EVALUATING EFFECTIVENESS OF BUTTRESSES AND CROSS WALLS BY REFERENCE ENVELOPES

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ABSTRACT

The effectiveness of buttresses and cross walls in reducing deflections of diaphragm walls in two cases is evaluated by studying the wall deflection paths and reference envelopes. Both sites are located in the K1 Zone of the Taipei Basin and excavations were carried out to a depth of 32 m by using the top-down method of construction. It has been found that cross walls were effective in reducing wall movements in these two cases. On the other hand, the effectiveness of buttresses was highly dependent on their configurations.

Key words: Buttress, cross wall, deep excavation, wall deflection path, reference envelope.

1. INTRODUCTION

Buttresses and cross walls have commonly been adopted to reduce deflections of diaphragm walls in deep excavations in thick soft deposits. The effectiveness of these auxiliary measures is usually studied by comparing the maximum wall deflections at the final stage of excavation and the results are often inconclusive. First of all, the reductions in wall deflections are dependent on the depth of excavation. The experience learned in one case may not be applicable to other cases with different depths of excavation. Furthermore, there are many other factors which may affect the results obtained. It is therefore recommended to compare wall deflection paths which are plots of maximum wall deflections at various depths of excavation, as such, the experience learned can be generalized for all depths of excavation.

Two case histories are discussed herein to illustrate the approach proposed. The excavations in both cases were carried out to nearly the same depth by using the top-down method of construction and the diaphragm walls were of the same thickness. This eliminates the influences of two important variables, *i.e.*, method of construction and stiffness of wall member, on the results of analyses.

Figure 1 shows the locations of the sites for the case histories presented herein. Both sites are located in the K1 Zone of the Taipei Basin. At the surface is a thick layer of soft deposits, i.e., the so-called Sungshan Formation, underlain by the Chingmei Grovels at depths of 50 m or so. As the sandy sublayers in the Sungshan Formation diminish toward the east of the Taipei Basin, the ground consists predominately of clays. For the convenience of readers, Fig. 2 shows the results of a cone penetration test carried out nearby the site of Case B. Readers are advised to refer to Chin, et al., (2006) and Lee (1996) for more information on local geology and ground conditions.

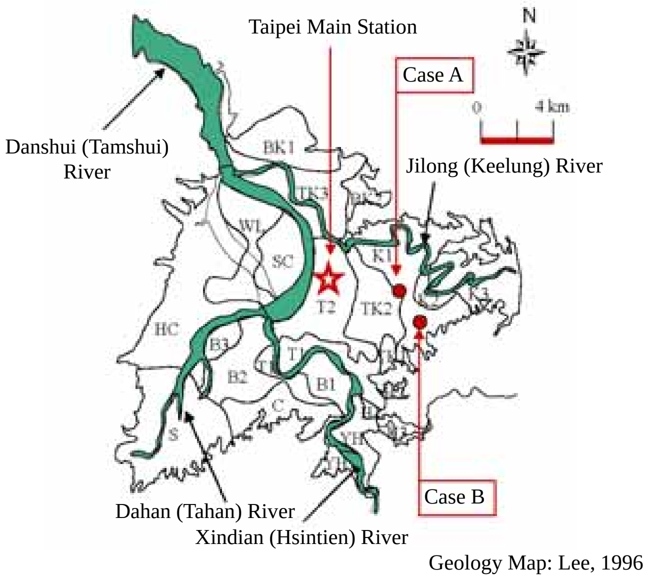

Fig. 1 Locations of the sites studied

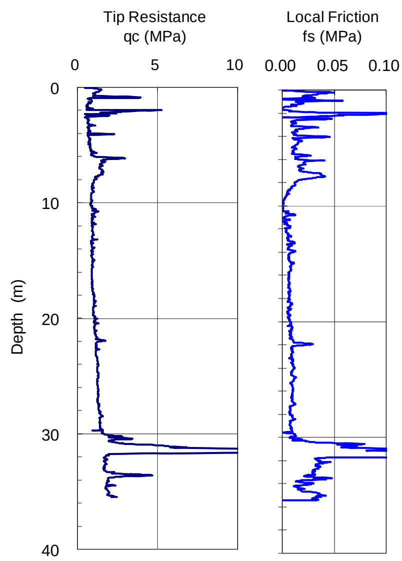

Fig. 2 Typical results of cone penetration tests in the K1 zone of the Taipei Basin

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2. CONCEPT OF WALL DEFLECTION PATH AND REFERENCE ENVELOPE

The concept of wall deflection path and reference envelope was first introduced in Moh and Hwang (2005) and Hwang, *et al*. (2006). Figure 3(a) shows ideal profiles of wall deflections for deep excavations in soft ground and Fig. 3(b) shows the wall deflection path which is a plot of the maximum deflections versus depth of excavation. There are many factors affecting wall deflection paths and readers are advised to refer to Hwang and Moh (2007a) for detailed discussions.

Wall deflection paths tend to converge to a narrow band, if plotted in a log-log scale, after the depth of excavation exceeds, say, 10 m or so and are apparently linear between depths of 10 m and 20 m. This stimulates the idea of "reference envelope" which is the envelope of a family of wall deflection paths and is defined by the wall deflection at a depth of excavation of 4 m, *i.e.*, Δ_4 and the wall deflection projected to a depth of excavation of 100 m, *i.e.*, Δ_{100}. 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, extension of envelopes to this depth does make it easier to study the differences among various cases. However, the adoption of 100 m is difficult for readers to comprehend because excavations seldom reach such a depth. Therefore, a depth of 30 m, which is the practical limit of basement constructions in soft ground, is also adopted in parallel and Δ_{30} values are quoted as supplementary information. This, however, does not change the essence of the approach.

Reference envelopes have been established for excavations using the bottom-up method of construction with walls of different thicknesses in the T2, TK2, and K1 Zones of the Taipei Basin and Table 1 shows the Δ_4 and Δ_{100}, as well as Δ_{30}, values obtained based on the observations, mainly, in the last 15 years (Hwang and Moh, 2007a). This table will serve as the basis for many studies for evaluating the influences of various factors on wall deflections. It is important to note that this table is valid only for excavations carried out by using the bottom-up method of construction. It should also be noted that as workmanship is also a factor affecting wall deflections, the table is applicable to diaphragm walls designed to normal practice and excavations carried out to the normal workmanship in Taiwan, particularly in Taipei.

According to Table 1, it appears that the Δ_4 values are insensitive to wall stiffness while the Δ_{100} values are insensitive to ground conditions. If this indeed is the case, it will be very convenient to establish reference envelopes for new cases based on past experience. However, since the number of cases studied is extremely limited, the validity of this assumption is subject to confirmation as more case histories are studied.

The influences of various factors, not only the use of buttresses but also many others, can be studied by comparing the Δ_4 and Δ_{100} values, instead of wall deflections at a certain depth (usually, the final depth of excavation) as illustrated as follows.

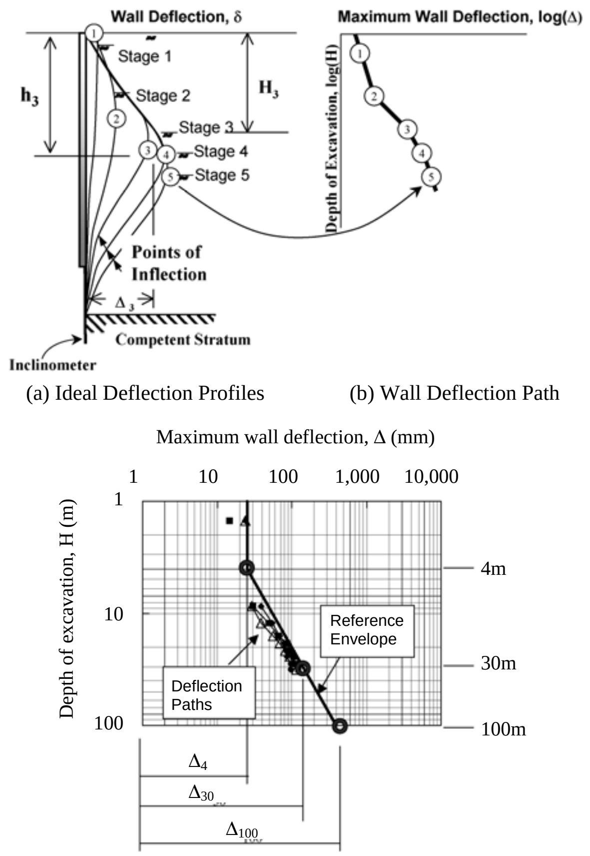
3. CASE A: USE OF BUTTRESSES

Construction for this 12-story shopping mall commenced in 1998 and the mall was open for business in 2001. The lot is about 118 m by 118 m in size as depicted in Fig. 4. The excavation for the 7-level basement was carried out to a maximum depth of 32 m in 9 stages by using the top-down method of construction. The pit was retained by diaphragm walls of 1,500 mm in thickness and 52 m in depth as depicted in Fig. 5. Also shown in the figure are the sequence of excavation and the bracing system next to the southern wall.

There exists a thick layer of soft deposits, *i.e.*, the so-called Sungshan Formation at surface as depicted in Fig. 6. The gravelly

Table 1 Reference envelopes for excavations using the bottom-up method of construction in the T2, TK2, and K1 Zones (after Hwang and Moh, 2007a)

Geological zone	Wall thickness (mm)	Δ_4 (mm)	Δ_{100} (mm)	Δ_{30} (mm)
T2	600	10	1,600	240
	800	10	800	155
	1000	10	400	100
	1200	10	200	65
TK2	600	12	1,600	255
	700	12	1,200	215
	800	12	800	165
	900	12	600	140
K1	800	30	800	235
	900	30	600	195
	1000	30	400	150



(a) Ideal Deflection Profiles (b) Wall Deflection Path

(c) Reference Envelope

Fig. 3 Ideal profiles of wall deflections and wall deflection paths

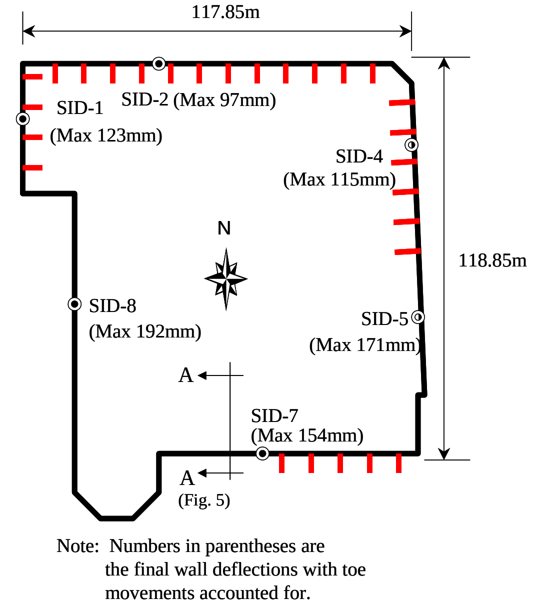


Fig. 4 Site plan and locations of inclinometers, Case A

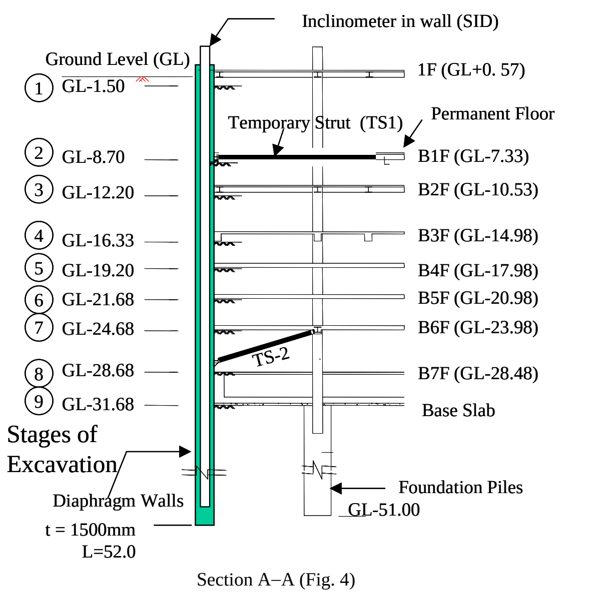


Fig. 5 Excavation sequence and configuration of retaining system, Case A

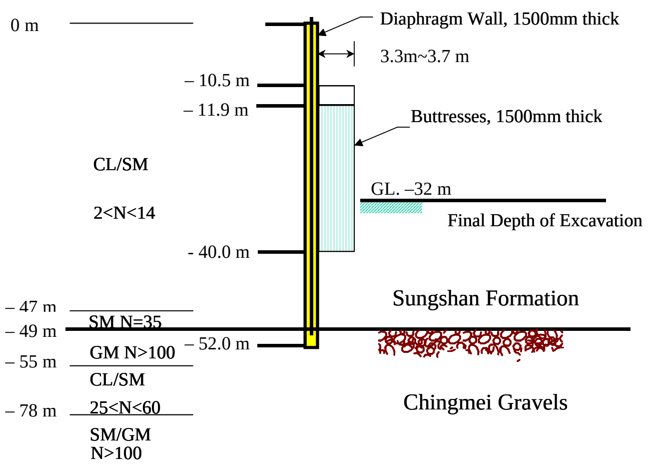


Fig. 6 Soil profile and configuration of buttresses, Case A

sublayer in the Chingmie Gravels, which underlies the Sungshan Formation at a depth of 49 m below ground surface, was considered to be a competent bearing stratum for anchoring the toes of diaphragm walls. However, back analyses indicated that the toes of diaphragm walls indeed moved by as much as 45 mm as depicted in Fig. 7 (Hwang, *et al*., 2007b). The same approach adopted for Case B, as to be illustrated in Section 4.2, was adopted in the back analyses for toe movements. All the inclinometer readings presented herein have been corrected for the toe movements.

There were quite a few buildings of 3 to 5 stories in height outside the northern half of the site. To protect these buildings, buttresses were used to reduce the deflections of diaphragm walls and, hence, ground settlements behind these walls. These buttresses were 1,500 mm in thickness and 3.3 m to 3.7 m in width, and extended from a depth of 10.5 m to a depth of 40 m below ground surface as depicted in Fig. 6. They were installed at, typically, spacings of either 8.25 m or 8.75 m and were cast together with the diaphragm walls with reinforcing steel rebars interlocked to form T-sections. However, rebars were omitted in the western wall at the northwestern corner of the site, where the neighboring buildings were to be demolished shortly.

Wall deflection profiles are available in Hwang, *et al.* (2007b). Wall deflection paths have also been analyzed and reference envelopes established. The results are shown in Figs. 8, 9, and 10 and the Δ_4, Δ_{30}, and Δ_{100} values are summarized in Table 2. It should be noted that Fig. 9 is interpreted differently from what is given in the said article as more experience has been gained.

3.1 Walls without Buttresses

Inclinometer SID-8 was more than 32 m, which is the depth of final excavation, away from the nearest buttress and the readings obtained by this inclinometer can be considered representative of deflections of walls without buttresses. The Δ_4 value, *i.e.*, 30 mm, of the reference envelope is in agreement with those for walls in the K1 Zone shown in Table 1. Although Table 1 is supposed to be applicable to only excavations using the bottom-up method of construction, there is really no difference in the performance of walls between excavations using the bottom-up or the top-down method of construction during the first digs. Therefore, it is quite reasonable for the Δ_4 values to be the same in both cases. The diaphragm walls were 1,500 mm in thickness and the agreement of the Δ_4 value with those for walls with other thicknesses again confirms the assumption that the Δ_4 values are insensitive to the stiffness of walls.

Table 2 Reference envelopes for walls with and without buttresses, Case A

	Location	Δ_4 (mm)	Δ_{100} (mm)	Δ_{30} (mm)
Without buttresses (Fig. 8)	SID-8	30	1,200	300
With buttresses (Fig. 9)	SID-1, SID-2, SID-4	20	400	130
With partial effects (Fig. 10)	SID-5, SID-7	30	600	195

The large Δ_{100} value, *i.e.*, 1,200 mm, is rather surprising. Based on the data given in Table 1, the Δ_{100} values are roughly inversely proportional to the wall thickness to the third power. The Δ_{100} values are reduced to a half as wall thickness increases from 600 mm to 800 mm, from 800 mm to 1,000 mm, from 1,000 mm to 1,200 mm, and from 1,200 mm to 1,500 mm. Accordingly, the Δ_{100} value for walls of 1,500 mm in thickness would be expected to be only 100 mm. The exceptionally large Δ_{100} value in the case of interest could presumably be attributable to the factors listed in Table 3. Wall deflections are caused mainly by (1) bending of walls and (2) contraction of floor slabs and/or struts. First of all, the vertical spacings between floor slabs in excavations using the top-down method of construction are usually larger than those between struts in excavations using the bottom-up method of construction, resulting in larger wall deflections due to bending of walls. Secondly, the contraction of floor slabs/struts is proportional to the spans of slabs/struts. Table 1 is applicable to excavations for constructing basements of highrise buildings and underground stations of rapid transit systems, of which the spans of struts are typically 20 m to 60 m. The excavation in the case of interest was exceptionally large in size and the long spans, *i.e.*, 118 m, of floor slabs were partially responsible for the large wall deflections. Thirdly, preloading of struts is a very effective way of reducing wall deflections (Hwang, *et al.*, 2007a) and the lack of it in excavations using the top-down method of construction was also a major contributing factor to the large wall deflection in the case of interest.

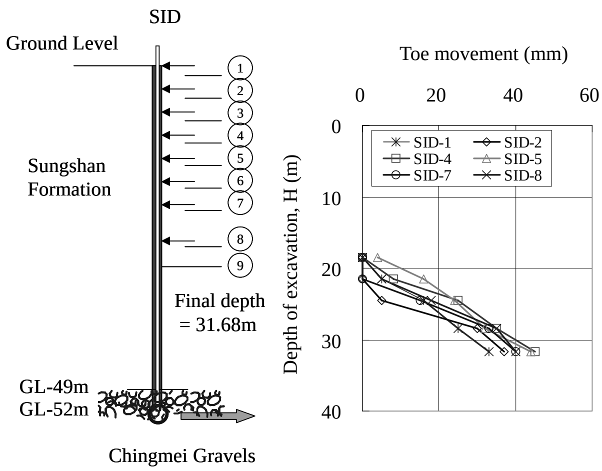


Fig. 7 Progressive movements at toes of diaphragm walls, Case A (after Hwang, *et al.*, 2007b)

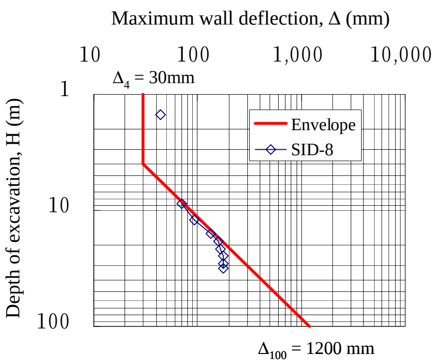


Fig. 8 Deflection path and reference envelope for walls without buttresses, Case A

It has been consistently observed in many other cases that the Δ_{100} values for excavations using the top-down method of construction are many times those for excavations using the bottom-up method of construction. This finding contradicts to the general belief that wall deflections will be smaller if the top-down method of construction is adopted because floor slabs are stiffer than struts. Although the axial stiffness (*i.e.*, the product of sectional area and Young's modulus) of solid concrete floor slabs is indeed much greater than that of struts in usual cases, there are always large openings in floor slabs for handling materials and equipment and the overall axial stiffness of floor slabs is believed to be, at most, equivalent to the axial stiffness of struts for the same configuration of excavation.

3.2 Walls with Buttresses

The effectiveness of buttresses is conventionally evaluated by comparing the wall deflections at the end of excavation. As depicted in Fig. 4, the maximum deflection of Inclinometer SID-8 is 192 m, while the average maximum deflection of Inclinometers SID-1, SID-2, and SID-4 is 123 mm, leading to a reduction factor of 64%. A drawback of this approach is that the reduction factors so obtained are highly dependent on the depth of excavation.

The results will be more consistent if reference envelopes are compared. Based on Table 1, it may be concluded that the Δ_4 values are more or less the same for walls with different thicknesses for a given set of ground conditions. In other words, the Δ_4 values are independent of the stiffness of walls. This is again confirmed by Fig. 8 as discussed in Section 3.1. However, in the case of interest, the buttresses, which were cast together

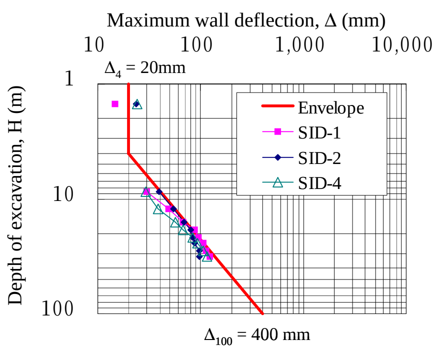


Fig. 9 Deflection paths and reference envelope for walls braced by buttresses, Case A

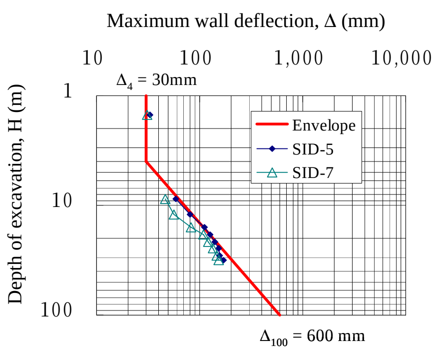


Fig. 10 Deflection paths and reference envelope for walls partially braced by buttresses, Case A

Table 3 Comparison of Case A with the cases referred to in Table 1

	Case A	Table 1
Method of construction	Top-down	Bottom-up
Vertical spacings between two levels of props	Averaging 4 m	Usually 2.5 m ~ 3.5 m
Spans of slabs/struts	118 m	Usually 20 m ~ 60 m
Preloading of props	No	Normally to 50% or more of design loads

with the diaphragm walls to form T-sections, not only increased the stiffness of the walls but also worked as props to resist wall movements. Therefore, the situation is different and this conclusion is subject to reconsideration.

As mentioned previously that reference envelopes should be established by considering primarily wall deflections for depths of excavations in the range of, say, 10 m to 20 m (Hwang and Moh, 2007a). Accordingly, the data in Fig. 9 suggest: Δ_4 = 20 mm, Δ_{30} = 130 mm and Δ_{100} = 400 mm. The Δ_{30} value is 43% of that for walls without buttresses, *i.e.*, 300 mm.

In fact, wall deflection paths tend to deviate from reference envelopes as excavation exceeds a depth of 20 m due to the presence of the rigid base stratum as depicted in both Figs. 8 and 9. These effects will be implicitly included in the results if the conventional way of evaluating the effectiveness of buttresses is adopted but are excluded if the evaluation is based on comparing reference envelopes. Therefore, the results obtained by the latter are expected to be more consistent.

3.3 Walls Partially Supported by Buttresses

Inclinometers SID-5 and SID-7 were not located in the sections of walls with buttresses but were within 32 m, which is the depth of final excavation, from the nearest buttresses. The readings obtained by these inclinometers were thus partially affected by the presence of buttresses. The wall deflection paths and the reference envelope for these two inclinometers are shown in Fig. 10 and the Δ_4, Δ_{100}, and Δ_{30} values are compared with those for walls with and without buttresses in Table 2. As can be noted, the Δ_4 value is the same as that for walls without buttresses. This is quite reasonable because the distances from these inclinometers to the nearest buttresses were much greater than the depth of excavation, *i.e.*, 4 m and wall deflections were not affected by the presence of buttresses in this stage. It is also self-explanatory for the Δ_{100} and Δ_{30} values to fall in-between those for walls without buttresses and walls with buttresses.

4. CASE B: USE OF BUTTRESSES AND CROSS WALLS

Construction for this 37-storey business/office building commenced in 2001 and was completed in 2004. The case was previously reported in Ou, *et al*., (2006) and all the data given herein were obtained from this article.

Figure 11 shows a site plan and the locations of inclinometers and Fig. 12 shows the ground conditions and the sequence of excavation. The pit was about 118.9 m by 63.1m in size and was retained by diaphragm walls of 1,500 mm in thickness. The walls extended to depths varying from 56.8 m to 61 m and were embedded in the gravelly layer by at least 4 meters. The embedment was checked and confirmed before panels were cast. The excavation for the 7-level basement was carried out to a maximum depth of 32.5 m in 9 stages by using the top-down construction method and the side walls were braced by floor slabs. Although there were no buildings in the immediate vicinity of the site, buttresses and cross walls were used to reduce the deflections of walls because of the unprecedented depth of excavation and the very poor ground conditions. Buttresses were 1,000 mm in thickness and 6 m to 15 m in width. The configuration of these buttresses is quite different from that in Case A as compared in Fig. 13.

The buttresses were installed from a depth of 1.5 m below ground surface to the same depths as diaphragm walls, that means, they toed in the gravelly layer for at least 4 m as well. To make them easier to demolish as excavation proceeded, buttresses were lightly reinforced and cast by using lean concrete

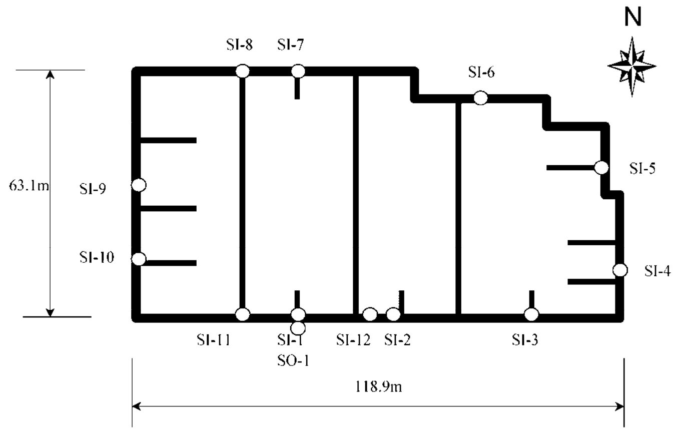


Fig. 11 Site plan and locations of inclinometers, Case B (after Ou, *et al.*, 2006)

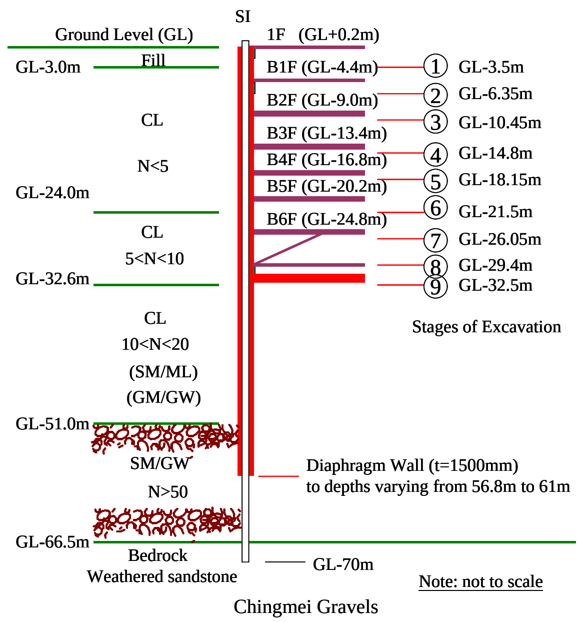
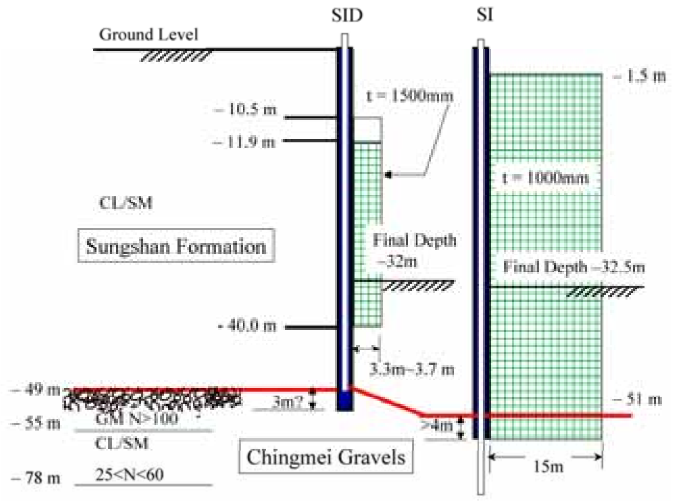
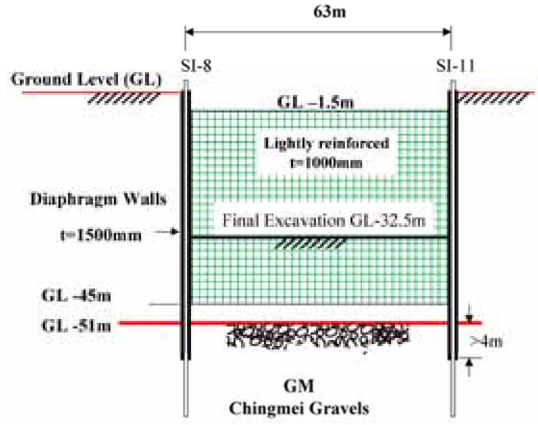


Fig. 12 Soil profile and sequence of excavation, Case B



Note: not to scale

Fig. 13 Comparison of configurations of buttresses in Cases A and B



Note: not to scale

Fig. 14 Configuration of cross walls, Case B

(with a compressive strength of 14 N/mm^2 above a depth of 22 m and 24.5 N/mm^2 below this depth). Steel plates were fixed to the sides of diaphragm walls at the joints to provide flat contacts with these buttresses. These plates were brushed before casting buttresses to make sure that the slime on these plates was removed.

Three cross walls were used to brace the northern and southern walls and stopped at a depth of 45 m as depicted in Fig. 14. They were installed in the same way as buttresses.

4.1 Inclinometer Readings

There were all together 13 inclinometers (*i.e.*, SI-1 ~ 12 and SO-1 in Fig. 11) for monitoring wall deflections. Wall deflection profiles for Inclinometers SI-2, SI-6, SI-8, SI-9, and SO-1 are available in Ou, *et al.*, (2006) and are reproduced in Part (a) of Figs. 15 to 19. For better readability, only the data for Stages 1, 3, 5, 7, and 9 are presented. Outward movements can be observed in the upper portion of the inclinometers in later stages. Outward movements of the walls are unlikely to be real because of the lack of mechanism for them to occur. The readings are most likely misleading due to the movements of the toes of inclinometers and have to be corrected. Although the inclinometers penetrated into the bedrock by a few meters as depicted in Fig. 12, this does not guarantee that the toes of inclinometers would not move.

4.2 Correction of Readings for Toe Movements

Procedures are available for calibrating inclinometer readings to account for toe movements by referencing to the movements at the upper floor levels (Hwang, *et al*., 2007a). Wall movements at the two ends of a slab are associated with the contraction of the slab. The contraction of upper floor slabs will be small once they are cast. Back analyses indicate that the rates of increases in wall movements at the first floor level will be about 2 mm for each stage of excavation for typical configuration of floor slabs and could go up to 6 mm for each stage of excavation floor slabs with large openings and long spans (Hwang and Moh, 2007b). Readings can thus be calibrated accordingly.

As depicted in Fig. 12, the ground floor is located right at ground surface. Because the top portion of inclinometers were

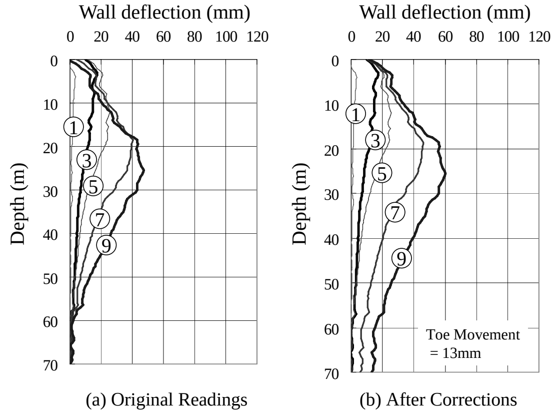


Fig. 15 Wall deflection profiles obtained by Inclinometer SO-1, Case B

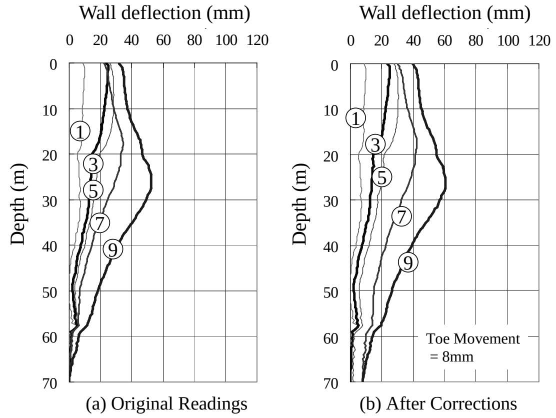


Fig. 16 Wall deflection profiles obtained by Inclinometer SI-2, Case B

easy to be disturbed and readings taken near the ground surface are likely to be erroneous, wall movements at a depth of 1.5 m below ground surface were analyzed. The wall movements at this depth are plotted versus depth of excavation in Fig. 20. They were supposed to move progressively inward, however, all the four figures clearly show reductions of wall movements in later stages of excavation, indicating outward movements of walls. Because these readings were obtained on the assumption that the toes of inclinometers would not move during excavation, they would be misleading if the toes indeed moved.

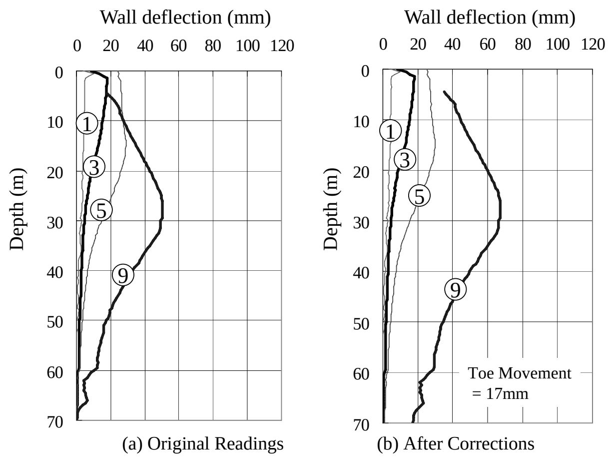


Fig. 17 Wall deflection profiles obtained by Inclinometer SI-6, Case B

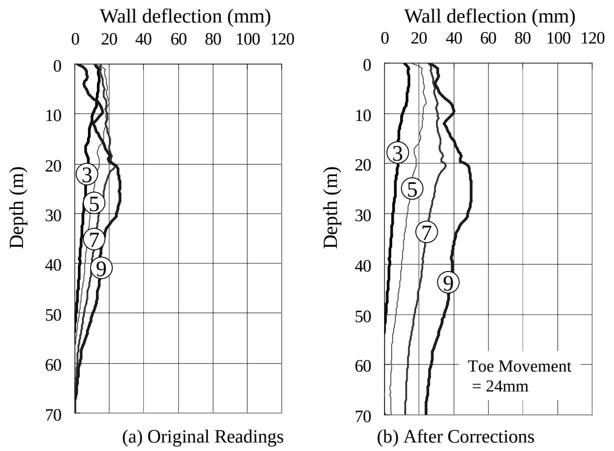


Fig. 18 Wall deflection profiles obtained by Inclinometer SI-8, Case B

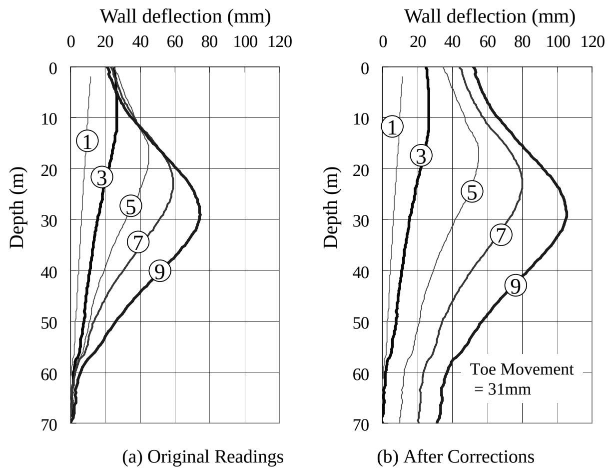


Fig. 19 Wall deflection profiles obtained by Inclinometer SI-9, Case B

Attempts were made to figure out what the "real" wall movements should be and the best estimates are plotted and denoted as "ideal" in these figures. Wall movements at a certain floor slab level are suggested to be classified as follows (Hwang and Moh, 2007b):

Phase 1: before the casting of the floor slab at the 1F (*i.e.*, the ground floor) 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. Take the first floor slab for example, the slab was cast at the end of Stage 1 excavation and, therefore, wall movements in Stage 2 and subsequent stages are considered as Phase 3 movements which are denoted by solid discs with stage numbers in white in Fig. 20.

Contractions of floor slabs occurred only in Phase 3 excavations. As depicted in Table 4, the average rates of increases in the "real" wall movements at a depth of 1.5 m varied from 0.305 mm to 1.292 mm per meter of excavation in Phase 3 excavations. Since the wall movements in the first stage of excavation were unavailable for Inclinometers SI-8 and SI-9 and, furthermore, it is unsure whether the adjustment made is correct because Inclinometer SI-2 behaved differently in Stage 9 excavation, the averages were taken in the range of Stage 3 to Stage 8 (both inclusive) only. These rates of increases in wall movements were of the same magnitude reported in Hwang and Moh (2007b) for typical configuration of floor slabs in excavations using the top-down method of construction. For practical purpose, the rates can be assumed to vary from 1 mm to 5 mm for each stage of excavation with a typical depth of 4 m per stage.

The adjustments made to the readings, *i.e.*, the differences between the two sets of curves shown in Fig. 20, correspond to the movements of the toes of the inclinometers and are plotted versus depth of excavation in Fig. 21. As can be noted, toe movements varied from 10 mm to 30 mm at the end of excavation. It is unsure whether or not the toe movement of Inclinometer SI-2 increased in the last two stages of excavation. Other than that, the trends are quite similar for all the inclinometers despite the many factors which might have influences on the results. The deflection profiles with toe movements accounted for are depicted in part (b) of Figs. 15 to 19 and the maximum wall deflections in various stages of excavations are listed in Table 5.

The fact that the toes of these inclinometers indeed moved is rather amazing because they were embedded in the weathered sandstone, in which the N-values exceed 50, at a depth of 38 m below the bottom of final excavation as depicted in Fig. 12. To the authors' knowledge, this is the first time that ground movements were monitored to such a depth in the Taipei Basin and the depth of excavation of 32.5 m is also rarely exceeded, the experience learned is thus extremely valuable.

4.3 Wall Movements of Toes of Diaphragm Walls

The toes of the diaphragm walls were located at depths varying from 56.8 m to 61 m below ground surface. Toe movements are undeniable, even before calibration, as evidenced by the inclinometer readings shown in part (a) of Figs. 15 to 19. The progressive movements at a depth of 56 m, with inclinometer readings duly corrected, are shown in Fig. 22. As can be noted, the toe movements of the western wall were of the same magnitudes as the toe movements depicted in Fig. 7 for Case A. The ground conditions are quite similar in the two cases and the diaphragm walls have the same thickness. Therefore, the agreement between the two cases is very encouraging and provides much confidence on the approach adopted for correcting inclinometer readings.

Table 4 Rates of increases in wall movements in Phase 3 excavations, Case B

Level	Stages	Rates of increases, mm per meter of excavation			
		SO-1	SI-2	SI-8	SI-9
1F (GL−1.5 m*)	3 to 8	0.305	0.525	0.812	1.292
B1F (GL−4.5 m)	3 to 8	0.528	0.665	0.893	1.479
B2F (GL−9 m)	4 to 8	0.825	0.774	1.370	1.806

* Readings at a lower level was analyzed because the top portion of inclinometers were likely to be disturbed

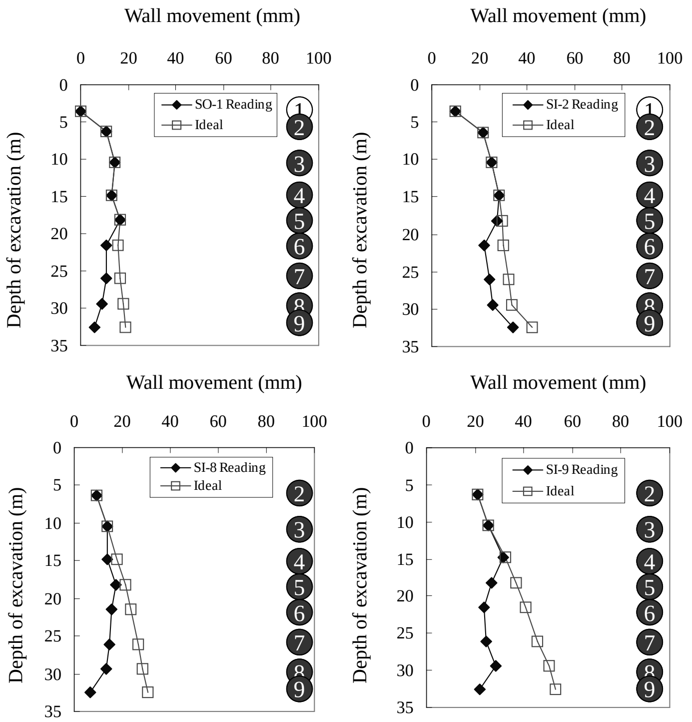


Fig. 20 Progressive wall movements at GL−1.5m, Case B

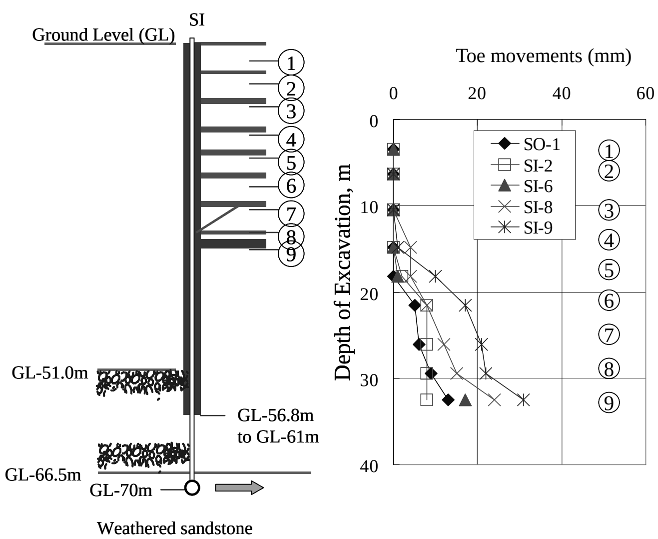


Fig. 21 Progressive movements at toes of inclinometers, Case B

Table 5 Maximum wall movements with toe movements accounted for, Case B

Stage	Depth (m)	Maximum wall movement (mm)				
		SO-1	SI-2	SI-6	SI-8	SI-9
1	3.50	3.4	10.0	9.9		11.7
2	6.35	13.8	22.1	14.1	10.1	20.9
3	10.45	17.5	25.2	18.0	14.3	26.7
4	14.80	19.0	28.6	25.4	18.8	38.5
5	18.15	25.6	30.6	30.2	23.9	55.1
6	21.50	39.8	38.6		27.1	66.2
7	26.05	46.3	42.4		35.4	80.0
8	29.40	55.5	50.6		44.0	95.7
9	32.60	60.4	60.6	67.4	50.1	105.5

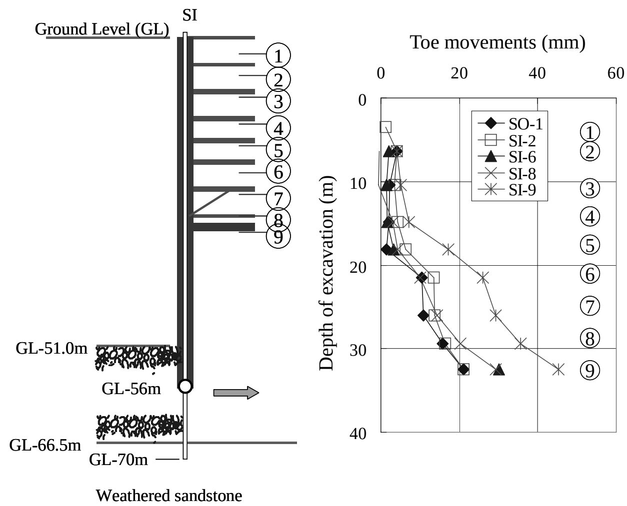


Fig. 22 Progressive movements at the toes of diaphragm walls, Case B

The three cross walls across the northern and the southern walls, refer to Figs. 11 and 14, extended to a depth of 45 m below ground surface, or 12.5 m below the bottom of the final excavation. They served as buried struts and limited wall movements. In fact, they did their job as evidenced by the fact that the toe movements of these walls were reduced by nearly a half as compared with those of the western wall.

4.4 Wall Movements at Other Floor Levels

The progressive wall movements at the B1F level and the B2F levels are shown in Figs. 23 and 24, respectively. The "ideal" curves appear to be very reasonable. The rates of increases in wall movements, with toe movements accounted for, at these levels are compared with those at the first slab level in Table 4. As wall movements in Phase 3 excavation were closely associated with the contraction of the slabs, the fact that the rates of increases in movement for Inclinometer SI-9 were about twice as much as those for Inclinometers SO-1 and SI-2 is believed to be primarily due to the longer spans of the slab in the east-west direction. The high rates for Inclinometer SI-8 were due to the redistribution of the forces released by the cross wall at this location as this cross wall was demolished. The discussion, however, is beyond the scope of this paper.

Although it is not a sufficient proof of the accuracy of the toe movements back-calculated by referencing to the readings at the first slab level as discussed in Section 4.2, checking the reasonableness of wall movements at other slab levels is a necessary process for confirming the reasonableness of the corrections made to the readings. The excellent results depicted in Figs. 23 and 24 do increase the confidence on the approach adopted.

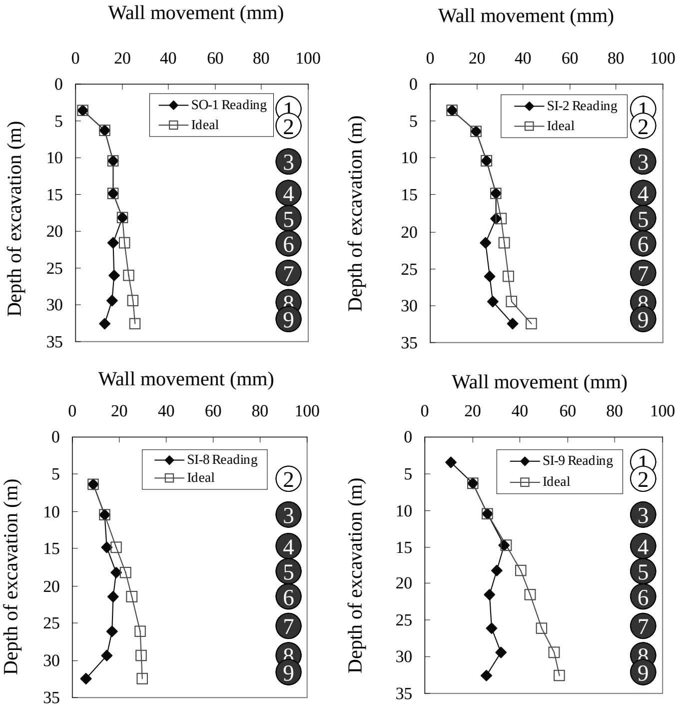


Fig. 23 Progressive wall movements at the B1F level

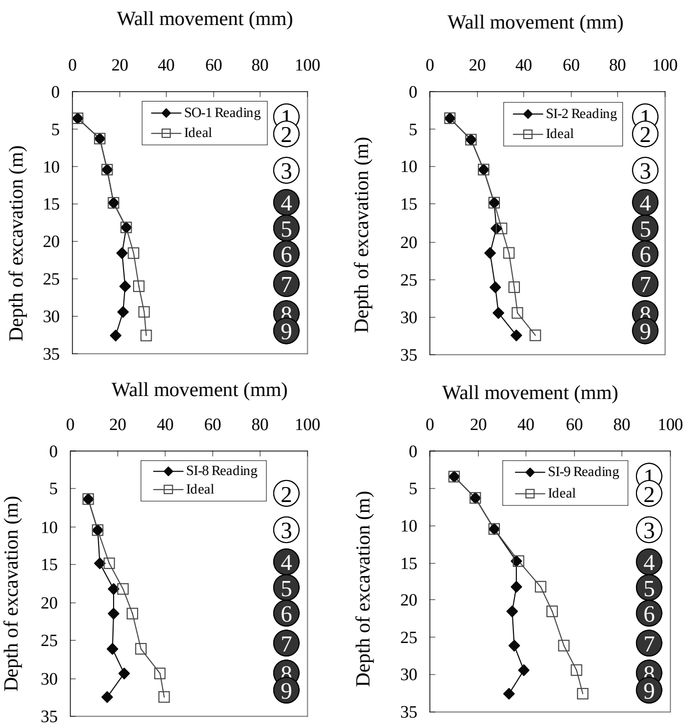


Fig. 24 Progressive wall movements at the B2F level

4.5 Wall Deflection Paths and Reference Envelopes

The wall deflection paths, which are the plots of the maximum wall movements listed in Table 5 versus depths of excavation, are shown in Figs. 25, 26, and 27. Also shown in these figures are the reference envelopes which are the envelopes of wall deflection paths. The Δ_4 and Δ_{100}, as well as Δ_{30}, values corresponding to these envelopes are summarized in Table 6.

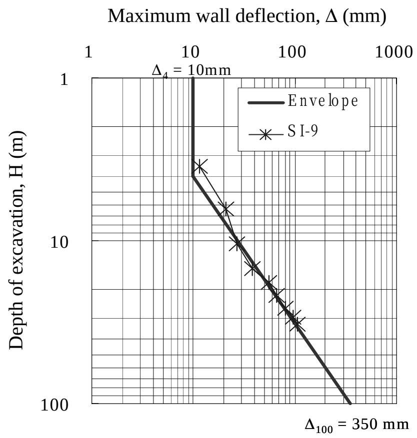


Fig. 25 Deflection paths and reference envelope for walls with buttresses only, Case B

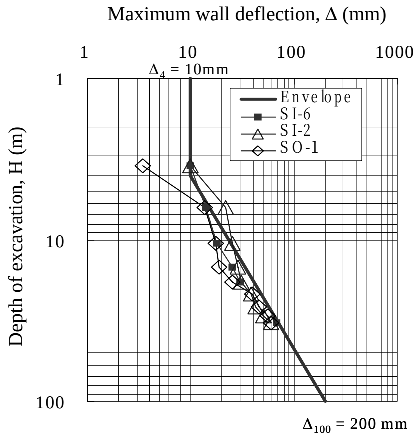


Fig. 26 Deflection paths and reference envelope for walls with buttresses and cross walls, Case B

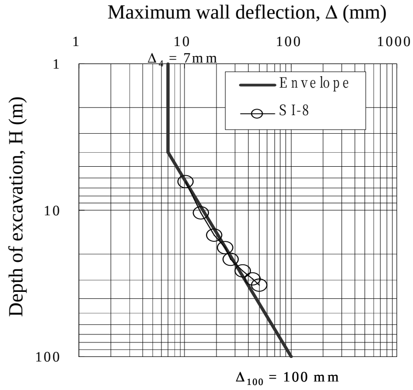


Fig. 27 Deflection paths and reference envelopes for walls at joints with cross wall, Case B

Table 6 Effectiveness of buttresses and cross walls, Case B

Wall conditions	Location	Δ_4 (mm)	Δ_{100} (mm)	Δ_{30} (mm)
Walls with buttresses (Fig. 25)	SI-9	10	350	95
Walls with buttresses and cross walls (Fig. 26)	SO-1, SI-2, SI-6	10	200	65
Walls at the joints with cross walls (Fig. 27)	SI-8	7	100	35

5. DISCUSSIONS

5.1 Performance of Buttresses

The reference envelope for walls with buttresses only is compared with that obtained in Case A in Fig. 28. Also shown in the figure is the envelope for flat walls without buttresses. The buttresses in Case B appear to be more effective than those in Case A. For a depth of excavation of 20 m, for example, the maximum wall movements were reduced from 190 mm for flat walls to 60 mm by the former and to 90 mm by the later. The buttresses in Case B were much wider and much longer than those in Case A as depicted in Fig. 13. Besides, they were embedded in the Chingmei Gravels by a few meters. Therefore, it is reasonable for them to out-perform their counterparts in Case A.

For depths of excavations exceeding 20 m, the difference between the two cases diminishes as the two envelopes converge toward each other. For a depth of excavation of 30 m, the Δ_{30} values are 300 mm for flat walls without buttresses, 95 mm for walls with buttresses in Case B and 130 mm for walls with buttresses in Case A.

It, however, should be noted that the deflection path for flat walls tend to bend down, as shown in Fig. 8, as the bottom of excavation approached the base stratum and the comparison of Δ_{30} values may not be valid. For example, the maximum wall movement at the location of Inclinometer SID-8 was only 192 mm as read from the corrected inclinometer readings, instead of 300 mm as extrapolated from the reference envelope, at the end of final excavation. The competent base stratum indeed helped to restrain wall movements and reduced the reliance on buttresses for the purpose.

5.2 Performance of Cross Walls

The reference envelope for the northern and southern walls, *i.e.*, the one shown in Fig. 26, is compared with that for the western wall, *i.e.*, the one shown in Fig. 25, in Fig. 29. Although the buttresses supporting the northern and the southern walls were much narrower in comparison with those supporting the western wall, the three cross walls apparently made up the deficiency as the wall movements of the northern and southern walls were obviously smaller than the wall movements of the western wall. However, it should be noted, the fact that the slabs are shorter in the north-south direction is also a contributing factor to the reductions in wall movements, but its influence is difficult to quantify.

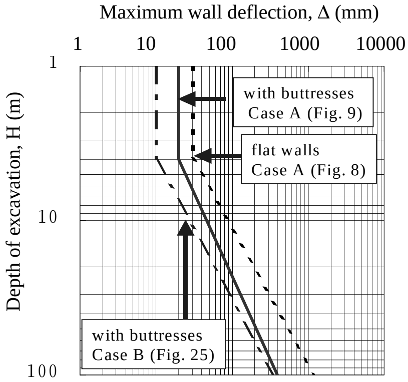


Fig. 28 Comparison of reference envelopes for walls with and without buttresses

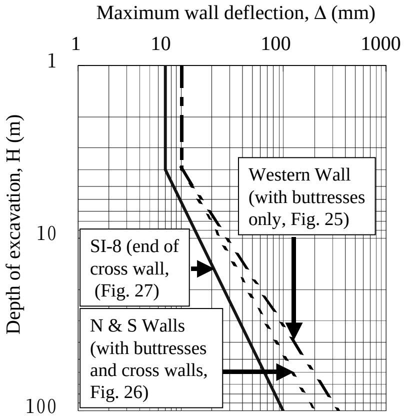


Fig. 29 Comparison of reference envelopes for walls with and without cross walls, Case B

Also compared in Fig. 29 is the envelope for wall movements at the location of Inclinometer SI-8 which was installed right at the end of one of the cross walls. It is apparent that cross walls were very effective in reducing wall movements.

6. CONCLUSIONS

The foregoing discussions lead to the following conclusions:

1. Movements of the toes of diaphragm walls in the two cases were as much as 40 mm and it is therefore important to correct inclinometer readings.
2. For flat walls without buttresses nor cross walls, the Δ_4 values are insensitive to the stiffness of walls.
3. The Δ_{100} values for excavations using the top-down method of construction are larger than those for excavations using the bottom-up method of construction.
4. Cross walls are very effective in reducing wall deflections.
5. The effectiveness of buttresses will highly depend on the configuration of buttresses.

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