PERFORMANCE OF FLOOR SLABS IN EXCAVATIONS USING TOP-DOWN METHOD OF CONSTRUCTION AND CORRECTION OF INCLINOMETER READINGS

Richard N. Hwang[1] and Za-Chieh Moh[2]

ABSTRACT

The performance of floor systems in two cases in which excavations were carried out using the top-down method of construction is compared and is correlated with the progressive movements of diaphragm walls at the top four floor levels. It has been found that the progressive movements of walls at the first floor level will be limited to 2 mm per stage subsequent to the casting of the slabs for typical basement excavations and, up to, 6 mm for very large sites with flexible floor systems. Inclinometer readings can be corrected by referencing to the movements at the top to make them reasonable.

Key words: Deep excavation, toe movement, top-down construction, floor slabs.

1. INTRODUCTION

Movements of walls are routinely monitored by using inclinometers during excavation. It is usually assumed that the toes of inclinometers will not move and wall movements at other depths are computed accordingly. However, readings frequently indicate outward movements in the upper portion of inclinometers in later stages of excavations. Except in rare cases, it is highly unlikely for diaphragm walls to move outward and the readings could well be erroneous due to movements at the toes of inclinometers.

For excavations using the bottom-up method of construction, wall movements are a result of shortening of struts and can be correlated with strut load measurements. Data indicate that the shortening of struts at the first and the second level is usually very small and toe movements of inclinometers can be back-calculated by assuming that the walls would not move at the first or the second strut level once the struts at these levels were preloaded. For very large sites, inward movements, say, up to, a couple of millimeters, can be allowed between consecutive stages of excavation as a result of shortening of long struts. Once toe movements are obtained, inclinometer readings at all other depths can be corrected accordingly. Figure 1 shows the potential lateral movements at the toes of diaphragm walls of different lengths in the T2, TK2, and K1 Zones of the Taipei basin back-analyzed by using this approach (Hwang *et al.* 2007a). For diaphragm walls of 35 m in length, for example, the toes could move by 20 mm if excavation is carried out to a depth of 15 m. Movements of such a magnitude will certainly affect the results of analyses and can not be overlooked.

For excavations using the top-down method of construction, diaphragm walls are propped by floor slabs in which the axial loads are not monitored. Attempts are made herein to study the performance of floor slabs based on wall movements to see if the above-mentioned procedures of correcting inclinometer readings are still applicable.

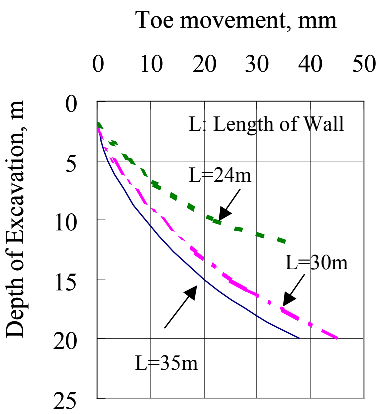

Fig. 1 Movements of toes of diaphragm walls in excavations using the bottom-up method of construction (after Hwang *et al.* 2007a)

The performance of floor slabs observed in two case histories is studied and correlated to the recorded wall movements. As shown in Fig. 2, although the two sites are located in two different geological zones, they are not too far away from each other and, hence, the ground conditions at these sites are quite similar. In Case 1, the movements at the top of inclinometers were monitored by precision survey and readings at other depths were calibrated accordingly. Therefore, the performance of floor slabs in this case is considered reliable and representative. On the other hand, the inclinometer readings in Case 2 had to be corrected to make the progressive movements of the diaphragm walls reasonable because movements at the top of inclinometers were not monitored. The performance of floor slabs is then compared with that in Case 1 to see if the corrections made are real.

2. CASE 1 – DEEP EXCAVATION IN THE TK2 ZONE

Construction for this 15-story hotel commenced in 1997 and the hotel was open for business in 1999. The site, as depicted in

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[1] Senior Vice President, corresponding author, Moh and Associates, Inc., Taipei, Taiwan, R.O.C. (email: richard.hwang@maaconsultants.com)
[2] President, Moh and Associates, Inc., Taipei, Taiwan, R.O.C.

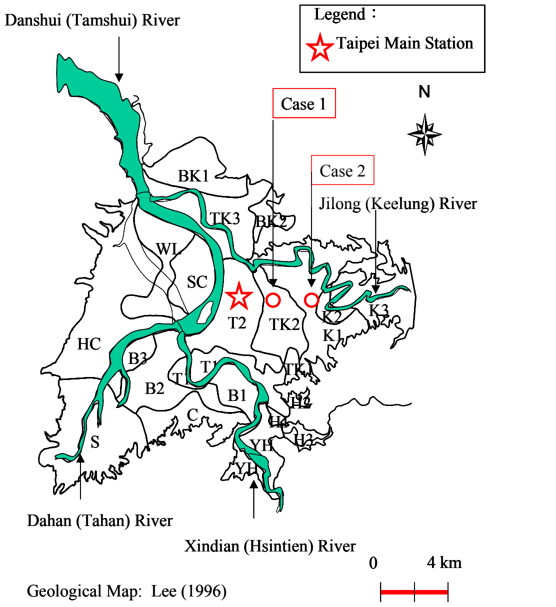


Fig. 2 Geological zoning map of the Taipei basin and locations of the sites

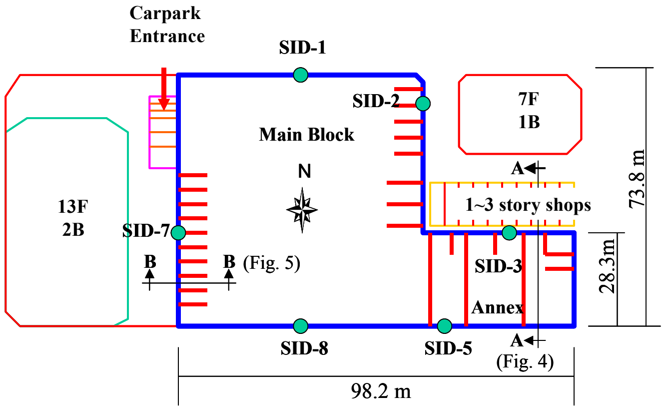
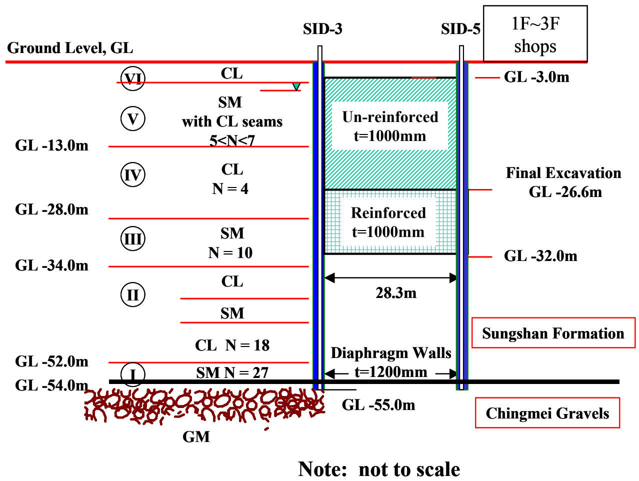
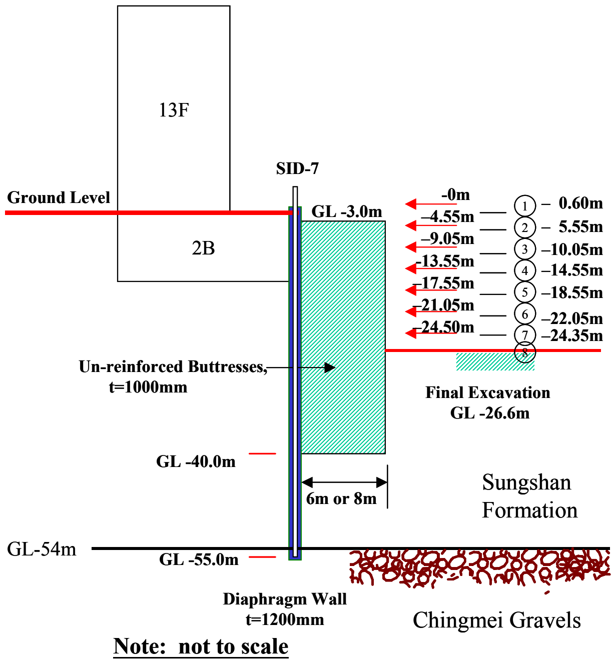


Fig. 3 Site plan and locations of inclinometers, Case 1



Section A-A (Fig. 3)

Fig. 4 Ground conditions and configuration of cross walls, Case 1



Section B-B (Fig. 3)

Fig. 5 Sequence of excavation and configuration of buttresses, Case 1

Fig. 3, has a L-shape with an annex attached to the east of the main block and is about 74 m in the north-south direction and 98 m in the east-west direction. It is located in the TK2 Zone of the Taipei basin. At the surface is the so called Sungshan Formation which consists of 6 alternating sublayers of silty sand and silty clay as depicted in Fig. 4. The excavation for the 7-level basement was carried out to a maximum depth of 26.6 m in 8 stages by using the top-down method of construction. Diaphragm walls of 1200 mm in thickness were used and were braced by floor slabs. All the walls extended to a depth of 55 m and, theoretically, penetrated into the Chingmei Gravels by 1 m. The penetrations, however, were not confirmed during installation of individual panels.

There were buildings on the east and west of the site and buttresses were used to reduce the movements of walls as a building protection measure. The configuration of the buttresses is given in Fig. 5. There were a few shops to the north of the annex. Therefore, in addition to buttresses, three cross walls were added to further reduce wall movements as depicted in Fig. 3 and their configuration is shown in Fig. 4. The buttresses and cross walls were all 1000 mm in thickness and were cast using concrete with a compressive strength of 14 N/mm^2.

2.1 Inclinometer Readings and Wall Deflection Profiles

There were 6 inclinometers installed inside the diaphragm wall panels for monitoring wall movements. Because the lower portion of some of the inclinometers, namely, inclinometers SID-2, SID-3, SID-5, and SID-7, were damaged and readings could not be taken, the movements of the top of all the inclinometers were measured by survey and wall movements at other depths were calibrated accordingly. Figure 6 shows the wall movements recorded by inclinometers SID-1 and SID-8 which were installed in the northern and the southern walls of the main block respectively. The readings of these two inclinometers were not affected by buttresses or cross walls.

The readings of inclinometers installed in walls with buttresses and cross walls are shown in Figs. 7 and 8. The maximum

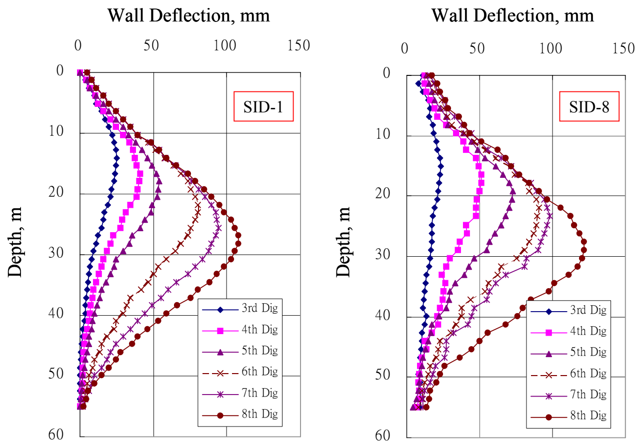


Fig. 6 Deflections of walls without buttresses, Case 1

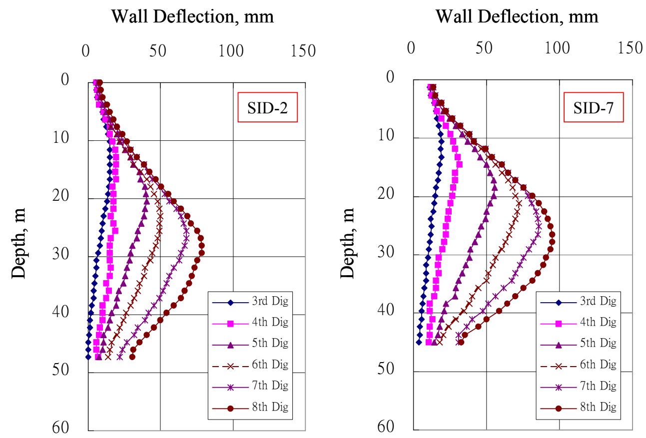


Fig. 7 Deflections of walls with buttresses, Case 1

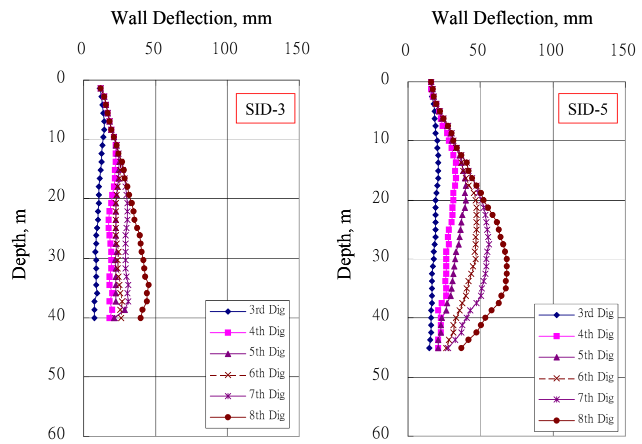


Fig. 8 Deflections of walls with buttresses and cross walls, Case 1

movements of walls with and without buttresses/cross walls are compared in Table 1. As can be noted, cross walls were very effective in reducing wall movements while buttresses appear to be much less effective in comparison. The influences of cross walls on wall movements and contractions of floor slabs will be further discussed in Section 2.3.

Table 1 Maximum wall movements, Case 1

	Maximum wall movements, mm			Notes
	Inclinometer	Max.	Ave.	
Main block (N&S walls)	SID-1	108.0	114.8	Flat walls
	SID-8	121.6		
Main block (E&W walls)	SID-2	78.5	86.8	With buttresses
	SID-7	95.0		
Annex (N&S walls)	SID-3	39.6	54.1	With buttresses and cross walls
	SID-5	68.5		

2.2 Progressive Wall Movements at Floor Levels

The movements of the northern and the southern walls at the top four floor levels are plotted versus depth of excavation in Fig. 9. As can be noted, they increased progressively as excavation proceeded. For convenience, wall movements at a certain floor level are classified as follows:

Phase 1: before the casting of the floor slab at the first level

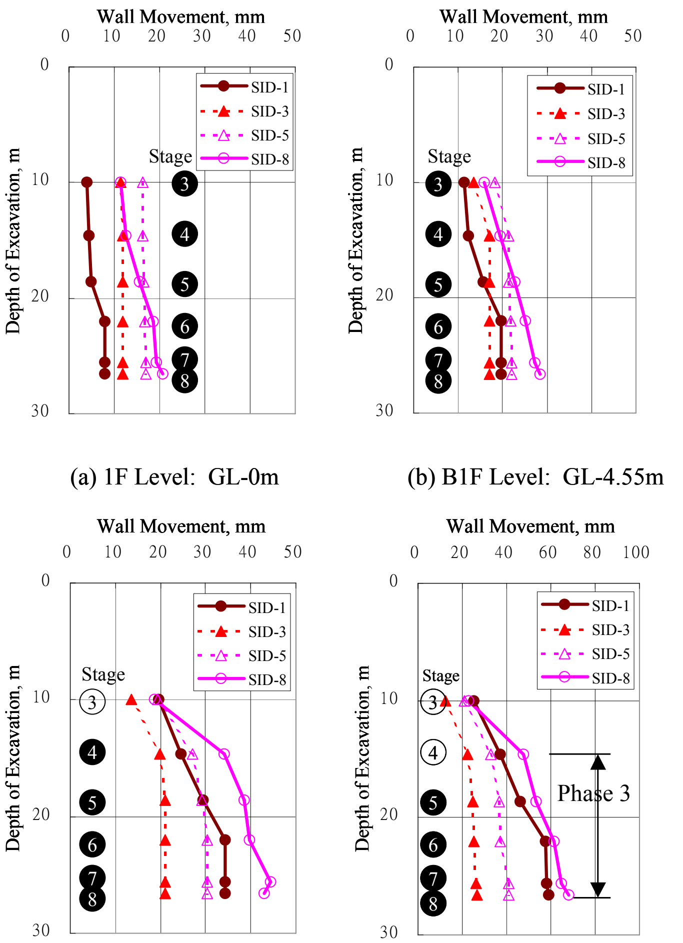
Phase 2: before the casting of the floor slab at this level

Phase 3: after the casting of the floor slab at this level

and the corresponding excavations are referred to as Phase 1, Phase 2 and Phase 3 excavations respectively. Contractions of floor slabs occurred only in Phase 3 excavations which are identified by solid discs with white stage numbers in Fig. 9. Take the B3F level for example, the floor slab was cast after the Stage 4 excavation to a depth of 14.55 m below ground surface, therefore, Phase 3 excavation started from this depth and ended at the formation level and the total thickness of excavation is 26.6 – 14.55 = 13.05 m in this phase.

In Phase 1 excavation, the active earthpressures on the outer face of the walls are resisted by the passive pressures on the inner face of the walls and the walls essentially behave as cantilevers. The wall movements are governed by ground conditions and have little to do with the stiffness of the walls and nothing to do with the configuration of floor slabs because they have not been cast. In Phase 2 excavation, as illustrated in Fig. 10, the active earthpressures are resisted by floor slabs which have already been cast and also by the soil plug below the bottom of excavation. As excavation proceeds further, a block of soil immediately below the bottom is removed and the passive resistance offered by this block no longer exists. The deficit in passive resistance has to be made up by increases in the axial loads in the floor slabs and the increases in passive resistance in the remaining soil plug. Wall movements are caused primarily by the bending of the wall and, to a much less degree, by the contractions of the floor slabs at the upper levels. In Phase 3 excavation, wall movements are caused primarily by the contraction of the floor slab at the corresponding level.

The movements of the northern and the southern walls at the top four levels are summarized in Table 2. Because inclinometer readings for Stage 1 excavation are unavailable, Phase 1 wall movements cannot be identified. Since wall movements are strongly dependent on depth of excavation, analyses will be much simpler if they are normalized to the depth of excavation to obtain the rate of increase for each meter of excavation. The rates of Phase 3 wall movements are summarized in Table 3. They are in fact the inverse of the slopes of the lines shown in Fig. 9.



(a) 1F Level: GL-0m (b) B1F Level: GL-4.55m

(c) B2F Level: GL-9.05m (d) B3F Level: GL-13.55m

Fig. 9 Progressive wall movements at upper floor levels, Case 1

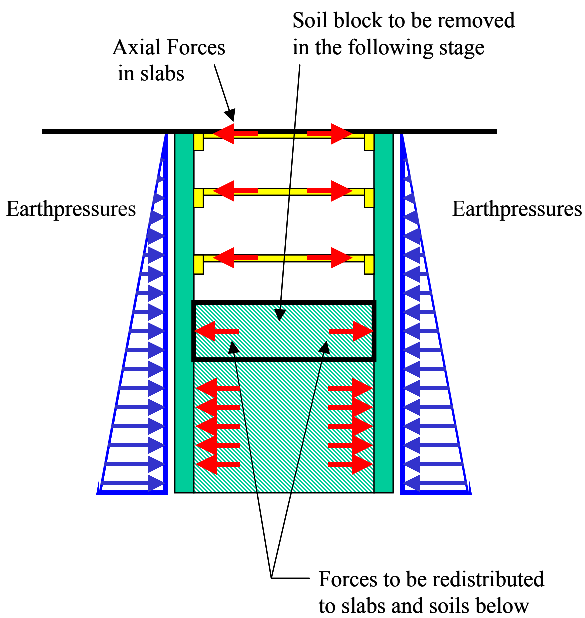


Fig. 10 Mechanism of redistribution of passive resistance

Table 2 Movements of northern and southern walls in different phases, Case 1

	Net wall movements, mm			
	Main block		Annex	
	SID-1	SID-8	SID-3	SID-5
1F level				
Phase 1&2	3.93	11.40	11.30	16.21
Phase 3	3.92	9.40	0.57	0.78
Total	7.85	20.80	11.87	16.99
B1F level				
Phase 1&2	11.30	15.91	13.57	18.30
Phase 3	8.30	12.50	3.39	3.66
Total	19.60	28.41	16.96	21.96
B2F level				
Phase 1&2	19.64	18.75	13.57	19.35
Phase 3	14.72	24.20	7.34	10.98
Total	34.36	42.95	20.91	30.33
B3F level				
Phase 1&2	37.31	47.73	22.61	32.94
Phase 3	21.60	20.45	3.96	7.84
Total	58.91	68.18	26.57	40.78

The progressive wall movements at the 1F level are of primary interest for the purpose of this study and were 0.237 mm and 0.568 mm for each meter of excavation for inclinometers SID-1 and SID-8, respectively. Accordingly, it can be expected that the top of diaphragm walls will move by 1 mm to 2 mm for each stage of excavation with a typical depth of excavation of 4 m per stage. These magnitudes can be used as a guide for calibrating inclinometer readings in excavations using the top-down method of construction to account for toe movements, if any. The extremely low rates obtained for the annex at the 1F level are considered exceptional and non-representative.

2.3 Performance of Floor Slabs

Contraction of a slab is a result of increasing axial loads in the slab and is proportional to the span of the slab and inversely proportional to the axial stiffness of the slab. Although reinforced concrete slabs are very stiff, however, there are always openings in slabs for handling materials and equipment. As a result, the overall stiffness of the floor system is much reduced. The configuration of the floor system in the case studied is unavailable and therefore the stiffness of the floor system cannot be estimated. For practical purpose, it can be assumed that the configuration of the floor system in this case is "typical" for excavations using the top-down method of construction.

Contractions of slabs are equal to the relative wall movements at the two ends of the slabs in the Phase 3 excavations. The contractions of the top four floor slabs, *ie.,* the sums of Phase 3 wall movements at the two ends of the slabs shown in Table 2, are summarized in Table 4. They are also plotted versus depth of excavation in Fig. 11. Because the inclinometer readings for Stages 1 and 2 excavations are unavailable, the contractions of the 1F and B1F floor slabs are underestimated. However, the errors are believed to be insignificant for practical purposes.

Table 3 Rates of Phase 3 wall movements, Case 1

		Rates of increases per meter of excavation, mm/m		
		SID-1	SID-8	Average
Main block	1F level	0.237	0.568	0.402
	B1F level	0.504	0.755	0.630
	B2F level	0.887	1.458	1.172
	B3F level	1.800	1.704	1.752
Annex		SID-3	SID-5	Average
	1F level	0.034	0.047	0.041
	B1F level	0.205	0.221	0.213
	B2F level	0.442	0.661	0.552
	B3F level	0.330	0.653	0.492

Table 4 Contractions of floor slabs, Case 1

	Main block		Annex	
	Contraction, mm	Axial strain, mm/m	Contraction, mm	Axial strain, mm/m
1F slab	13.32	0.18	1.35	0.05
B1F slab	20.85	0.28	7.05	0.25
B2F slab	38.93	0.53	18.33	0.65
B3F slab	42.05	0.57	11.80	0.42

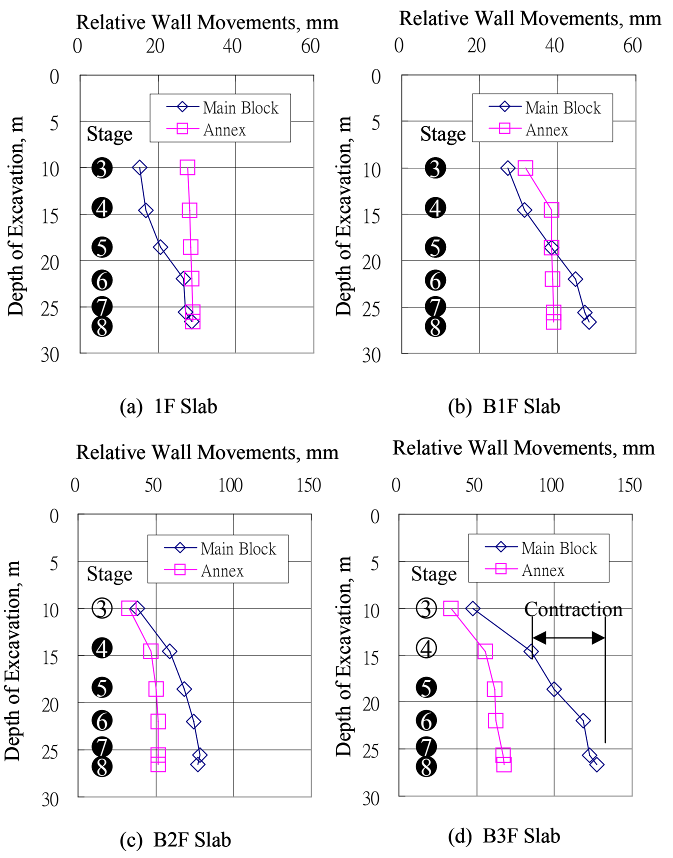


Fig. 11 Relative wall movements and contractions of floor slabs, Case 1

As can be noted from Table 4, the contractions of floor slabs in the main block varied from 13.32 mm to 42.05 mm and those in the annex varied from 1.35 mm to 18.33 mm. Except in the 1F slab, the axial strains in the slabs were about the same for the main block and for the annex. This indicates that the loads in the slabs were of the same order and the reductions in the contractions of the slabs in the annex were due to the shorter spans of the slabs, not a result of reduction of loads in slabs due to the presence of cross walls. This is logical because as the cross walls were demolished, all the earth pressures had to be taken by the floor slabs anyway. In the case studied, the cross walls did go below the formation level, therefore, the loads in the slabs at lower levels are expected to be somewhat reduced by the presence of the cross walls which essentially served as buried struts even at the end of excavation and should take some loads away from these slabs.

2.4 Performance of Cross Walls

In the case studied, the cross walls extended from a depth of 3 m below ground surface to a depth of 32 m as depicted in Fig. 4. At a depth of 30 m below surface, for example, inclinometer SID-3 indicated a wall movement of 41 mm at the end of excavation and inclinometer SID-5 indicated a wall movement of 68 mm as depicted in Fig. 8, giving a relative movement of 109 mm which corresponds to an axial strain of 0.39% in the cross walls for a span of 28.3 m. This axial strain could have exceeded the strains corresponding to the peak strengths of low-strength concrete. This implies that the cross walls could have failed structurally and became ineffective in the later stages of excavation. It should be noted, however, these cross walls were cast against diaphragm walls. Although the joints were treated by using the CCP technique, there is no way to ensure that the contacts between the cross walls and the diaphragm walls were solid. The closure of gaps at these joints, if any, could partially contribute to the large wall movements observed.

3. CASE 2 – DEEP EXCAVATION IN THE K1 ZONE

Construction for this 12-story shopping mall commenced in 1998 and the mall was open for business in 2001. The excavation for the 7-level basement was carried out to a maximum depth of 31.68 m in 9 stages, as depicted in Fig. 13, by using the top-down construction method. The pit was retained by diaphragm walls of 1500 mm in thickness installed to a depth of 52 m. As depicted in Figs. 12 and 14, buttresses were used to reduce the movements of walls, hence, ground settlements which were potentially damaging to adjacent buildings.

3.1 Inclinometer Readings

There were 6 inclinometers installed in diaphragm wall panels for monitoring the movements of the walls. The readings obtained by inclinometers SID-5 and SID-8 are given in Figs. 15 and 16, respectively. The upper portion of these two inclinometer, as indicated by the readings, moved outward significantly subsequent to the 5^{th} dig. The progressive wall movements at the top four levels are plotted versus depth of excavation in Figs. 17 and 18 and the trend of outward movements is more evident.

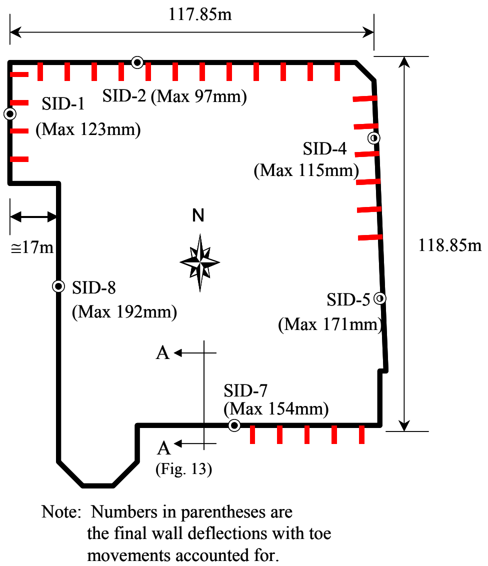


Fig. 12 Site plan and locations of inclinometers, Case 2

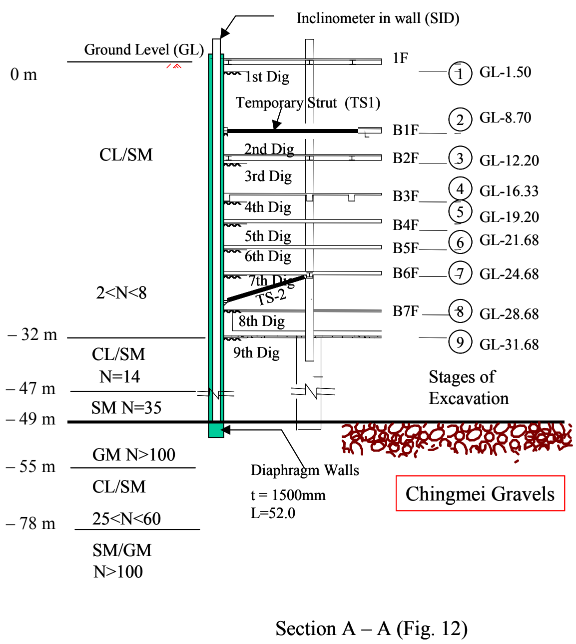


Fig. 13 Excavation sequence and retaining system, Case 2

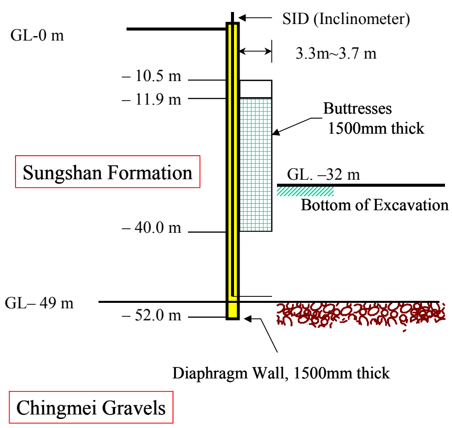


Fig. 14 Configuration of buttresses, Case 2

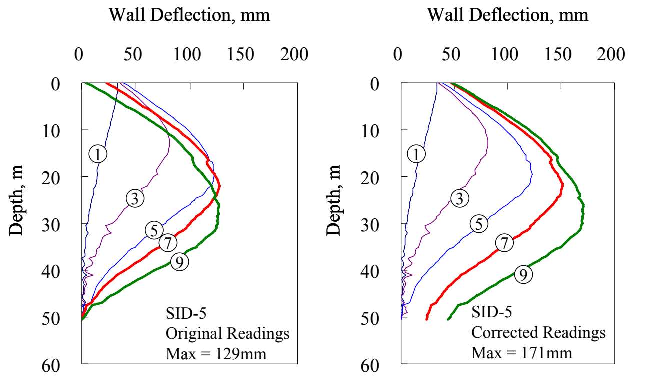


Fig. 15 Readings and corrections to readings, inclinometer SID-5, Case 2

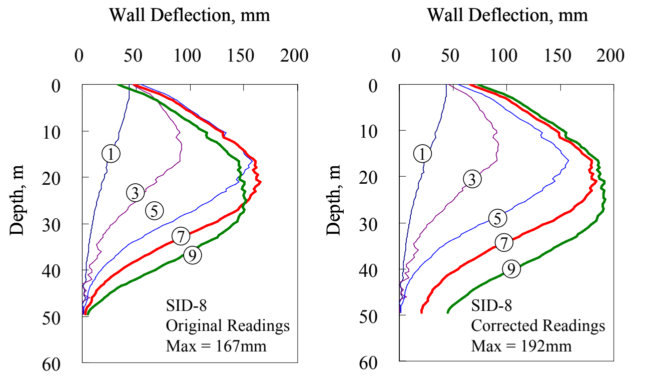


Fig. 16 Readings and corrections to readings, inclinometer SID-8, Case 2

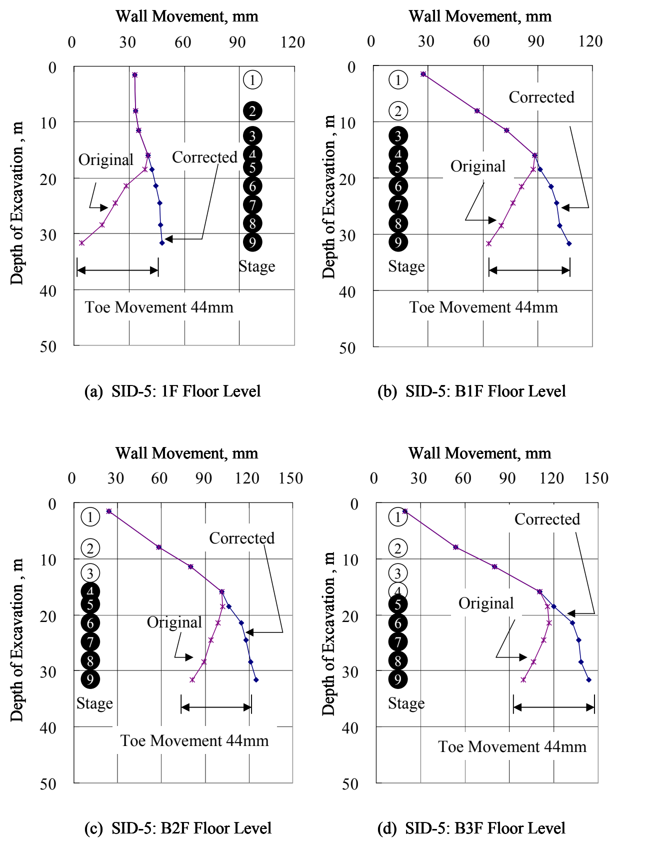


Fig. 17 Progressive wall movements and corrections of readings, inclinometer SID-5, Case 2

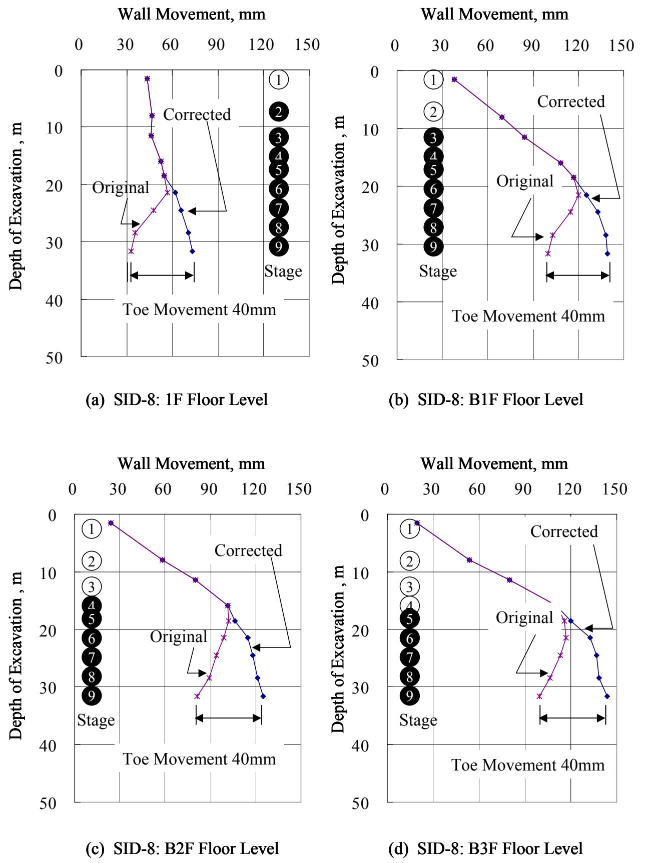


Fig. 18 Progressive wall movements and corrections of readings, inclinometer SID-8, Case 2

3.2 Corrections of Inclinometer Readings for Toe Movements

The curves corresponding to the original inclinometer readings shown in Figs. 17 and 18 are drastically different from what is shown in Fig. 9. The outward movements of the walls subsequent to Stage 5 excavation, as indicated by the readings, must be due to movements of the toes of the inclinometers. Although the toes of the diaphragm walls were supposed to penetrate into the Chingmei Gravels by, theoretically, 3m as depicted in Fig. 13, the penetrations were not confirmed during the installation of individual panels. Furthermore, even if the diaphragm walls indeed penetrated into the Chingmei Gravels by a few meters, toe movements were necessary for the passive resistance to develop. As depicted in Figs. 17 and 18, corrections of, up to, 44 mm and 40 mm have to be made to the readings for inclinometers SID-5 and SID-8, respectively, to make the curves look reasonable (Hwang *et al.* 2007b). These corrections correspond to the movements at the toes of these inclinometers. The progressive toe movements of all the inclinometers are shown in Fig. 19 and the final toe movements varied from 33 mm (for SID-1) to 45 mm (for SID-4). Toe movements of such magnitudes certainly should not be overlooked. As can be noted in Fig. 16, the maximum wall movements at the location of inclinometer SID-5 should be 171 mm after corrections instead of 129 mm as indicated by the original data. Similarly, the maximum wall movement at the location of SID-8 should be 192 mm instead of 162 mm. The differences are significant enough to affect the results of studies, such as estimation of ground settlements associated with wall deflections and soil-structural interaction analyses. It should be noted, however, the deformed shapes of the walls are not affected because the profiles, before and after the calibration, are parallel to each other.

3.3 Progressive Wall Movements

The wall movements in different phases are summarized in Table 5 and the rates of progressive wall movements at the top four floor levels in Phase 3 excavations are summarized in Table 6. As can be noted, the average rates of movements in the two directions are of the same order of magnitude. Since the spans of slabs in the two directions are also about the same, the finding appears to be reasonable.

3.4 Contractions of Floor Slabs

Although the progressive wall movements appear to be reasonable, whether or not the corrections made to the inclinometer readings are real still has to be verified by studying the performance of floor slabs. Figures 20 and 21 show the relative movements of inclinometers installed in the opposite walls and they were, in fact, contractions of floor slabs in the east-west and the north-south directions, respectively. As can be noted from Figs. 20(a) and 21(a), the slab at the 1F level would have been in tension in both directions at the end of excavation if corrections were not made. The trends of increasing wall movements with depth of excavation become quite similar to those for the main block shown in Fig. 11 after corrections are made. This validates the approach adopted for correcting inclinometer readings.

3.5 Effects of Buttresses on Contractions of Slabs

As can be noted from Fig. 12, the performance of inclinometers SID-2 and SID-7 was obviously influenced by the presence of buttresses while the performance of inclinometers SID-5 and SID-8 was less influenced. It will then be interesting to see how much the influence was on the contractions of the floor slabs. The contractions of the floor slabs, *i.e.*, the sums of the Phase 3 wall movements shown in Table 5, at the top four floor levels are summarized in Table 7. As can be noted, except for the 1F level, the differences in contractions of slabs in the two directions are within 20% which is not large enough to prove the significance of the influences of the buttresses. Although these buttresses were cast together with the diaphragm walls to form T-sections, they only increased the flexural stiffness of the walls and would not take any horizontal loads. All the earthpressures acting on the walls had to be resisted by floor slabs, therefore, the loads in the floor slabs were not significantly affected by the presence of these buttresses.

4. DISCUSSIONS

4.1 Progressive Wall Movements at the 1F Floor Level

The rates of increases in Phase 3 wall movements at the 1F levels in the two cases are compared in Table 8. For the results of the study to be generalized, also shown in the table are the rates obtained in a case which was originally presented in Ou *et al.* (2006) and was re-analyzed in Hwang *et al.* (2007). This case is quite similar to Case 2 in that they both were located in the K1

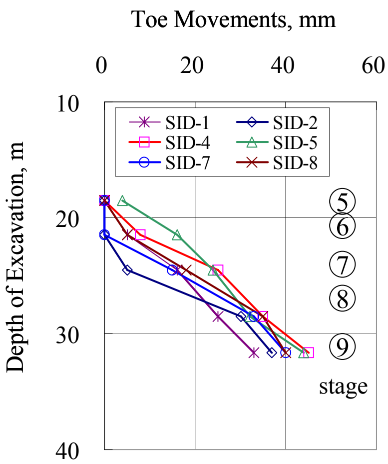


Fig. 19 Estimated movements of toes of inclinometers, Case 2 (after Hwang *et al.* 2007b)

Table 5 Movements of the northern and southern walls in different phases, Case 2

	Wall movements, mm			
	E-W direction		N-S direction	
	SID-5	SID-8	SID-2	SID-7
1F level				
Phase 1	33.21	43.69	23.81	30.68
Phase 2				
Phase 3	14.83	29.35	15.65	45.25
Total	48.04	73.04	39.46	75.93
B1F level				
Phase 1	27.31	37.79	19.51	27.77
Phase 2	29.61	31.42	19.82	17.43
Phase 3	50.08	70.36	36.59	65.14
Total	107.00	139.57	75.92	110.34
B2F level				
Phase 1	23.43	33.76	17.59	24.36
Phase 2	57.26	53.28	36.80	31.68
Phase 3	47.83	68.70	33.58	67.41
Total	128.52	155.74	87.97	123.45
B3F level				
Phase 1	17.08	25.22	16.88	21.05
Phase 2	91.92	109.72	52.02	58.83
Phase 3	37.66	47.41	26.94	57.53
Total	146.66	182.35	95.84	137.41

Table 6 Rates of Phase 3 wall movements, Case 2

		Excavation to final depth, m	Rates of increases per meter of excavation, mm/m		
E-W direction			SID-5	SID-8	Average
	1F level	26.65	0.49	0.97	0.73
	B1F level	22.98	2.18	3.06	2.62
	B2F level	19.48	2.46	3.53	2.99
	B3F level	19.40	2.45	3.09	2.77
N-S direction			SID-2	SID-7	Average
	1F level	26.65	0.49	1.43	0.96
	B1F level	22.98	1.59	2.83	2.21
	B2F level	19.48	1.72	3.46	2.59
	B3F level	19.40	1.76	3.75	2.75

Zone, excavation were carried out to nearly the same depth, *i.e.*, 32.5 m, and both pits were retained by diaphragm walls of 1500 mm in thickness. Figure 22 shows the configuration of the retaining system and the locations of inclinometers.

The two extremely low values associated with the annex in Case 1 in Table 8 are considered to be exceptional and are applicable only to walls of narrow pits braced by solid floor slabs. The data indicate that the presence of buttresses is not a dominating factor affecting the rates of wall movements because there is no clear correlation between the presence of buttresses and the rates of movements. The same can be said to the cross walls.

As the wall movements in the Phase 3 excavations were a direct result of contraction of slabs, they were certainly affected by the flexibility of floor slabs. The spans of slabs are not the only factor affecting the flexibility of the slabs. There are always large openings in floor slabs for handling equipment and materials. Figure 23, for example, shows the design of the temporary works at the 1F level in Case 2. As can be noted, there were indeed large openings in the slab. It is evident that these openings would greatly increase the flexibility of the slab and, hence, the contraction of the slab. Photos taken during construction even indicated that the struts in the opening in front of inclinometer SID-8 were in fact absent. Unfortunately, the plans used for construction is unavailable for study. Also as shown in Fig. 24, the openings at the B1F floor level occupied even more areas than those at the 1F floor level.

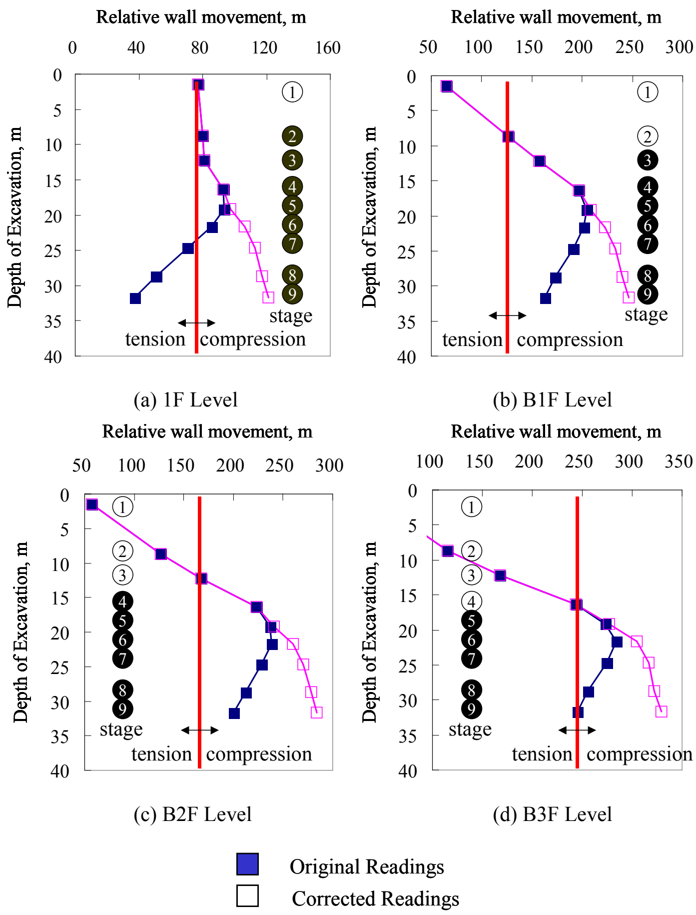


Fig. 20 Relative movements between inclinometers SID-5 and SID-8 and contraction of upper slabs, Case 2

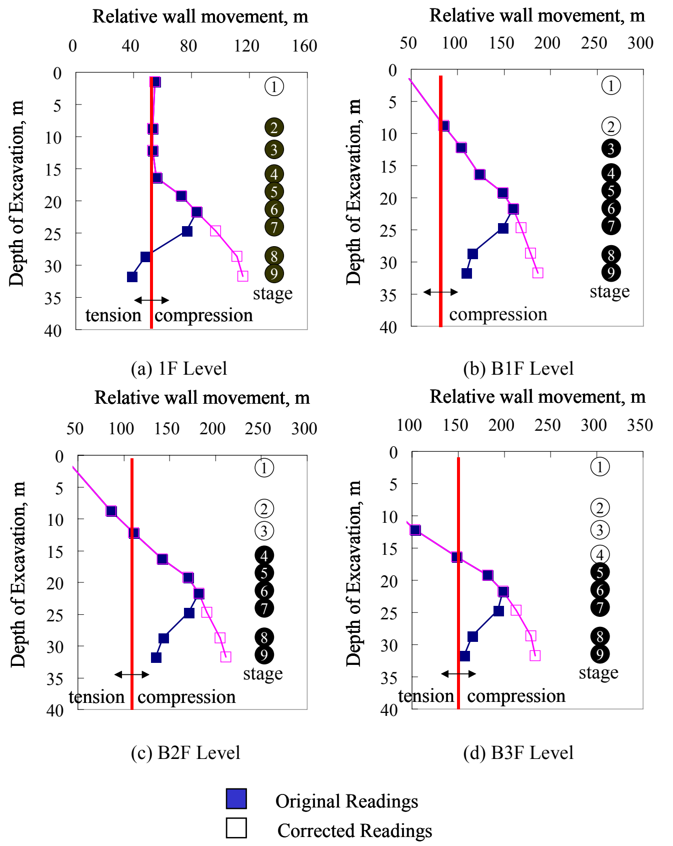


Fig. 21 Relative movements between inclinometers SID-2 and SID-7 and contraction of upper slabs, Case 2

Table 7 Contractions of upper floor slabs, Case 2

	E-W direction (SID-5 & SID-8)		N-S direction (SID-2 & SID-7)	
	Contraction, mm	Axial strain, mm/m	Contraction, mm	Axial strain, mm/m
1F slab	44	0.44	61	0.51
B1F slab	120	1.20	102	0.86
B2F slab	116	1.16	101	0.85
B3F slab	85	0.85	84	0.71

Table 8 Rates of Phase 3 wall movements at the 1F level

Case		Location	Rates of inc. (mm/m)	Wall condition
Case 1	N-S main block	SID-1	0.237	flat
		SID-8	0.568	
	N-S annex	SID-3	0.034	Buttress + cross wall
		SID-5	0.047	
Case 2	E-W	SID-5	0.49	Near buttresses
		SID-8	0.97	flat
	N-S	SID-2	0.49	buttresses
		SID-7	1.43	Near buttresses
Case B (see note)	N-S	SO-1	0.305	Buttress + cross walls
		SI-2	0.525	
		SI-8	0.812	Cross wall
	E-W	SI-9	1.292	buttresses

Note: originally presented in Ou *et al.* (2006) and re-analyzed in Hwang *et al.* (2007)

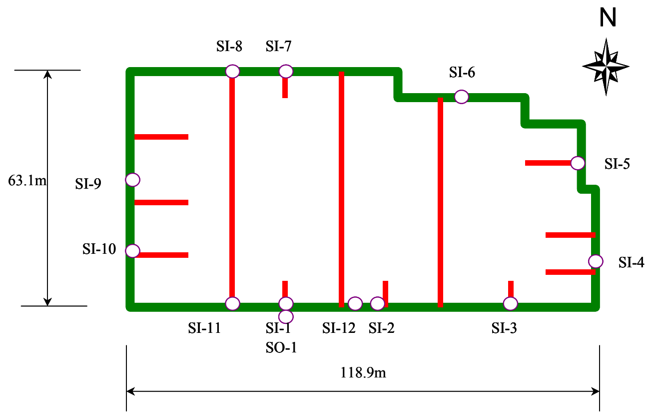


Fig. 22 Configuration of retaining system and locations of inclinometers, Case B (after Ou *et al.* 2006)

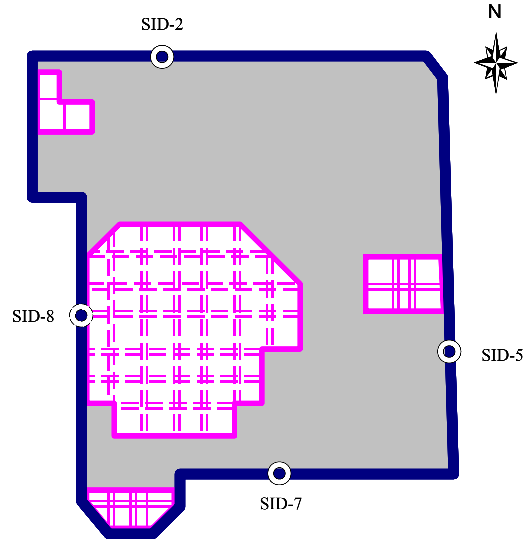


Fig. 23 Configuration of floor system at the 1F level, Case 2

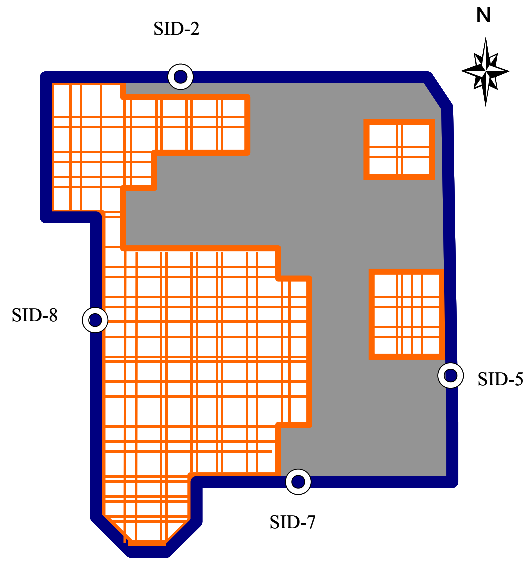


Fig. 24 Configuration of floor system at the B1F level, Case 2

Based on the data given in Table 8, for practical purposes, wall movements at the 1F level can be assumed to increase at rates ranging from 0.5 mm to 1.5 mm per meter of excavation, or, simply, 2 mm to 6 mm per stage of excavation with a typical depth of 4 m in each stage. The former is applicable to narrow pits with floor systems of normal configurations while the latter is applicable to large pits with abnormally flexible floor systems. These magnitudes can be used to calibrate inclinometer readings to account for toe movements.

4.2 Comparison of Performance of Floor Slabs and Struts

It will be interesting to compare the performance of floor slabs in excavations using the top-down method of construction with that of struts in excavations using the bottom-up method of construction. Figure 25 shows the layout of BL8 station of the Taipei Metro (Hwang *et al.* 2007a). Excavation was carried out to a depth of 18.5m in 7 stages by using the bottom-up method of construction and strut loads were monitored in 5 sections. The struts at the first level were preloaded to 22.8 tonnes to 52.5 tonnes. As can be noted from Fig. 26, the strut loads in Sections A and D immediately dropped below the preloads as excavation proceeded. The strut loads in the other three sections increased by, up to, 25 tonnes in Stage 2 excavation and then dropped subsequently. The fact that the strut loads dropped below zero, presumably, because the initial loads applied to these struts for closing up the gaps between the struts and the walings and the gaps between the walings and the walls were not included in the readings (Hwang *et al.* 2007a).

At the end of excavation (April 1994), all the strut loads were smaller than the preloads as depicted in Table 9. A maximum reduction of 52.5 tonnes was observed in Section D and corresponds to an elongation of 4.4 mm of the strut for a sectional area of 173.9 cm^2 of the member (1H350 × 350 × 12 × 19) and an E-value of 200,000 N/mm^2 for steel. During the entire period of excavation, the contraction of struts were 1.5 mm or less and the elongation of were 5 mm or less. Wall movements at the two ends of struts were only half of these values. Therefore, it can be assumed that, for all practical purpose, walls did not move at all at the first level once the struts at this level were preloaded.

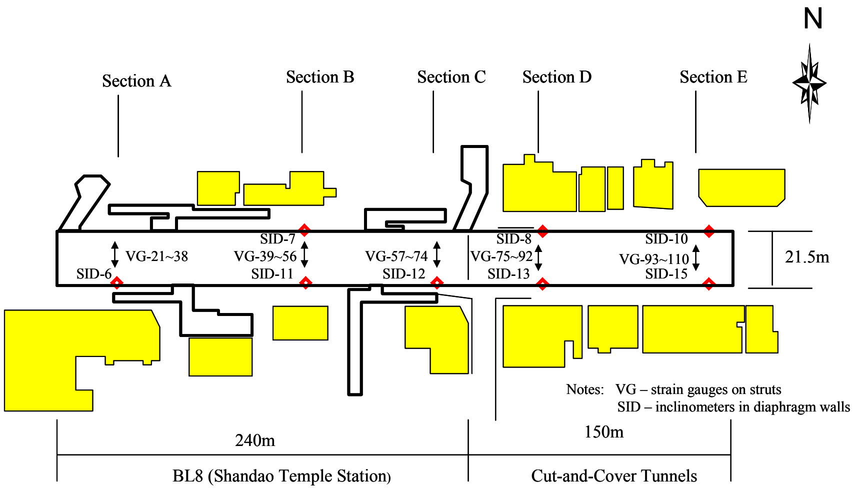


Fig. 25 Layout of BL8 station of the Taipei Metro (after Hwang *et al.* 2007a)

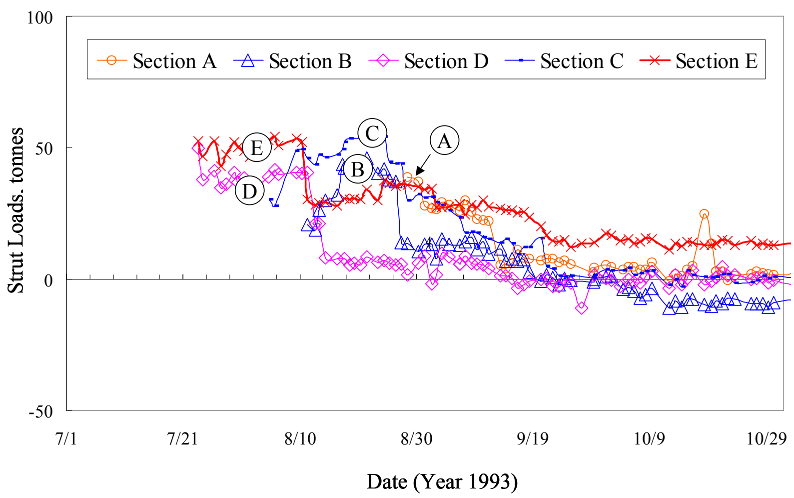


Fig. 26 Strut loads at the first level, BL8 station of the Taipei Metro

It then becomes very clear that preloading is a very effective way of reducing wall movements and it is even possible for walls to move outward as the loads in struts drop below the preloads. The performance of struts is highly dependent on the magnitudes of the preloads applied and the preloading of struts in the neighborhood. To be on the safe side, it has been suggested that small increments, say, up to 2 mm per stage of excavation be allowed in analyses for extraordinarily long struts, say, 60 m or longer (Hwang *et al.* 2007a).

Table 10 shows the recommended rates of Phase 3 wall movements to be used in back analyses for calibrating inclinometer readings to account for toe movements. At the second level, the rates could be twice as much (Hwang *et al.* 2007a).

Table 9 Strut loads and changes in lengths of struts, BL8 station of the Taipei Rapid Transit System

Section	A	B	C	D	E
Strut loads, tonnes					
Preload	38.7	22.8	30.3	49.7	52.5
Maximum		46.0	54.9		54.1
Minimum	−2.3	−11.7	−2.7	−11.1	13.0
End of excavation	−2.3	−10.1	1.1	−2.5	NA
Changes in lengths of struts, mm					
Max contraction		−1.5	−1.5		−0.1
Max elongation	2.5	2.3	2.5	5.0	3.6
End of excavation	2.5	2.3	2.3	4.4	

Table 10 Rates of Phase 3 wall movements at the first level

Span of slab or strut	Increments in wall movement per stage of excavation	
	Top-down	Bottom-up
< 20 m	0 ~ 2 mm	0 mm
20 m ~ 60 m	2 ~ 4 mm	0 ~ 2 mm
> 60 m	2 ~ 6 mm	1 ~ 2 mm

5. CONCLUSIONS

The foregoing discussions lead to the following conclusions:

1. It is important to correct inclinometer readings to account for the movements at the toes of inclinometers.
2. Since diaphragm walls are braced by floors in excavations using the top-down method of construction, the flexibility of floors has dominating influences on the movements of walls. The flexibility of the floors is not governed by the sections of slabs but by factors such as openings in the slabs, bracings in these openings, and many other construction details.
3. For typical basement excavations of, say, 20 m or so in width, the progressive movements of diaphragm walls at the first slab level will be of an order of 1 mm to 2 mm for each stage of excavation subsequent to the casting of the floor slabs at this level.
4. For excavations of, say, 60 m or greater in width and with flexible floor systems, the progressive movements of diaphragm walls at the first slab level will be of an order of 2 mm to 6 mm for each stage of excavation subsequent to the casting of the floor slabs at this level.
5. The above-mentioned rates of progressive wall movements can be used as a guide to correct inclinometer readings.

ACKNOWLEDGEMENTS

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