithfully report wall deflections. It is usually assumed that the toes of inclinometers will not move and the movements at other depths are computed accordingly. This assumption is certainly untrue unless the toes of inclinometers are embedded in competent strata for sufficient lengths. As a result, the readings are often erroneous and have to be calibrated.

It will be easy to calibrate inclinometer readings if the top of inclinometer is monitored. But this rarely is the case. For deep excavations in soft ground, Fig. 1 shows the results normally expected from monitoring of wall deflections. The wall behaves as a cantilever in the first stage of excavation (*i.e.*, the 1st dig) and significant movement would normally occur before the struts at the first level are installed. During this stage of excavation, the rigidity of the wall contributes very little in reducing wall deflections. Once the struts at the first level are installed and preloaded, the wall will behave as a plate supported at its upper end and the rigidity of the wall starts to show its significance. In normal cases, the wall will bulge inward toward the pit in subsequent stages of excavation while the movements of the wall at each of the strut levels, once struts are preloaded, are mainly induced by the shortening of struts and are expected to be very small. Accordingly, it has been proposed to calibrate the readings based on the assumption that walls at a specific level, say, the first or the second level, will no longer move, or move inward by only small amounts, once the struts at this level are installed and preloaded (Hwang and Moh, 2007a, 2007b; Hwang *et al.*, 2007). The validity of this assumption is verified herein.

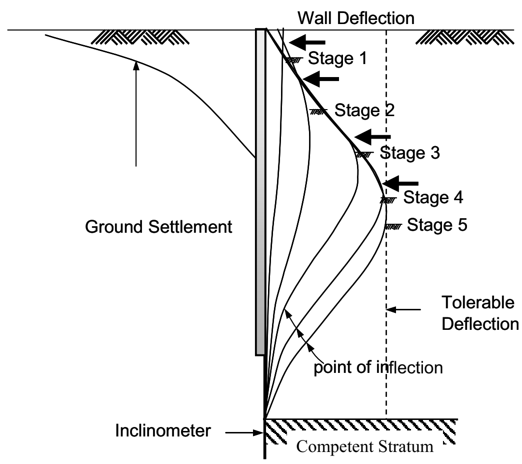

Fig. 1 Ideal profiles of wall deflections

2. GEOLOGY AND GROUND CONDITIONS IN THE TAIPEI BASIN

Three case histories are studied and the locations of the sites are shown in Fig. 2. Although one of them is located in the T2 zone while others are located in the TK2 zone of the Taipei Basin, these 3 sites are very close to each other and thus have quite similar ground conditions. Basically, the subsoils consist of the 6 sublayers commonly present in the Sungshan Formation. A typical CPT (cone penetration test) profile is given in Fig. 3 for the convenience of readers. As can be noted, the 6 sublayers in the Sungshan Formation are clearly identifiable. The properties of these sublayers have been well documented in literature. Readers are advised to refer to Woo and Moh, (1991), Lee (1996), and

Manuscript received April 9, 2007; revised May 29, 2007; accepted July 26, 2007.

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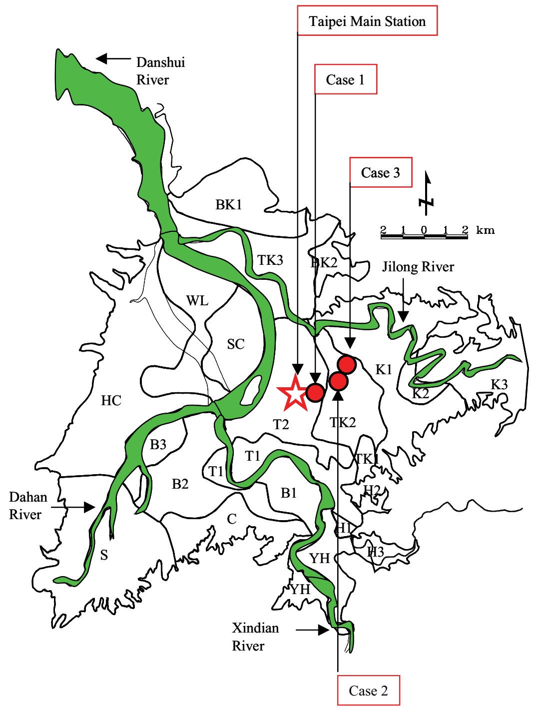


Geology Map: Lee, 1996

Fig. 2 Locations of the sites of the cases studied

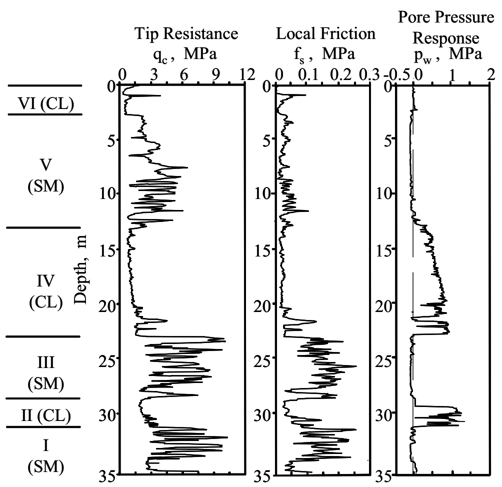


Fig. 3 Typical results of piezocone tests in the Sungshan Formation

Chin *et al*. (2006) for local geology and detailed information on the properties of various sublayers in the Sungshan Formation.

The Sungshan Formation is underlain by the Chingmei Gravels at depths varying from 40 m to 60 m in the T2 and TK2 zones. This gravelly layer consists of gravels, cobbles and boulders and is normally assumed to be a competent base stratum for anchoring diaphragm wall toes. This, however, is a major subject to be studied herein.

3. CASE 1: CALIBRATING WALL MOVEMENTS BY PERFORMANCE OF STRUTS

Inward movements of walls will lead to shortening of struts and increase in strut loads while outward movements of walls will result in lengthening of struts and reduction in strut loads. Therefore, the validity of aforementioned assumption can be verified by studying the performance of struts. Contrary to inclinometer readings which are usually reliable, strut loads are sensitive to construction activities and reliable readings are very difficult to obtain. A comprehensive monitoring program was carried out and data with an excellent quality were obtained during the construction of BL-8 Station (Shandao Temple Station) of the Taipei Rapid Transit Systems (Taipei Metro). It is thus possible to correlate wall deflections with shortening of struts.

Figure 4 shows a site plan for the station and the cut-and-cover section of tunnels to the east of the station. The station is 240 m in length and 21.5 m in width and the tunnel section is 150 m in length with the same width. Excavation was carried out for the station together with the tunnel section at the same time and was carried out to the final depth of 18.5 m in 7 stages as shown in Fig. 5. The pit was retained by diaphragm walls of 1000 mm in thickness and 30.5 m in length. The toes of the walls were embedded in Sublayer II which consists of clayey silts and silty clays with an average N-value of about 17 in Standard Penetration Tests (SPT). It is highly questionable that such materials would be sufficiently competent to resist toe movements of diaphragm walls.

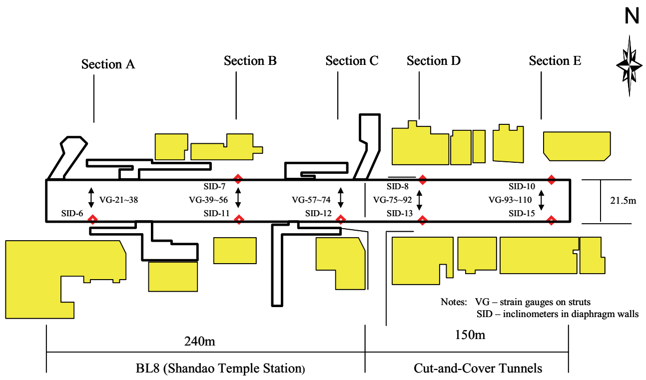


Fig. 4 Site plan and locations of instruments, Case 1

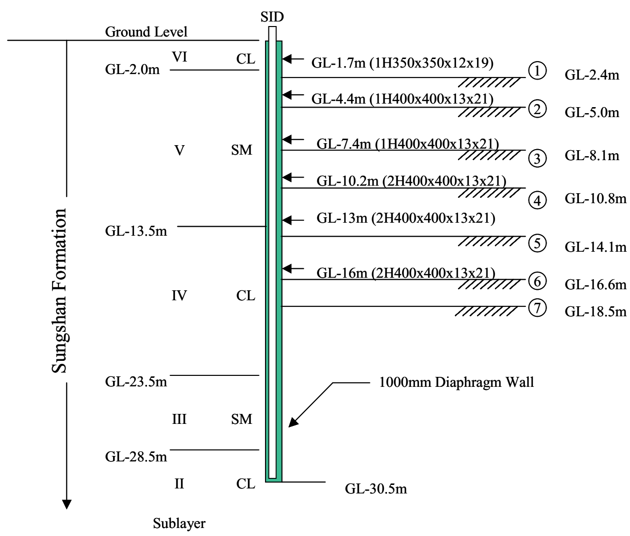


Fig. 5 Soil profile and retaining system, Case 1

3.1 Loads in Struts

Strain gauges were available in 5 sections for monitoring strut loads and Figs. 6 to 10 show the readings obtained for struts at the top 4 levels. The loads in all the struts in Section B, before and after preloading of struts at various levels, are listed in Table 1 for information. Also shown in the table are the maximum increases and reductions of loads in these struts after being preloaded.

Take Section B for example, refer to Fig. 7, the strut at the first level was preloaded to 22.8 tonnes at the end of the first stage of excavation. The load in this strut increased as excavation proceeded and reached 46 tonnes before the strut at the second level was preloaded. It dropped to 13 tonnes as a result of preloading of the strut at the second level. The influence of subsequent excavation and preloading of struts became smaller and smaller as excavation went deeper and deeper. The strut load dropped to its lowest value of –11.7 tonnes (negative value means tensions) at the end of the 5th stage of excavation before the strut at the 5th level was preloaded. The fact that tension was recorded is somewhat puzzling because struts and walings were not rigidly fixed to walls and, hence, tension was unlikely to occur in struts physically. However, such a phenomenon has been observed in a majority of records for struts at the first level and deserves explanations.

It is a normal practice to apply certain forces to jack struts against walings to close up gaps between struts and walings and gaps between walings and walls before preloading. Therefore, there were already loads in struts to start with and these loads were not included in readings. Although other possibilities cannot be ruled out, this does explain why tensions were recorded. The loads in the strut at the second level varied in a similar manner as those in the strut at the first level except that tension was not observed presumably due to the heavy preload.

The strut loads at the 1st, 2nd, and the 6th levels reached their maximums during excavation while those at the 3rd, 4th, and 5th levels reached their maximums when the immediately lower struts were removed for casting the permanent structures subsequent to the completion of excavation. The minimum loads were all recorded in the excavation stages.

Although the magnitudes were different, the strut loads in other sections varied in a similar manner and the maximum increases and maximum reductions of the loads observed in Section B can be considered typical not only in this case but in all excavations using the bottom-up methods of construction.

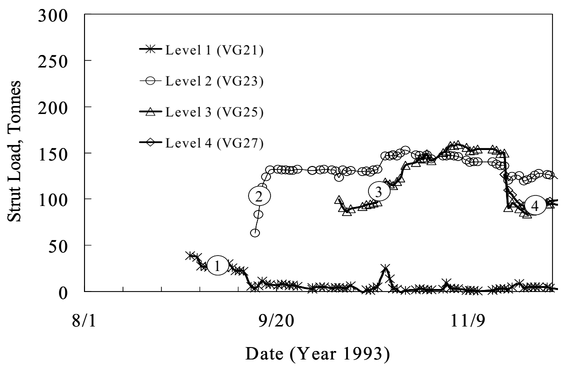


Fig. 6 Strut loads recorded in Section A, Case 1

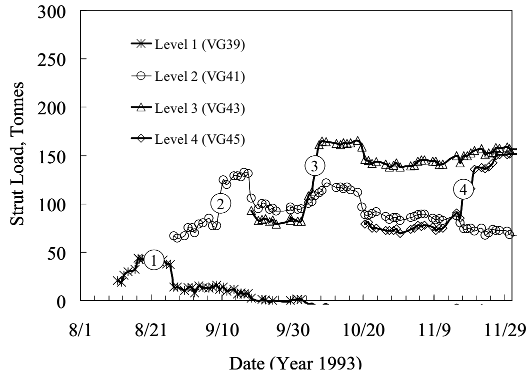


Fig. 7 Strut loads recorded in Section B, Case 1

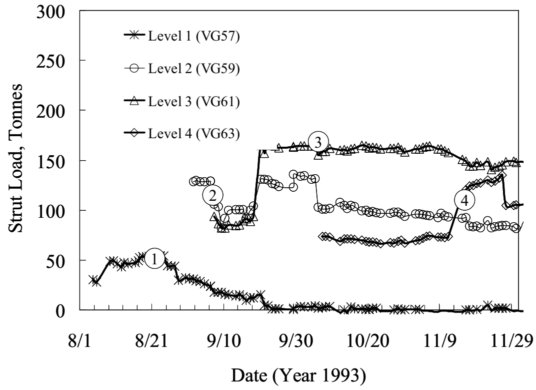


Fig. 8 Strut loads recorded in Section C, Case 1

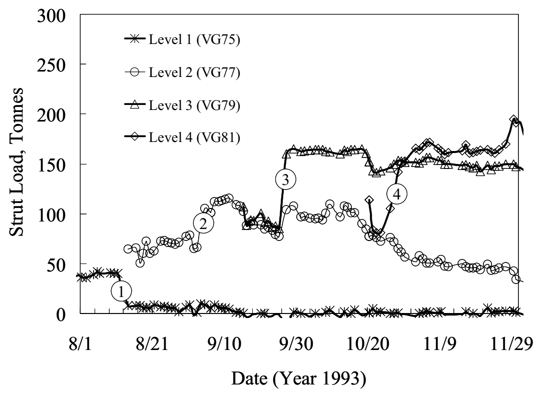


Fig. 9 Strut loads recorded in Section D, Case 1

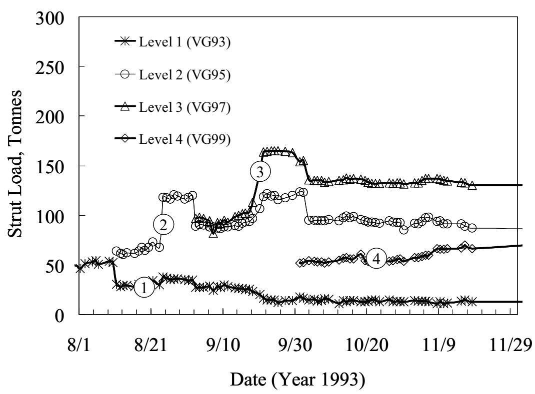


Fig. 10 Strut loads recorded in Section E, Case 1

Table 1 Loads in struts and changes in length of structural members, Section B, Case 1

	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Structural member	1H350 × 350 × 12 × 19	1H400 × 400 × 13 × 21	1H400 × 400 × 13 × 21	2H400 × 400 × 13 × 21	2H400 × 400 × 13 × 21	2H400 × 400 × 13 × 21
Sectional area (cm²)	1 × 173.9	1 × 218.7	1 × 218.7	2 × 218.7	2 × 218.7	2 × 218.7
	Strut loads during excavation (tonnes)					
Design load	84	164	212	440	336	432
Preloading Level 1 strut						
after	22.80					
Preloading Level 2 strut						
before	46.00					
after	13.00	66.40				
Preloading Level 3 strut						
before	15.90	132.10				
after	3.40	100.80	85.00			
Preloading Level 4 strut						
before	−11.20	124.70	164.80			
after	−7.40	92.3	145.60	76.40		
Preloading Level 5 strut						
before	−11.70	91.30	159.00	153.00		
after	−7.70	70.40	145.50	120.60	79.90	
Preloading Level 6 strut						
before	−10.10	70.80	146.10	138.10	124.20	
after	−7.30	58.50	132.30	125.50	130.00	90.10
Before casting base slab	−10.90	65.70	137.00	125.50	136.70	157.40
Maximum increase in load after preloading	23.2	65.7	79.8	76.6	56.8	67.3
Maximum reduction in load after preloading	−34.5	−7.9				
	Change in length of strut during excavation (mm)					
Maximum shortening after preloading	1.4	3.2	3.9	1.9	1.4	1.7
Maximum elongation after preloading	−2.1	−0.4				
	Strut loads during casting of structures (tonnes)					
After casting base slab	−7.80	67.90	135.70	117.60	132.40	136.50
After removing Level 6	−2.10	81.10	145.80	133.00	180.00	
After removing Level 5	−6.50	68.10	160.80	183.80		
After removing Level 4	−9.50	88.60	202.70			

3.2 Shortening of Struts and Corresponding Wall Movements

Struts were shortened as the loads in struts increased. Take the strut at Level 1 in Section B for example, the maximum increase in loads were 23.2 tonnes, corresponding to a shortening of the strut of only 1.4 mm for an E value (Young's Modulus) of 200,000 N/mm^2 and a length of strut of 21.5 m. Wall movements at the two ends of the strut subsequent to the preloading of this strut would be a half of these values, *i.e.*, less than 1 mm. Similarly, the shortening of the strut at the second level was 3.2 mm and the inward movements of the wall at the two ends would be about 1.6 mm after preloading. The maximum shortening of all the struts during excavation was 3.9 mm, occurring at the third level and corresponding to an inward movement of 2 mm after preloading of the strut at this level.

It is interesting to note that the load in the strut at the first level dropped below the preload at the end of excavation. This also happened to the strut at the second level. That means, the wall should move outward a little bit at these two levels at the end. However, the magnitudes of these outward movements were so small and it can be assumed that, for all practical purposes, the wall did not move at all once struts were preloaded.

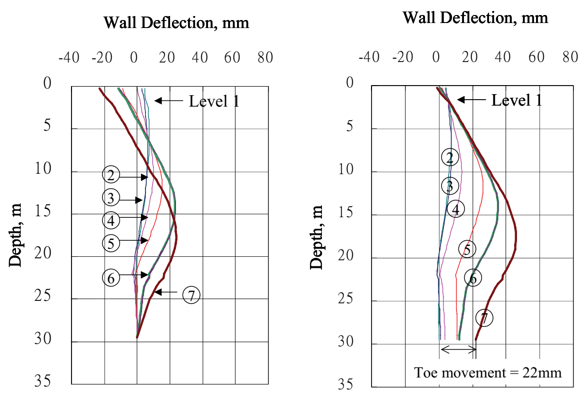
The fact that shortening of a strut will be minimal once the strut is preloaded can be proved by calculation without substantiation by observations. Take Grade 50 steel for example, the axial strain in struts is limited to 0.875×10^{-3} for an allowable stress of 0.5 f_y (f_y = yield stress = 350 N/mm^2) and an E value (Young's Modulus) of 200,000 N/mm^2. That means, the shortening of a strut is limited to 0.875 mm per meter of length if loaded to 100% of design load, or 0.44 mm per meter if already preloaded to 50% of design load. Therefore, the shortening of a strut of, say, 20 m in length will be limited to 9 mm if the strut has already been preloaded to 50% of its design load.

This example fully demonstrates the feasibility of calibrating inclinometer readings by assuming that the wall at the first strut level, and/or the second level, will no longer move, or will move by only a small amount once the strut is preloaded. It should be noted, however, shortening of struts is proportional to the lengths of struts. In this particular case, struts were only 21.5 m long while the struts for most basement excavations are much longer, say, 40 m to 100 m in length. Therefore, wall movements are expected to be somewhat larger, say, 10 mm or larger, for practical purposes, it will be appropriate to assume an increment of 1 mm to 2 mm per stage of excavation for long struts. After all, it is a small amount in comparison with wall deflections of many tens of millimeters in general cases.

3.3 Correcting Inclinometer Readings for Toe Movements

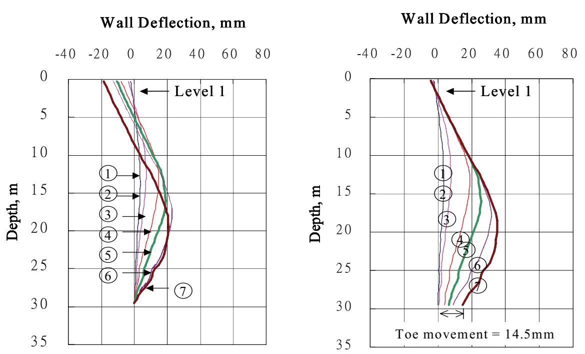
Incremental wall movements at the two ends of a strut will be a half of the changes in length of the strut. There were a total of 8 inclinometers for monitoring wall movements in these 5 sections and their locations are shown in Fig. 4. The readings obtained by inclinometers SID-7 and SID-11 installed in appositive walls in Section B are shown in Figs. 11(a) and 12(a) respectively. As can be noted from these two figures that the top of the walls moved outward by as much as 20 mm at the end of excavation in both cases. At the first strut level of 1.7 m below surface, the walls also moved outward by more than 15 mm subsequent to preloading of the strut in both cases. If these inclinometer readings were truly reliable, the strut at the first level would have been elongated by more than 30 mm. This certainly cannot be true. As depicted in Table 1 and as discussed in the preceding section, the changes in the length of the strut and the associated wall movements at the first level were really negligible for practical purposes. The controversy is doubtlessly due to movements of inclinometers at toes which were taken as reference points for calculating wall deflections at other depths.

It then becomes apparent that the connecting point where the strut jointed the wall was more stable than the toe of the inclinometer and can be used as the reference point instead. Figures 11(b) and 12(b) show the wall deflection profiles obtained by adjusting inclinometer readings so the wall movements at the first strut level were negligible subsequent to the preloading of the strut at this level. These profiles well resemble the ideal profiles shown in Fig. 1. The corrections made correspond to toe movements of inclinometer and were found to be as much as 22 mm for inclinometer SID-7 and 14.5 mm for inclinometer SID-11.



(a) before correction (b) after correction

Fig. 11 Wall deflection profiles, SID7, Case 1



(a) before correction (b) after correction

Fig. 12 Wall deflection profiles, SID11, Case 1

3.4 Progressive Toe Movements

The movements at the toes of all the 8 inclinometers in various stages of excavation are shown in Fig. 13. The final toe movements varied from 5 mm to 31 mm. The movements of inclinometers SID-10 and SID-15 were smaller than those of others because these two inclinometers were very close to the eastern wall which helped to reduce wall movements. Although inclinometer SID-6 was also located at the corner of the site, grouting was once carried out to stop leakage on the diaphragm wall at this location and presumably increased the toe movement of this inclinometer.

4. CASE 2: MOVEMENTS OF LONG INCLINOMETERS EMBEDDED IN GRAVELS

To further illustrate the application of the aforementioned approach, the inclinometer readings obtained in an excavation for constructing 6 highrise apartments, 2 in each of the 3 blocks shown in Fig. 14, were analyzed. The dimensions of the pits were

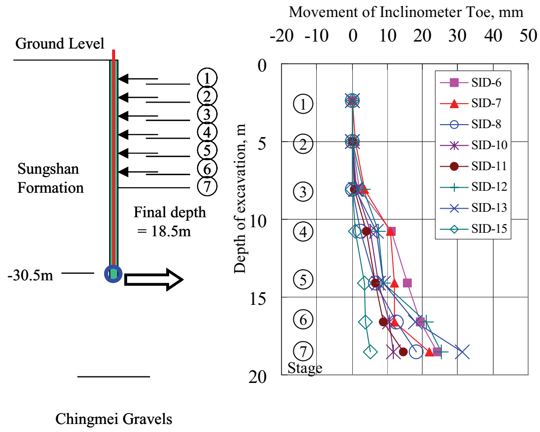


Fig. 13 Progressive toe movements of inclinometers, Case 1

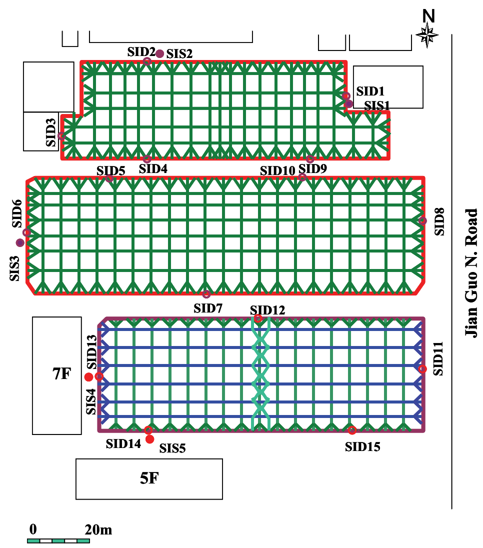


Fig. 14 Site plan and locations of inclinometers, Case 2

108 m by 33 m for the North Block, 132 m by 40 m for the Central Block and 109 m by 37 m for the South Block. Excavations were carried out to a depth of 17.5 m in 7 stages for constructing 4-level basements. All the 3 pits were retained by 900 mm diaphragm walls installed to a depth of 35 m as depicted in Fig. 15.

4.1 Original Wall Deflection Profiles

Wall deflections were monitored by 20 inclinometers at this site, of which 15 (SID-1 ~ SID-15) were installed in the wall panels and 5 (SIS1 ~ SIS5) were installed in soil immediately next to the walls to pair with those in the wall panels so the difference in performance can be studied. The readings obtained by Inclinometer SIS2 which was installed in soil next to the walls are shown in Fig. 16(a). Significant outward movements of walls, as much as 20 mm, were recorded at shallow depths in the 5^{th} stage of excavation and subsequently. As discussed in Case 1, outward movements of such a magnitude are unlikely to be realistic because of the lack of mechanism for this to happen in reality. It is thus believed that the toe of this inclinometers did move as excavation proceeded. As all of these inclinometers were installed to a predetermined depth of 52 m while the top of the Chingmei Formation was supposed to be at a depth of 51 m, the penetrations into the gravel layer were supposed to be 1 m. However, the penetrations were not confirmed during the installation and could be unachieved because of the erratic top of the Chingmei Formation.

Wall deflection profiles obtained by inclinometers SIS-3, 4, and 5 are similar to those shown in Fig. 16(a). However, the profiles obtained by inclinometer SIS-1 which was located at the northeastern corner of the site are somewhat different. As can be noted from Fig. 17(a), the readings obtained by Inclinometer SIS-1 do look reasonable with only progressive inward movements of reasonable magnitudes at the upper strut levels. The diaphragm wall at this corner retreated by 15 m or so therein and formed a Z-section as depicted in Fig. 14. The web of this Z-section in fact served as a cross wall and reduced wall deflections. This leads to the conclusion that the toe of this inclinometer did not move much. This situation is similar to that for inclinometers SID-10 and SID-15, of which the toe movements were much smaller in comparison with the toe movements elsewhere, in Case 1.

Figure 18(a) shows the readings obtained by inclinometer SID-2 and the profiles shown are typical for those inclinometers installed in diaphragm walls and stopped at the toes of the walls, *i.e.*, inclinometers SID1 ~ SID15. It is not surprising that outward movements were recorded near surface because large movements occurred at toes of the diaphragm walls.

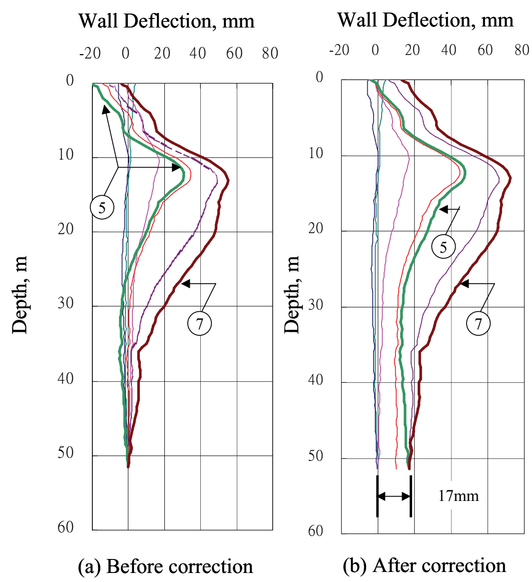


Fig. 16 Wall deflection profiles for inclinometer SIS-2, Case 2

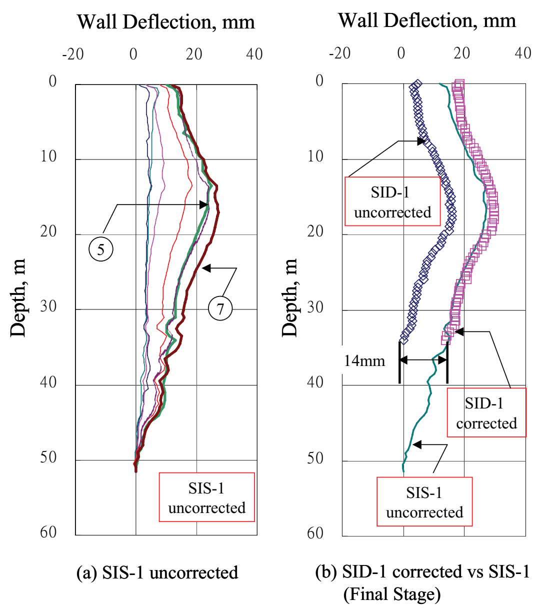


Fig. 17 Wall deflection profiles for inclinometers SIS-1 and SID-1, Case 2

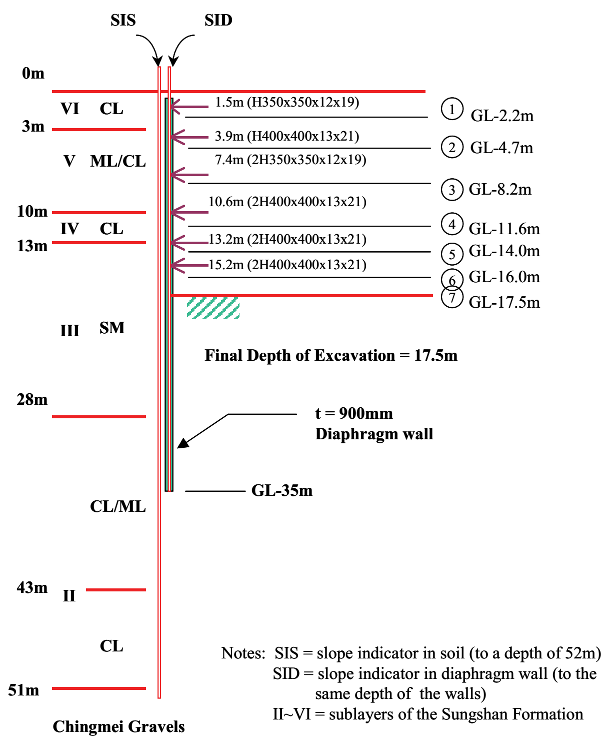
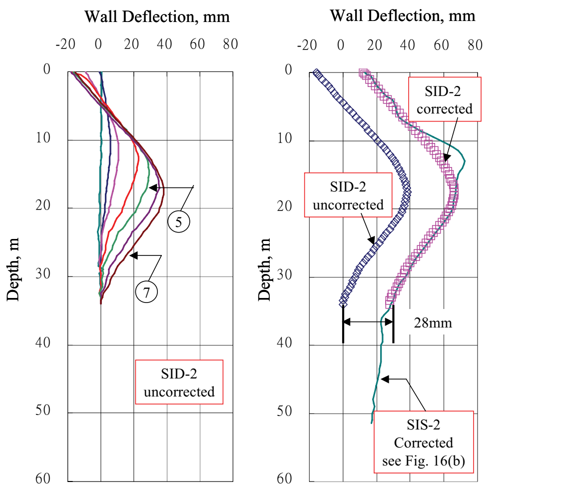


Fig. 15 Soil profile and retaining system, Case 2



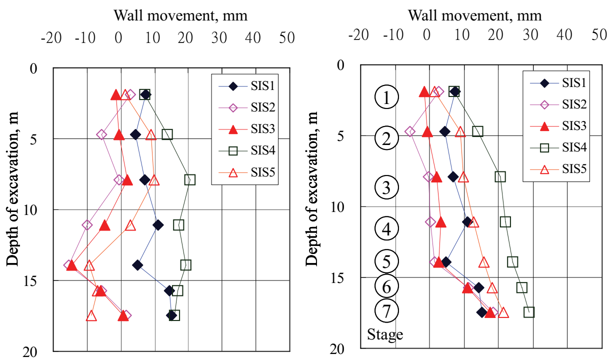
(a) SID-2 uncorrected readings (b) SID-2 vs SIS-2 (Final Stage)

Fig. 18 Comparison of wall deflection profiles for inclinometer SID-2 and SIS-2, Case 2

4.2 Progressive Wall Movements at the Upper Strut Levels

As mentioned above, the outward movements near surface obtained by inclinometers SIS-2, 3, 4, and 5 were unrealistic, presumably due to movements at the toes, and have to be corrected. Figure 19(a) shows the progressive movements of the walls at the first strut level, *i.e.*, at a depth of 1.5 m as depicted in Fig. 15, in various stages of excavation. As proposed in Section 3.3, adjustments are made to inclinometer readings so the plots of wall deflections versus depth of excavation become "increasing functions" with only positive increments (*i.e.*, inward movements) as shown in Fig. 19(b). The amounts adjusted correspond to toe movements of these inclinometers. Figures 20(a) and 20(b) show the wall deflections at the second strut level before and after corrections for toe movements respectively.

Although the excavation for the southern block lagged by 5 months to start, the three blocks can be considered together as a whole in the analyses because of the interaction effects. The entire excavation is then more than 100 m in length in both directions and, therefore, the shortening of struts is expected to be much larger than that for the struts in Case 1. As can be noted from Figs. 19(b) and 20(b), the wall movements were assumed to increase by 2 mm per stage of excavation subsequent to the preloading of these struts.



(a) before correction (b) after correction

Fig. 19 Progressive wall movements at the first strut level at a depth of 1.5 m, Case 2

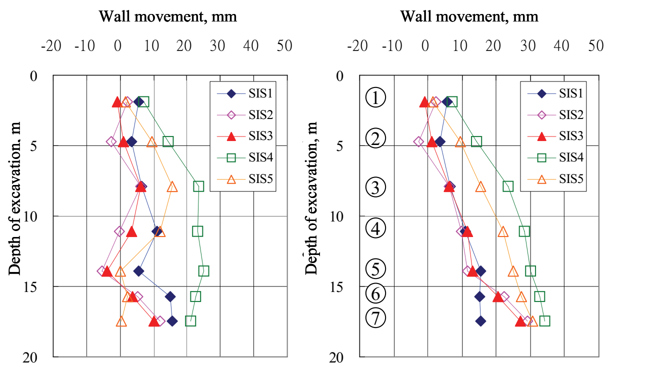
4.3 Progressive Wall Movements of Toes of Inclinometers

The toe movements of inclinometers are plotted against depth of excavation in Fig. 21. As can be noted, the toe movements in the final stage of excavation were 0 mm, 17 mm, 17 mm, 13 mm, and 30 mm for inclinometers SIS-1 to SIS-5, respectively. The fact that the toes of inclinometers moved by as much as 30 mm is rather amazing if they were indeed embedded in the Chingmei Gravels because diaphragm walls stopped at a level of 16 m above its top.

As mentioned above, the three blocks should be considered together as a whole because of the interaction effects and, therefore, the excavation was more than 100 m in length in both directions. As depicted in Fig. 22, the width of excavation exceeded 3 times of the distance between the bottom of excavation and the top of the Chingmei Gravels and the reduction in vertical stresses as a result of excavation must be sufficient for the Chingmei Gravels to deform laterally with noticeable magnitudes.

4.4 Wall Deflection Profiles after Correction

Figure 16(b) shows the wall deflection profiles for inclinometer SIS-2 with toe movements duly accounted for. The maximum deflection increases from 55 mm to 72 mm as a result of the correction. The profiles for inclinometer SIS-3, 4, and 5



(a) before correction (b) after correction

Fig. 20 Progressive wall movements at the second strut level at a depth of 3.9 m, Case 2

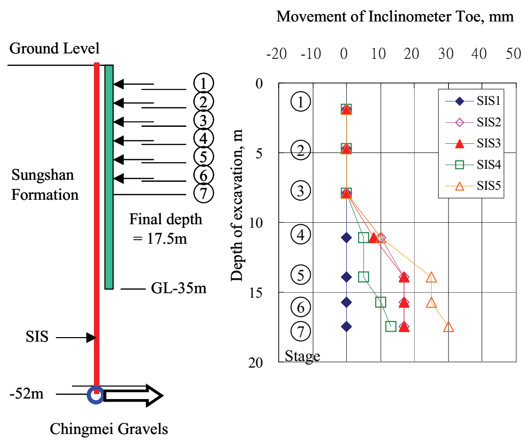


Fig. 21 Progressive movements at the toes of inclinometers at a depth of 52 m, Case 2

are quite similar in shape to what is shown in the figure. It is unnecessary to correct readings of SIS-1 because the toe did not move and Fig. 17(a) remains valid.

4.5 Progressive Movements at Toes of Diaphragm Walls

Since the SID series inclinometers stopped at the toe level of diaphragm walls, the readings obtained have to be corrected to account for the movements at this level. Figure 23 shows the progressive movements of the toes of the diaphragm walls at a depth of 35 m. The toe movements at the locations of SIS-2, 3, 4, and 5 ranged from 24 mm to 33 mm as the excavation reached its final depth. As can be noted, Fig. 23 is quite similar to Fig. 13 which is for movements of toes of diaphragm walls at a depth of 30.5 m. The wall movements at the location of SIS-1 were somewhat smaller because of the reasons which were already mentioned above.

The toe movements of diaphragm walls at various stages shown in Fig. 23 can be used to correct the readings obtained by those inclinometers installed in the diaphragm walls. Take inclinometers SID-1 and SID-2 for example, the toe movement in the final stage of excavation was about 14 mm at the locations of SIS-1 and SID-1 and 28 mm at the locations of inclinometers SIS-2 and SID-2. The readings obtained by inclinometers SID-1 and SID-2 were corrected accordingly and are compared with those obtained by SIS-1 and SIS-2 in Figs. 17(b) and 18(b). The two sets of readings appear to be very close.

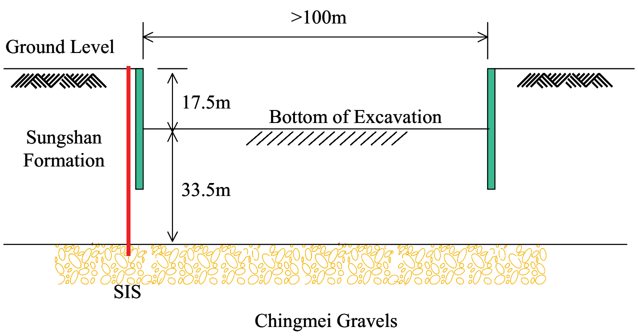


Fig. 22 Configuration of excavation, Case 2

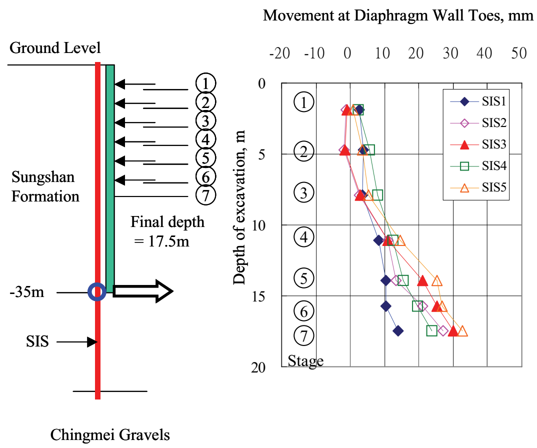


Fig. 23 Progressive wall movements at toes of diaphragm walls at a depth of 35 m, Case 2

5. CASE 3: PROBLEM WITH SHORT INCLINOMETERS

Figure 24 shows the plan for a commercial development constructed in 1998 and 1999 and Fig. 25 shows the soil profile and the retaining system. The site was about 33 m by 33 m in size and excavation was carried out in 4 stages to a maximum depth of 12 m by using the bottom-up method of construction. The pit was retained by 600 mm diaphragm walls installed to a depth of only 24 m. To protect the buildings to the north of the site, buttresses were installed to support the northern wall.

5.1 Original Wall Deflection Profiles

Wall deflections were monitored by 7 inclinometers, 3 in diaphragm walls and 4 in soils next to the walls. All the inclinometers stopped at the toe level of diaphragm walls. For illustration, Fig. 26 shows the original inclinometer readings obtained by inclinometers SIS-1, SIS-3, and SID-3. Considerable outward movements of the walls were recorded, presumably, due to toe movements. It is obvious that the readings have to be corrected before they can be meaningfully interpreted.

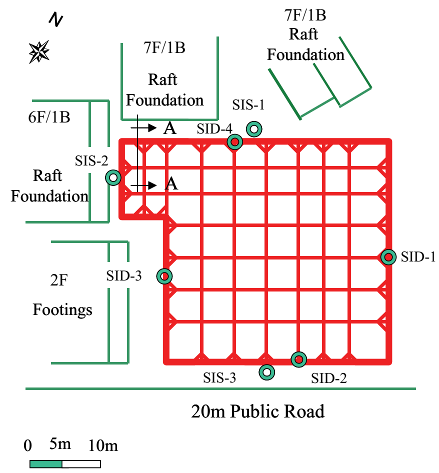


Fig. 24 Site plan and locations of inclinometers, Case 3

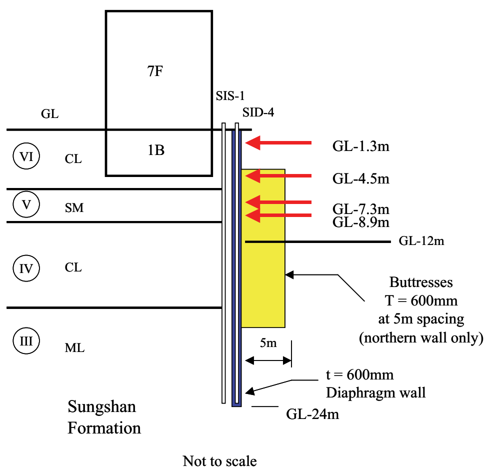


Fig. 25 Section A-A: Soil profile and retaining system, Case 3

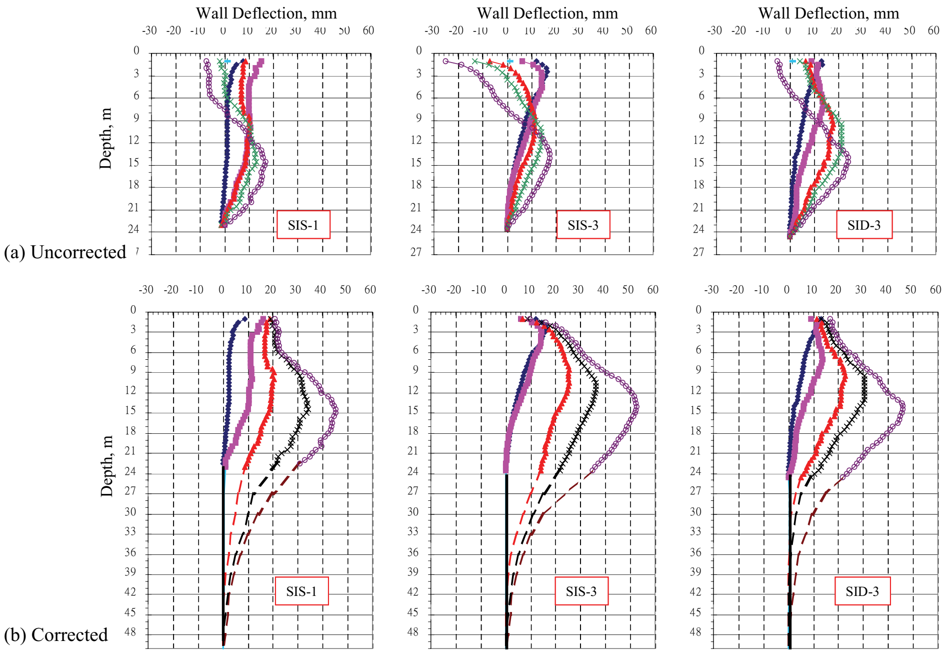


Fig. 26 Wall deflection profiles and ground movements beyond toe level, Case 3

5.2 Progressive Wall Movements at the First Strut Level

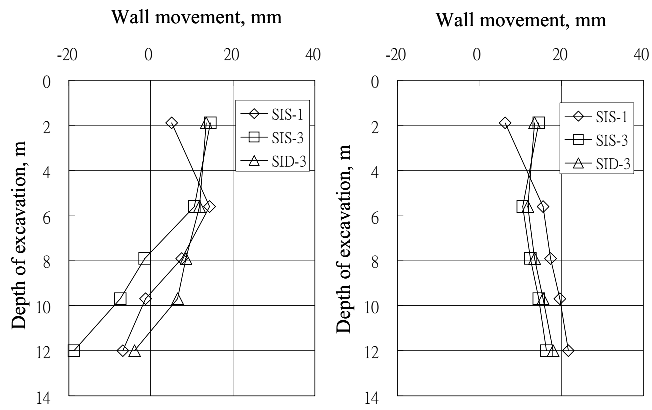
Figure 27(a) shows the progressive wall movements at the first strut level at a depth of 1.3 m and Fig. 27(b) shows the same with toe movements duly accounted for by following the procedure mentioned above. The struts were 33 m long and were longer than those in Case 1 (21.5 m) but shorter than those in Case 2 (more than 100 m), therefore, incremental wall movements subsequent to the preloading of the struts at the first level were assumed to be about 1 mm per stage of excavation as depicted in Fig. 27(b).

5.3 Progressive Movements at Toes of Diaphragm Walls

The differences between the two sets of readings shown in Fig. 27(a) and 27(b) correspond to the toe movements of diaphragm walls and are plotted versus depth of excavation in Fig. 28. As can be noted, toe movements ranged from 22 mm to 35 mm at the end as excavation reached a depth of 12 m.

5.4 Wall Deflection Profiles after Correction

The wall deflection profiles with corrections to account for toe movements are shown in Fig. 26(b). The lower portion of the profiles beyond the toe level were established by referring to the shapes of profiles shown in Figs. 1. Because of the lack of data, it is unsure whether or not there were ground movements in the Chingmei Gravels. According to Fig. 21, there could be ground movements of a few millimeters in this gravelly layer for a depth of excavation of 12 m despite the fact that the diaphragm walls stopped at a much higher level. However, this site (33 m by 33 m) is much smaller in size in comparison with that in Case 2 (more than 100 m in both direction) and ground movements in the Chingmei Gravels are thus expected to be negligible.



(a) before correction (b) after correction

Fig. 27 Wall deflections at the first strut level at a depth of 1.3 m, Case 3

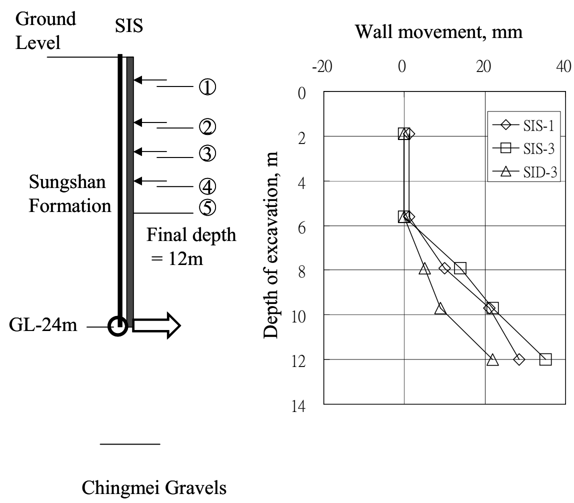


Fig. 28 Toe movement of diaphragm wall at a depth of 24 m, Case 3

As can be noted by comparing the profiles for inclinometer SIS-1, which is located in the section with buttress, with the profiles for inclinometer SIS-3, which is located in a section without buttresses, the reductions in wall deflections were not significant. This, however, is the subject of an on-going study and is beyond the scope of this paper.

6. DISCUSSIONS

More than often, inclinometers are installed in diaphragm walls and stop at the same depths as diaphragm walls. The readings obtained are inevitably affected by toe movements and have to be corrected if the toes of inclinometers are used as reference points for computing wall deflections. Short penetration into base strata which are presumed to be sufficiently competent to anchor the toes does not guarantee that the toes of inclinometers and/or diaphragm walls will not move.

If the movements of the top of inclinometer are monitored, the readings obtained at other depths can be calibrated accordingly. However, this is seldom the case. The procedure of correcting inclinometer readings obtained during excavations by assuming that walls at the two ends of a strut will no longer move or move by only small amounts once the strut is preloaded offers a viable solution to the problem and its validity and potential applications have been fully illustrated above.

Even in the design stage, the toes of diaphragm walls are also frequently assumed to be fixed for computing wall deflections. It is therefore desirable to establish procedures to estimate toe movements beforehand so designers can add these movements to the results obtained from their analyses.

Toe movements for walls with different lengths can be estimated by interpolating and extrapolating the three curves shown in Fig. 29 which was developed based on the information given in Figs. 13 (for 1000 mm walls to 30.5 m in Case 1), 23 (for 900 mm walls to 35 m in Case 2) and 28 (600 mm walls to 24 m in Case 3). Naturally, for the same depth of excavation, toe movements decrease as the lengths of walls increase. For example, toe movements for a 10 m excavation can be as much as 22 mm for walls of 24 m in length, reducing to 12 mm for walls of 30 m and 9 mm for walls of 35 m in length. For an excavation of 15 m, the toes of walls of 30 m in length will move as much as 25 mm while the toes of walls of 35 m will move 20 mm only. For such a depth of excavation in the T2 and TK2 zones, it will be inappropriate to adopt walls shorter than 30 m. As the thicknesses of walls usually go together with the lengths of walls, the former can be considered as an implicit factor and does not have to be considered in Fig. 29.

It should be noted that the three curves shown in Fig. 29 correspond to the upper curves in Figs. 13, 23, and 28 and it is thus sufficiently conservative to adopt these three curves in designs of walls in the T2 and TK2 zones of the Taipei Basin.

7. CONCLUSIONS

Based on the foregoing discussions, it is concluded that

(1) Movements of toes of inclinometers are inevitable even embedded in the Chingmei Gravels and inclinometer readings obtained by adopting the toes as reference points are likely to be misleading. The movements at the top of inclinometer casings should be monitored so readings can be calibrated accordingly.
(2) As an alternative, inclinometer readings can be calibrated by adopting the connections between the walls and struts at the first or the second levels as reference points.
(3) Wall movements at the connections at the first and the second strut levels can be assumed to be nil for short struts, say, 20 m or so in length, subsequent to the preloading of the struts. For long struts, say, longer than 60 m in length, wall movements of 2 mm per stage of excavation will be appropriate.
(4) For excavations using the bottom-up method of construction, Fig. 29 can be used to estimate movements at the toes of diaphragm walls in the T2 and TK2 zones of the Taipei Basin.

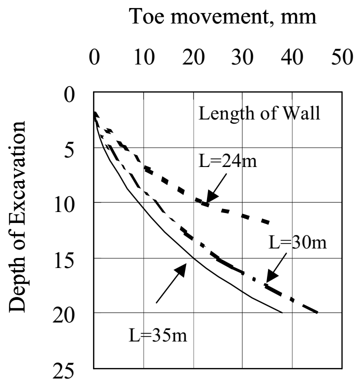


Fig. 29 Progressive movements of toes of diaphragm walls in the T2 and TK2 zones of the Taipei Basin

ACKNOWLEDGMENTS

The authors are grateful to Mr. Lup W. Wong for his review of the manuscript and many valuable suggestions. The permission from the Department of Rapid Transit Systems to publish the data presented herein is also appreciated.

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