PERFORMANCE OF WALL SYSTEMS DURING EXCAVATION FOR CORE PACIFIC CITY

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ABSTRACT

Discussed herein is the performance of the wall system during excavation for one of the deepest basement excavations carried out in Taiwan. The paper focuses on two issues: correction of inclinometer readings to account for toe movements and the effectiveness of buttresses in reducing wall deflections. Reference envelopes for diaphragm walls at this particular site were established and these reference envelopes can be used for evaluating the performance of diaphragm walls during excavations with similar ground conditions.

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

1. INTRODUCTION

The 7-level basement of Core Pacific City is one of the deepest building basements in Taiwan. Buttresses were adopted for a half of the site as a building protection measure for reducing wall deflections. Although the depth of excavation of 31.68 m has been exceeded by the recent excavations for constructing the rapid transit systems, the experience gained is still valuable for future underground works.

2. THE PROJECT

Construction for this 12-story shopping mall, claimed to be the largest in Southeast Asia in terms of floor area, 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, the deepest basement on the island at that time, 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 Fig. 1, there were quite a few buildings of 3 to 5 stories in height in the vicinity. To protect these buildings, as depicted in Fig. 2, buttresses were used to reduce the deflections of walls, hence ground settlements which were potentially damaging to these buildings. These buttresses were 1500 mm in thickness and 3.5 m to 3.7 m in length, and extended from a depth of 10.5 m to a depth of 40 m as depicted in Fig. 3. They were installed at, typically, horizontal spacings of 8.25 m or 8.75 m and were cast together with the diaphragm walls with rebars interlocked.

Excavation was carried in 9 stages and Fig. 4 shows the sequence of excavation next to the southern wall and the bracing system. Temporary struts (TS1) were used locally at the spans immediately next to the diaphragm walls to brace against the B1

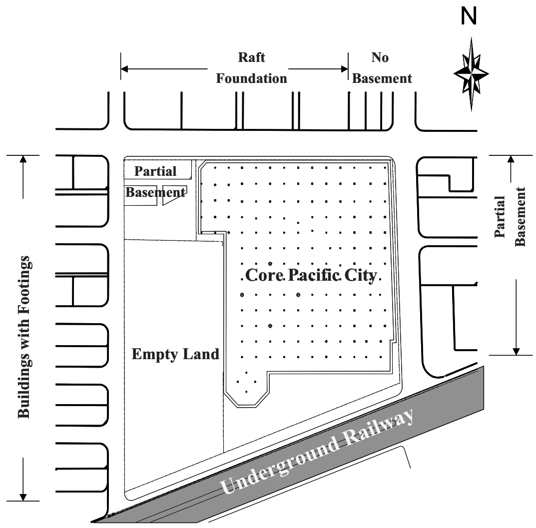
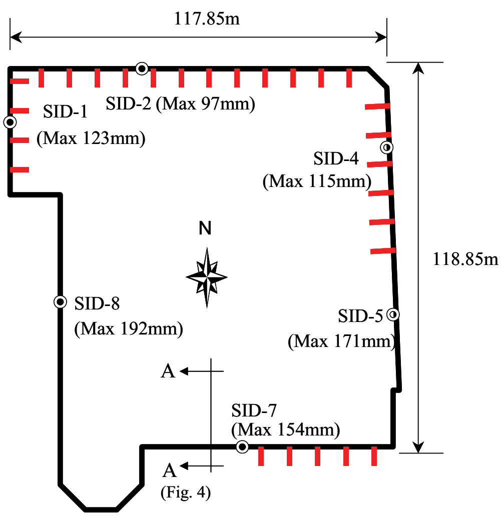


Fig. 1 Setting of the site



Note: The values in parentheses are the final wall deflections with toe movements accounted for.

Fig. 2 Site plan and locations of inclinometers

Manuscript received April 24, 2007; revised May 29, 2007; accepted July 18, 2007.

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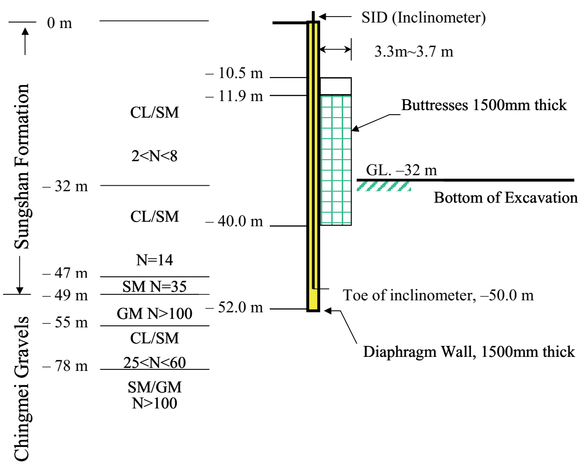
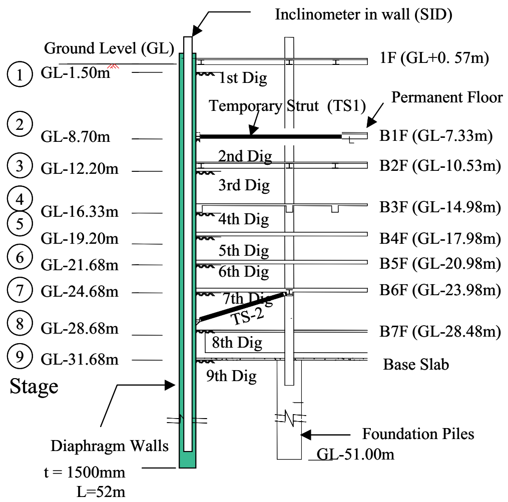


Fig. 3 Soil profile and configuration of buttresses



Section A – A (Fig. 2)

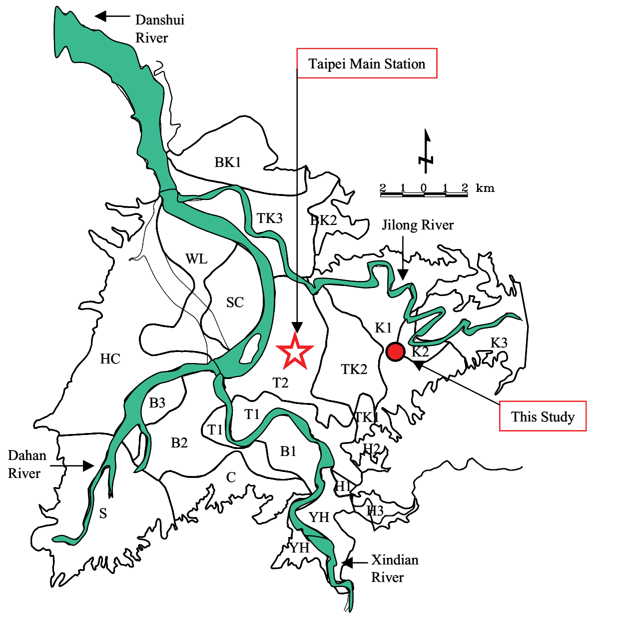
Fig. 4 Excavation sequence and retaining system

floor slab to provide an opening for transporting materials and inclined temporary struts (TS2) were used to brace against the B6 floor slab. Other than that, the walls were supported by floor slabs at various levels.

3. GROUND CONDITIONS

The site is located in the K1 zone of the Taipei Basin as depicted in Fig. 5. Readers are advised to refer to Chin, *et al.* (2006) and Lee (1996) for local geology and ground conditions in different geological zones.

A simplified soil profile at this site is shown in Fig. 3. The Sungshan Formation at the surface consists of alternating layers of silty clay and silty sand. It is underlain by the Chingmei Gravels which contains sands, gravels and cobbles and is rich in water-bearing. The groundwater table in the upper portion of the Sungshan Formation was at depths varying from 2 m to 2.5 m below surface. The piezometric level in the Chingmei Formation was 15 m below the hydrostatic level in 1988 due to excessive pumping of groundwater in the Taipei basin prior to 1970s. After pumping was banned in late seventies, the piezometric level



Geology Map: Lee, 1996

Fig. 5 Location of the site

recovered rapidly. During the period of construction commencing from 1998, it recovered to a few meters below the hydrostatic level. Table 1 summarizes the properties of various soil layers present at the site.

The gravelly layer at the top of the Chingmei Gravels was considered to be a competent bearing stratum for anchoring the toes of diaphragm walls. However, whether it indeed did its job is one of the subjects to be studied.

4. INCLINOMETER READINGS AND CORRECTIONS TO THE READINGS

There were 6 inclinometers, refer to Fig. 2 for their locations, embedded inside the diaphragm walls for monitoring wall deflections. The wall deflection profiles obtained by inclinometers far away from buttresses are shown on the left of Fig. 6 and those obtained by inclinometers near buttresses are shown on the left of Fig. 7. To make the figures legible, readings for some of the stages are omitted. Wall deflection reached a maximum of 167 mm, as recorded by inclinometer SID-8, in the 6th stage and dropped in the subsequent stages.

As can be noted from the two figures, the upper portion of the walls moved outward by significant amounts subsequent to the 5th stage of excavation as recorded by all the inclinometers. This is unlikely to be realistic because of the lack of mechanism for this to happen. Although outward wall movements are possible if the earthpressures on the opposite walls are drastically unbalanced due to different ground conditions or due to different progress in excavation, this is certainly not the case at this site.

Figure 8 shows the relative movements between inclinometers SID-5 and SID-8, which were located at the opposite sides of the excavation, at the 1F (ground floor) level at the ends of various stages of excavation. They are simply the sums of readings of these two inclinometers. The floor slab was cast at the end of the 1st stage of excavation and the relative movement between the two inclinometers had already reached 76 mm by then. It was

Table 1 Soil properties

	Bottom depth, m	Soil type	SPT N	γ_t kN/m^3	c' kPa	Φ' degrees	Su kPa
1	2	SF	4	18.7	0	32	30
2	4	CL	2	19.0	0	31	20 ~ 40
3	7	SM	8	19.0	0	32	
4	22	CL	3	18.4	0	31	40 ~ 60
	32	CL	7	19.0	0	32	60 ~ 120
5	34	SM	14	19.3	0	33	
6	47	CL	14	19.5	0	33	130 ~ 210
7	49	SM	35	20.3	0	35	
8	55	GM	> 100	21.9	0	> 38	
9	67	CL	25	19.5	0	36	
	69	SM	60	21.6			
	77.5	CL	29	19.9			
10	82.1	SM	23 ~ 100+	19.7			
		GM	> 100				

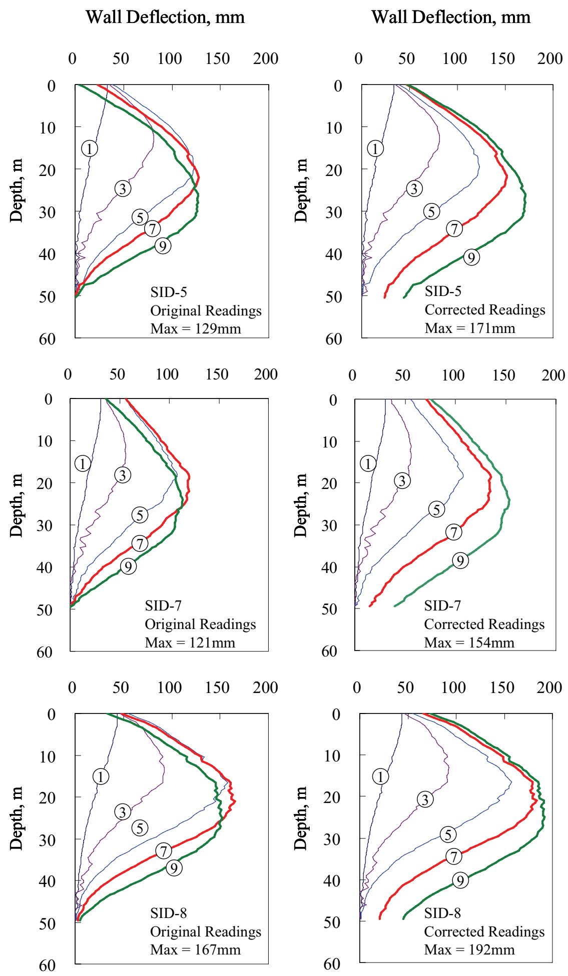


Fig. 6 Readings of inclinometer away from buttresses

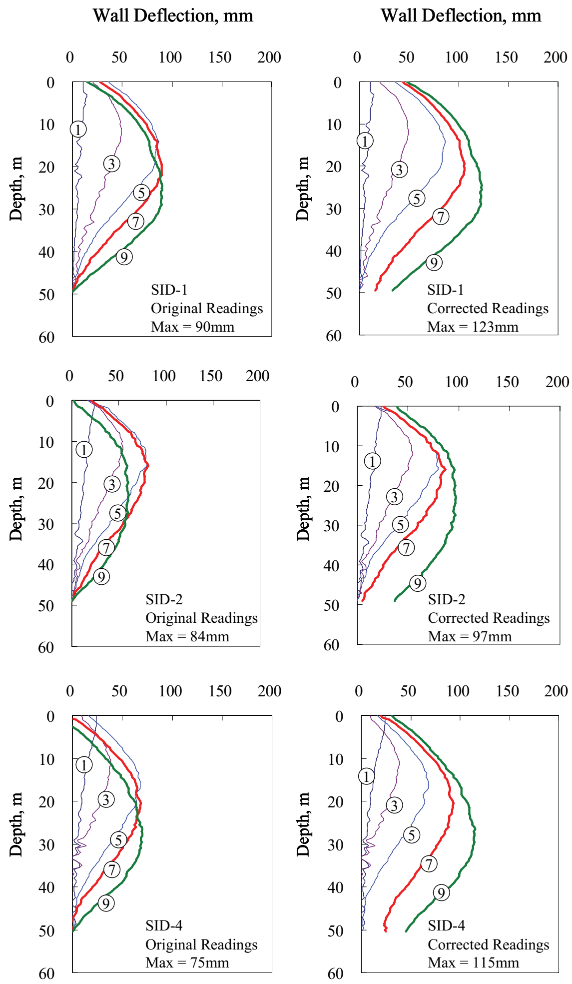


Fig. 7 Readings of inclinometer near buttresses

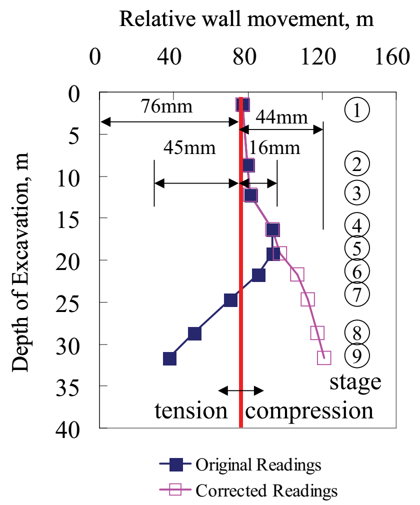


Fig. 8 Relative wall movements between inclinometers SID-5 and SID-8 at the 1F (ground floor) floor level

subjected to earthpressures from the walls at the two ends and would contract as a result as excavation proceeded. The inclinometer readings indicate that the floor slab was shortened by 16 mm in the first 5 stages but the trend was reversed subsequently. At the end, the floor was even 45 mm longer than it was to start with. It is certainly impossible for this to happen.

A similar phenomenon can be observed from Fig. 9 which shows the contraction of the B1F slab in the first 5 stages of excavation and a reversed trend in the subsequent stages. Although the slab was still in compression at the end, the relaxation of compression in the slab in the later stages contradicts the general belief that loads in struts/floors shall always increase as excavation proceeds.

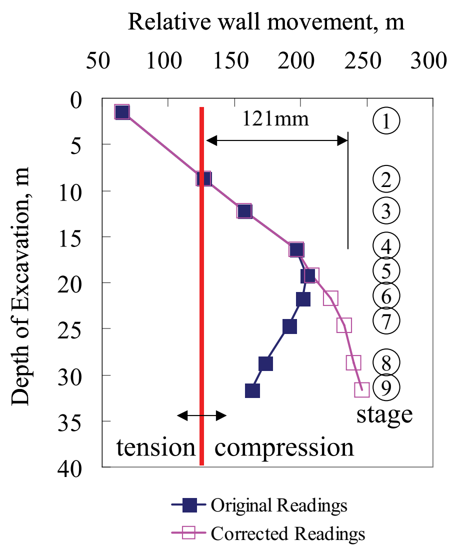


Fig. 9 Relative wall movements between inclinometers SID-5 and SID-8 at the B1F floor level

In the case of interest, the toes of inclinometers were assumed to be unmoved during excavation and readings at other depths were calculated accordingly. Diaphragm walls were installed to a depth of 52 m, or, theoretically, embedded in the Chingmei Gravels by 3 m. It is highly questionable whether such an embedment is sufficient to ensure the fixity of the toes of diaphragm walls, bearing in mind that excavation was abnormally deep. Besides, diaphragm walls were installed to the predetermined depth of 52 m and the embedment in the Chingmei Gravel was not confirmed at site. Inclinometers were even 2 m shorter than diaphragm walls. Therefore it is very likely that the toes of inclinometers did move during excavation and the readings obtained are thus misleading.

It than becomes obvious that inclinometer readings have to be corrected to account for toe movements. It would have been an easy job if the movements of the tops of inclinometers had been measured. But this is not the case. As an alternative, Hwang, *et al.*, (2007) proposed to estimate toe movements of inclinometers based on the wall movements at the first and the second strut/floor levels. Take inclinometer SID-5 for example, the readings are reasonable for the first 4 stages of excavation as depicted in Fig. 10. From the 5th stage and onward, the original inclinometer readings show that the wall kept on moving outward as excavation proceeded. The readings for both the 1F (ground floor) and B1F levels will look more reasonable if corrections (inward movements) of 4 mm, 16 mm, 24 mm, 32 mm, and 44 mm are added to the readings for the 5th to the 9th stages, respectively. The corrections made to the readings correspond to the movements of the toes in these stages.

Similarly, as depicted in Fig. 11, the toe movements for inclinometer SID-8 were found to be 5 mm, 18 mm, 35 mm, and 40 mm for the 6th to the 9th stage of excavation by adopting the above-mentioned procedure. The movements of the toes of all the inclinometers in various stages of excavation are shown in Fig. 12 and summarized in Table 2. As can be noted, the performance of all the 6 inclinometers is fairly consistent. It can also be noted, toe movements were negligible for excavations shallower than 20 m in this particular case.

(a) SID-5: 1F Floor Level

(b) SID-5: B1F Floor Level

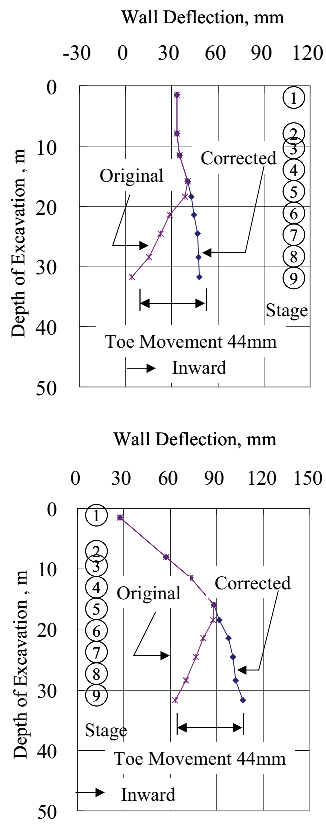


Fig. 10 Progressive wall movements for inclinometer SID-5

(a) SID-8: 1F Floor Level

(b) SID-8: B1F Floor Level

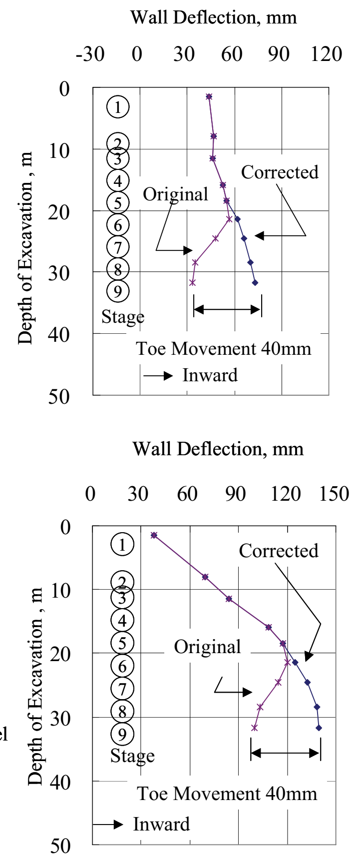


Fig. 11 Progressive wall movements for inclinometer SID-8

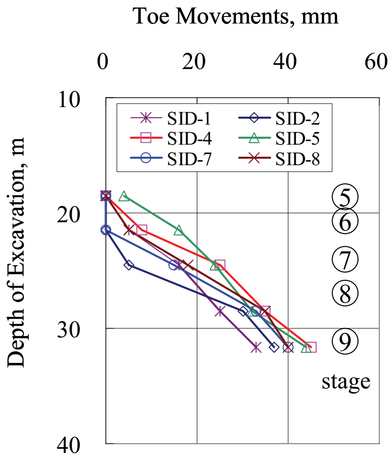


Fig. 12 Progressive movements of toes of inclinometers

Table 2 Back-calculated movements of toes of inclinometers

Excavation		Toe movement, mm						
Stage	Depth, m	SID-1	SID-2	SID-4	SID-5	SID-7	SID-8	Ave.
5	19.20	0	0	0	4	0	0	0.6
6	21.68	5	0	8	16	0	5	5.7
7	24.68	16	5	25	24	15	18	17.2
8	28.68	25	30	35	32	33	35	31.7
9	31.68	33	37	45	44	40	40	39.8

5. PERFORMANCE OF WALLS

The profiles for wall deflections obtained by all the six inclinometers, with toe movements shown in Table 2 duly accounted for, are shown at the right of Figs. 6 and 7. As can be noted by comparing the two sets of readings, as far as the maximum deflections are of concern, the influence of toe movement was the smallest for inclinometer SID-2 with a difference of only 13 mm and the largest for inclinometer SID-5 with a difference of 42 mm before and after corrections. The maximum deflections at various stages of excavation are summarized in Table 3 and those corresponding to the final excavation are also shown in Fig. 2.

As can be noted by comparing Fig. 6 with Fig. 7, the use of buttresses apparently did reduce wall deflections to a certain extent. The effectiveness of auxiliary measures, such as buttresses, grouted slab, *etc*., in reducing wall deflections is traditionally evaluated by calculating the ratio of final wall deflections with and without such measures. As a first attempt, this procedure is adopted to study the performance of buttresses. The average of the final wall deflections for inclinometers SID-5 and SID-8, which were located in the flat sections of walls without buttresses, is 181 mm while the average of the same for inclinometers SID-1, SID-2, and SID-4, which were located in the sections of walls with buttresses, is 112 mm, giving a reduction of 69 mm, or 38%. Inclinometer SID-7 was located at the mid-span of the southern wall of which a half was braced by buttresses. The maximum wall deflection recorded, 154 mm, falls in-between the above-mentioned two averages.

Table 3 Maximum wall deflections based on corrected inclinometer readings

Excavation		Maximum wall deflection, mm					
Stage	Depth, m	SID-1	SID-2	SID-4	SID-5	SID-7	SID-8
1	1.50	14.6	23.8	23.9	33.2	30.8	43.7
2	8.70	30.6	39.3	29.3	58.9	46.7	70.7
3	12.20	49.2	54.5	38.4	81.2	56.4	92.4
4	16.33	67.0	69.6	55.7	110.9	83.4	135.5
5	19.20	86.5	80.0	68.0	126.8	108.1	157.7
6	21.68	95.1	84.3	82.9	141.7	121.9	171.6
7	24.68	105.8	86.6	93.3	151.7	135.5	183.4
8	28.68	113.4	96.6	106.1	155.3	146.1	188.7
9	31.68	123.3	97.4	115.1	171.0	154.0	191.8

The reduction factors are obviously dependent on the depth of excavation. For example, the reduction will be 45% for a depth of 19.2 m (say, 20 m) in the 5th stage, 43% for a depth of 24.68 m (say, 25 m) in the 6th stage of excavation. Although these values are not too far different, it is desirable to have a more consistent way for evaluating the effectiveness of not only buttresses but also other factors affecting the performance of walls.

6. WALL DEFLECTION PATHS AND REFERENCE ENVELOPES

Wall deflections for shallow depths of excavation are likely to be affected by the presence of adjacent structures and the proximity of these structures to the wall. They are also affected by the promptness of installation and preloading of the struts at the first level. Therefore, evaluation of performance of different wall systems cannot be fairly conducted. On the other hand, wall deflections for excavations exceeding a certain depth are likely to be affected by the proximity of the bottom of excavation to the rigid base stratum and the results of comparison will also be misleading. Therefore, if the effectiveness of buttresses is to be evaluated fairly, it is necessary to compare only wall deflections which are not influenced by adjacent structures or boundary effects.

Experience obtained from deep excavations carried out in the T2, TK2, and K1 zones in the Taipei Basin indicates that wall deflection paths tend to converge to a narrow band after excavation exceeds a depth of 15 m (Hwang and Moh, 2007a). This indicates that the influences of adjacent structures have diminished to a negligible extent. On the other hand, wall deflections are likely to be influenced by the boundary effects as excavation exceeds 20 m. Between a depth of 15 m and a depth of 20 m, plots of wall deflections versus depth of excavation are more or less linear in a log-log scale. This stimulates the idea of the so-called reference envelopes.

Figure 13(b) shows "wall deflection path," which is a plot of maximum wall deflections, Δ, versus depth of excavation, *H*, in a log-log scale, in various stages for the hypothetical case shown in Fig. 13(a). Similar to the so-called "stress paths" which characterize soil behaviour in triaxial loading tests in laboratory, wall deflection paths characterize performance of walls during excavation (Hwang, *et al.*, 2006; Hwang and Moh, 2007a, 2007b; Hwang, *et al.*, 2007).

The wall deflection paths for the case of interest are shown in Figs. 14 to 19. Also shown in these figures are the reference envelopes which are supposed to be the envelopes of a family of wall deflection paths for a particular set of ground conditions and for a particular retaining system. However, for studying the performance of walls at individual locations, reference envelopes were established for individual paths herein. Reference envelopes are defined by two parameters, Δ_4 for the deflection at a depth of excavation of 4 m, and Δ_{100} for the deflection projected to a depth of excavation of 100 m. The depth of 4 m is chosen because first digs are normally shallower than 4 m and the depth of 100 m is chosen for convenience because Microsoft Excel plots only full cycles. Furthermore, the extension of envelopes to this depth does make it easier to study the differences among various cases.

Reference envelopes have been established previously for bottom-up excavations with walls of different thicknesses in the T2, TK2, and K1 zones of the Taipei Basin and Table 4 summarizes the Δ_4 and Δ_{100} values obtained based on the observations, mainly, in the last 15 years (Hwang and Moh, 2007a). It appears that the Δ_4 values are insensitive to wall stiffness while the Δ_{100} values are insensitive to ground conditions. Whether this can be generalized, however, is subject to confirmation as more case histories are studied.

For shallow excavations, there will be little difference between bottom-up and top-down excavations. Therefore, a Δ_4 value of 30 mm for bottom-up excavations in the K1 zone is believed to be applicable to top-down excavations in the K1 zone as well. The data shown in Figs. 14 to 19 also confirm the appropriateness of this value. Once this starting point is established, the reference envelope for a particular set of data can easily be constructed by drawing a straight line to reasonably cover all the data points and extending this line to a depth of excavation of 100 m. Since the Δ_4 values are insensitive to the stiffness of the wall system with or without buttresses at a given site, the effectiveness of buttresses can be evaluated by simply comparing the Δ_{100} values. This not only drastically simplifies the procedures but also makes the results much easier to be understood. In the case of interest, the Δ_{100} values are found to vary from 250 mm to 300 mm for walls with buttresses to 1200 mm for walls without buttresses as summarized in Table 5. In other words, the use of buttresses reduced Δ_{100} values, say, by a factor of, roughly, 4.

The fact that reference envelopes are defined by the Δ_4 and Δ_{100} values enables comparisons for various purposes to be carried out in a consistent manner. However, the extension of reference envelopes to a depth of 100 m is difficult for people to comprehend. Therefore, maximum wall deflections at a depth of excavation of 30 m which is the practical limit for most excavations are also shown in Table 5 for reference. The reduction factor is now 2.3 instead of 4.

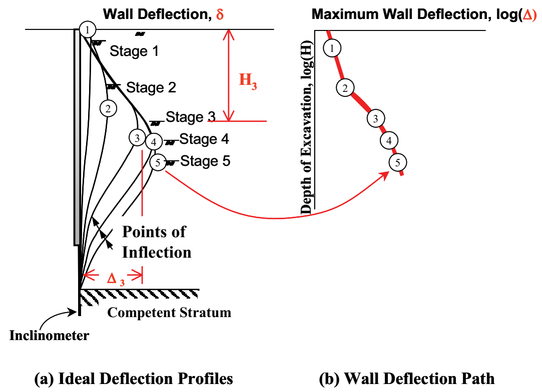


Fig. 13 Ideal wall deflection profiles and wall deflection path

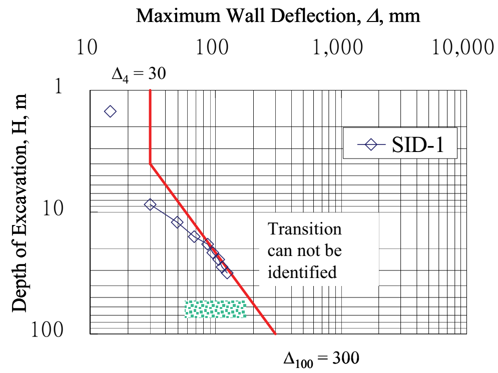


Fig. 14 Wall deflection path for inclinometer SID-1

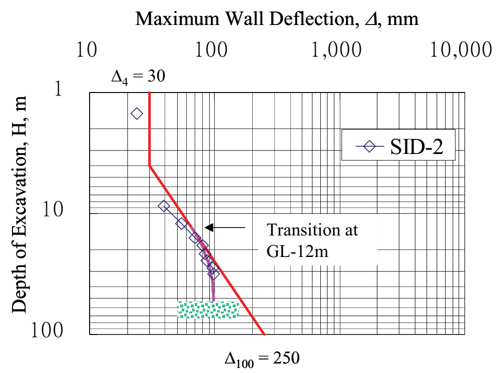


Fig. 15 Wall deflection path for inclinometer SID-2

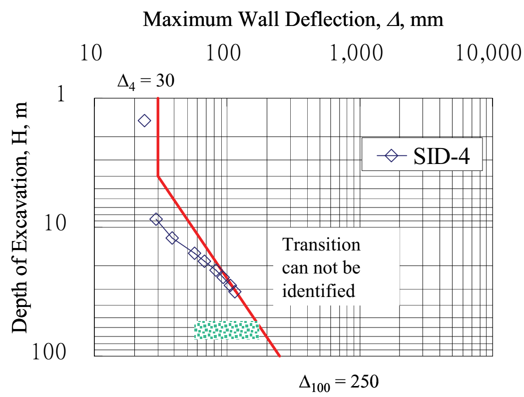


Fig. 16 Wall deflection path for inclinometer SID-4

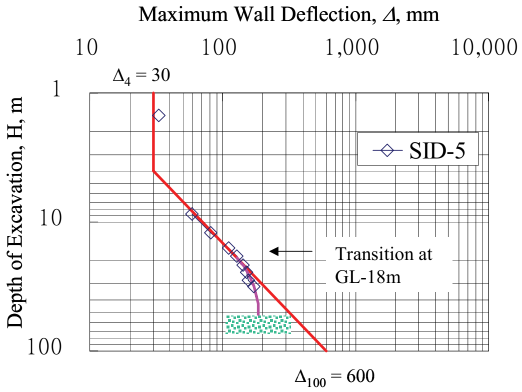


Fig. 17 Wall deflection path for inclinometer SID-5

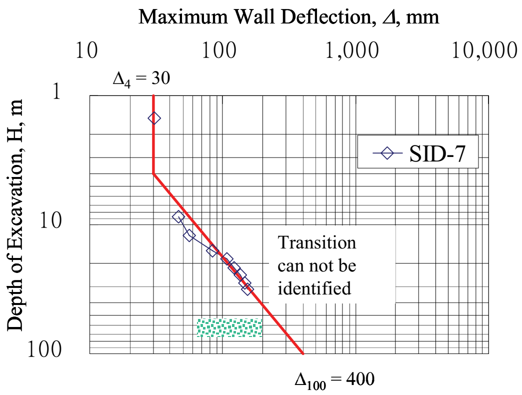


Fig. 18 Wall deflection path for inclinometer SID-7

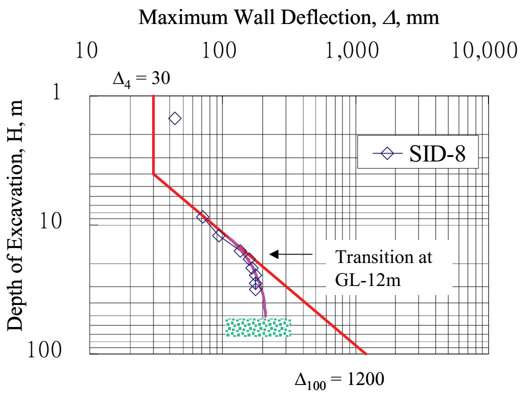


Fig. 19 Wall deflection path for inclinometer SID-8

As indicated in Table 4, the Δ_{100} values decrease as wall thickness increases. As a rule of thumb, it can be assumed that the Δ_{100} values are inversely proportional to wall thickness to the third power. A reduction factor of 4 would infer an increase of wall thickness by a factor of 1.6. That means, the 1500 mm walls with buttresses essentially performed as 2400 mm walls without buttresses. However, it should be noted that Table 4 is applicable to excavations using the bottom-up method of construction in which the strutting systems are more or less similar from case to case and the differences in performance of the retaining systems is governed mainly by the rigidity of the wall systems. This may not be true for excavations using the top-down method of construction. Therefore the above-mentioned rule of thumb will be valid only if the flooring systems are similar.

Table 4 Parameters for defining reference envelopes for bottom-up excavations in the T2, TK2, and K1 zones (Hwang and Moh, 2007a)

Wall thickness, mm	Δ_4, mm			Δ_{100}, mm		
	T2	TK2	K1	T2	TK2	K1
600	10	12		1,600	1,600	
700		12			1,200	
800	10	12	30	800	800	800
900		12	30		600	600
1000	10		30	400		400
1200	10			200		

Table 5 Effectiveness of buttresses as indicated by Δ_{100} and Δ_{30} values

	Inclinometer	Δ_{100}	Δ_{30}
without buttresses	SID-8	1200 mm	300 mm
with partial effects	SID-5 SID-7	600 mm 400 mm	200 mm 150 mm
with buttresses	SID-1 SID-2 SID-4	300 mm 250 mm 250 mm	130 mm 110 mm 110 mm

It is interesting to note that, as shown in Figs. 15, 17, and 19, wall deflection paths for inclinometers SID-2, SID-5, and SID-8 clearly bend downward as the depth of excavation exceeded 20 m. This was due to the boundary effects as the excavation was approaching the base stratum. The lower portion of these paths can be simulated by arcs. The transitions from straight lines to arcs were found to occur at depths of 12 m to 18 m by curve fitting following the procedures recommended in literature (Hwang, *et al.*, 2006; Hwang and Moh, 2007a, 2007b). Such a finding is consistent with previous experience. Readings obtained by the other three inclinometers do not show such bends for reasons which are not readily apparent.

7. CONCLUSIONS

The foregoing discussions lead to the following conclusions:

(1) In the case studied, the movements of the toes of inclinometers were as much as 45 mm and it is thus very important to correct inclinometer readings to account for toe movements for performance of walls to be evaluated properly.

(2) The concept of reference envelope is useful for evaluating the influences of various factors affecting wall deflections and the effectiveness of different auxiliary measures for reducing wall deflections.

(3) In the case studied, the use of buttresses reduced Δ_{100} values by a factor of, roughly, 4 and it is inferred that walls of 1500 mm in thickness with buttresses of similar configura-

tion and design will be equivalent to walls of 2400 mm in thickness without buttresses for excavations with similar flooring systems.

ACKNOWLEDGMENTS

The authors are indebted to Mr. T. C. Su for providing the data presented herein and to Mr. L. W. Wong for his review of transcript and his many valuable suggestions.

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