Deep Excavations in Taipei Basin and Performance of Diaphragm Walls

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ABSTRACT: Since movements of diaphragm walls are reduced by the presence of existing underground structures in the vicinity of excavation, comparison of the observed wall deflections with the results obtained by using two-dimensional analyses may lead to erroneous conclusions. Similarly, additions to diaphragm walls, such as buttresses, station entrances, ventilation shafts, etc., will also tend to reduce wall deflections. It is thus recommended to compare the results of two-dimensional analyses with the upper envelopes, designated as "reference envelope", of a family of wall deflection paths of the same geometry of excavation and the same characteristics of the retaining system.

Inclinometer readings obtained at Shandao Temple Station of the Bannan Line of Taipei Metro were studied to establish the relationship between wall deflections and depth of excavations. The results are verified by numerical analyses using computer program PLAXIS. Reference envelopes were developed for the T2 Zone for estimating maximum wall deflections and charts were established for correcting inclinometer readings to account for the movement at diaphragm wall toes. It has been found that the width of excavation has significant influence on wall deflections and toe movements. It has also been found that consolidation of the Songshan Formation due to the drawdown of groundwater in the Jingmei Formation reduce the movements of diaphragm wall toes.

KEYWORDS: Deep excavation, Taipei Basin, Diaphragm wall, Wall deflection, Toe movement, Parametric study, PLAXIS

1. INTRODUCTION

Ground movements induced by excavations often result in damage to adjacent structures and/or utilities, therefore it is necessary to minimize ground movements behind retaining structures by adopting suitable retaining systems together with suitable excavation schemes. This calls for optimization of designs in consideration of both safety and cost effectiveness. For deep excavations in soft ground, diaphragm walls are normally adopted to maintain the stability of side walls of excavations because of the high rigidity of the walls. Ground movements behind the walls are normally closely related to the wall deflections; therefore, it is necessary to estimate wall deflection for assessing the potential risk to adjacent structures and/or utilities.

To estimate wall deflections accurately, it is important to have correct soil properties which are normally obtained by comparing the observed wall deflections with the results of back analyses. However, wall deflections deduced from inclinometer readings were often misleading if the tips of inclinometers moved as excavation proceeded. Furthermore, wall deflections are frequently affected by buried structures and/or utilities in the vicinity of excavation, the comparison between the observed wall deflections with the results of numerical analyses may not be reliable.

This paper discusses movements of diaphragm walls in thick soft deposits with emphasis on the movements at the toes. The excavation carried out for constructing Shandao Temple Station of Taipei Metro was adopted for illustration and back analyses were performed by using the computer program PLAXIS (PLAXIS, 2009).

2. GEOLOGY OF THE TAIPEI BASIN

The Taipei Basin, refer to Figure 1, was formed by tectonic movements starting in Middle Pleistocene Epoch; and young deposits subsequently accumulated all the way to the surface with a maximum thickness exceeding 500m. At the top is the so-called Songshan Formation of, up to, 60m in thickness underlain by the Jingmei Formation followed by the Xinzhuang Formation (lately divided into Wugu and Banqiao Formations, Teng, et al. 1999) all the way to the bottom of the basin. Figures 2 and 3 show the north-south and east-west sections, respectively, of the basin. As can be noted, the Songshan Formation consists of an alternation of silty clay and silty sand sublayers and the six-sublayer sequence is most evident in the central city area where the Taipei Main Station (BL7/R13 Station of the Taipei Rapid Transit Systems) is located. Figure 4 shows typical results of cone penetration tests in the T2 Zone. Toward the east, the sandy sublayers diminish and clayey sublayers become dominating; and toward the west the stratigraphy becomes rather complicated with silty sand and silty clay seams interbedded in these sublayers. Based on the data collected from numerous boreholes sunk in the basin, Lee (1996) proposed to divide the Basin into 21 zones as depicted in Figure 1 which is adopted herein for categorizing ground conditions.

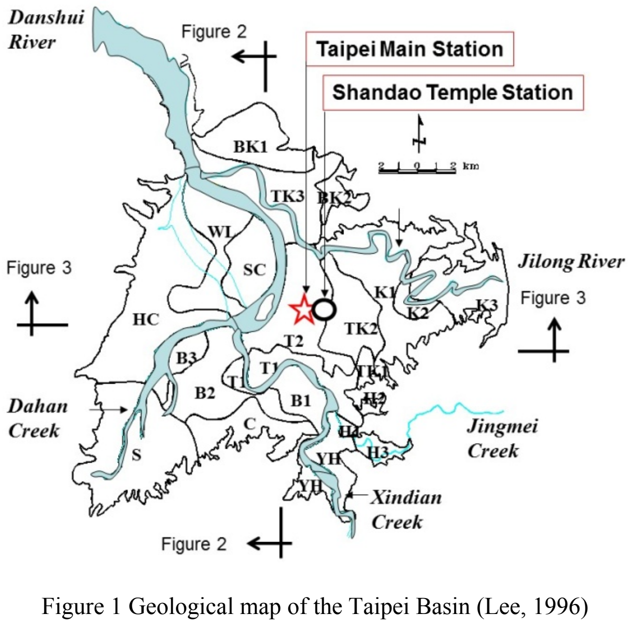


Figure 1 Geological map of the Taipei Basin (Lee, 1996)

The presence of the Jingmei Formation is a unique feature of the Taipei Basin. This water-rich, highly permeable gravelly stratum was responsible for several disastrous failures in underground constructions in the 1990's. It was frequently necessary to lower the piezometric level of the groundwater in this formation to avoid uplifting and/or piping in deep excavations. The characteristics of this formation and dewatering schemes adopted for the said purpose are discussed in Yang, et al. (2016) available in this volume.

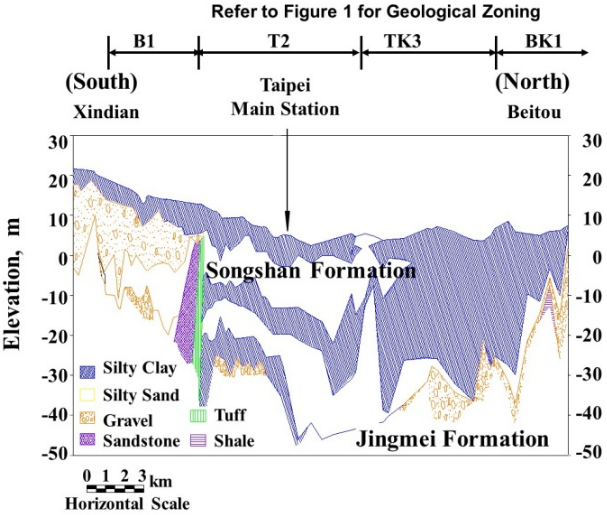


Figure 2 North-south geological section of the Taipei Basin

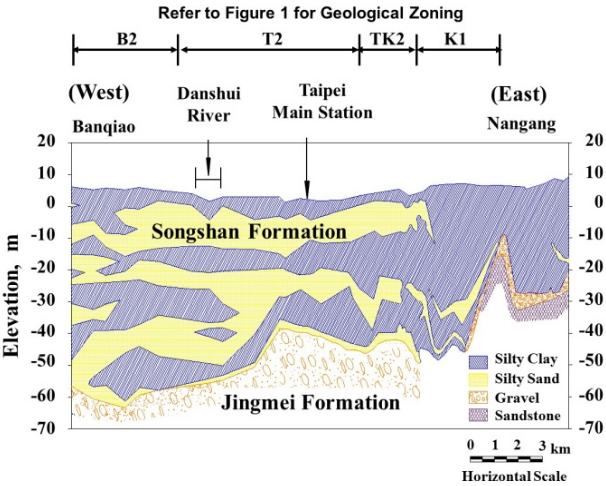


Figure 3 East-west geological section of the Taipei Basin

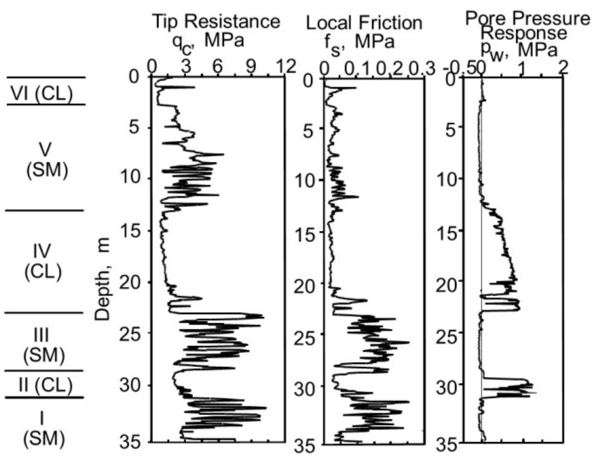


Figure 4 Typical results of cone penetration tests in T2 Zone

3. DEEP EXCAVATIONS IN THE TAIPEI BASIN

Excavations seldom exceeded 30m in depth in the old days for various reasons but, with increasing demand for underground spaces and with advanced construction technology, excavations exceeding this depth are very common nowadays. It is therefore desirable to re-define deep excavations to comply with the state-of-the-practice. Hwang (2006) proposed to classify excavations into 5 categories, from shallow to extremely deep, as depicted in Table 1.

Prior to the commencement of constructions of the Taipei Metro (i.e., Taipei Rapid Transit Systems) in the early 1990's, deep excavations were mainly carried out for constructing basements of highrise structures; and, as depicted in Figure 5, the depths of excavation were, in general, less than 20m. In the 2000's, depths of excavations of quite a few basements already exceeded 30m (Hwang, 2011). For Taipei Metro, excavations exceeding 30m in depth are listed in Tables 2 and 3 for Stage 1 construction carried out in the 1990's and Stage 2 construction carried out in the 2000's, respectively (Hwang, 2011).

Table 1 Classification of excavations (Hwang, 2006)

	Shallow	Median	Deep	Very Deep	Extremely Deep
Depth (m)	<5	5-10	10-20	20-30	>30
Basement Level	1	2-3	4-5	6-7	>7
Metro Station Level			2	3-4	>5

Table 2 Extremely deep excavations in Stage 1 Metro construction

Site	Metro Line	Depth (m)
Jingan Station (O18)	Zhonghe-Xinlu Line	30.23
Ventilation Shaft	Zhonghe-Xinlu Line	34.95
Ventilation Shaft A	Bannan Line	36.6
Ventilation Shaft B	Bannan Line	33.81

Table 3 Extremely deep excavations in Stage 2 Metro construction

Site	Metro Line	Depth (m)
Beimen Station (G14)	Songshan-Xindian	32.1
Dongmen Station (R10/O14)	Danshui-Xinyi	31.2
Taipei Bridge Station (O7)	Zhonghe-Xinlu	33
Turnout	Zhonghe-Xinlu	40
Daqiaotou Station (O8)	Zhonghe-Xinlu	32

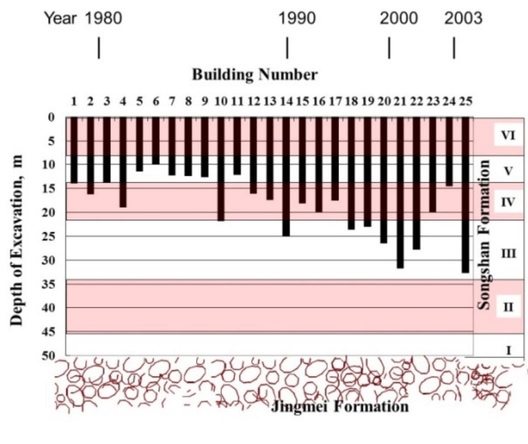


Figure 5 Basement excavations in Taipei Basin (Hwang, 2011)

4. WALL DEFLECTION PATHS AND REFERENCE ENVELOPES

Ground settlement which is one of the primary factors affecting the structures in adjacent to excavations are closely related to the maximum wall deflections. The maximum wall deflection thus become the most important subject in evaluating the performance of diaphragm walls. For deep excavations in thick soft deposits, Figure 6(a) shows the results normally expected from monitoring of wall deflections. The wall behaves as a cantilever in the first stage of excavation (i.e., the 1st dig) and significant movement would normally occur in soft ground before the struts at the first level are installed. During this stage of excavation, the rigidity of the wall contributes very little in reducing wall deflections. Once the struts at the first level are installed and preloaded, the wall will behave as a plate supported at its upper end and the rigidity of the wall starts to show its significance. In normal cases, the wall will bulge in toward the pit in subsequent stages of excavation while the movements of the wall at each of the strut levels, once struts are preloaded, are mainly induced by the shortening of struts and are expected to be small. Accordingly, it has been proposed to calibrate inclinometer readings by assuming that the joints between the 1st level struts and diaphragm walls would not move after preloading of the struts (Moh and Hwang, 2005, Hwang, et al., 2007).

Figure 6(b) shows a “wall deflection path”, which is a plot of maximum wall deflections versus depth of excavation at various stages of excavation in a log-log scale. This concept of wall deflection path was first introduced in Moh and Hwang (2005) as a tool for evaluating the performance of diaphragm walls. The wall deflection paths for walls of 1m in thickness at 3 sites in the T2 Zone are presented in Figure 7 (Moh and Hwang, 2005). The numerals in the legends denote site numbers and the alphabets following these numerals are the designations of inclinometers at these sites. The extension of the reference envelope beyond the true depth of excavation is merely for the convenience of defining the envelope, as to be illustrated in a later section, and does not imply the validity of the relationship between wall deflections and depth of excavation beyond the true depth of excavation.

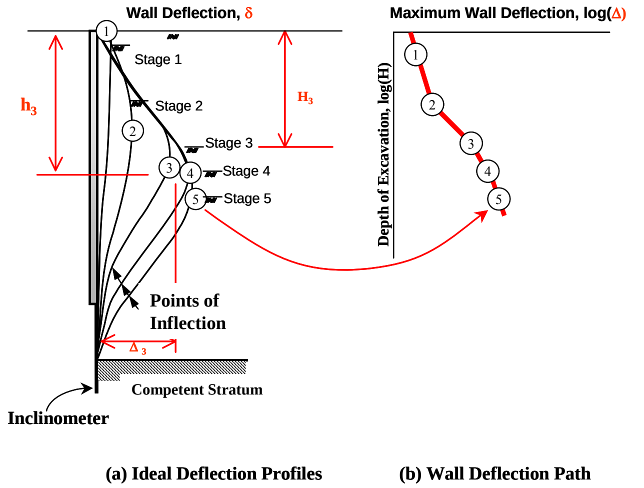


Figure 6 Idealized wall deflection profile and wall deflection path

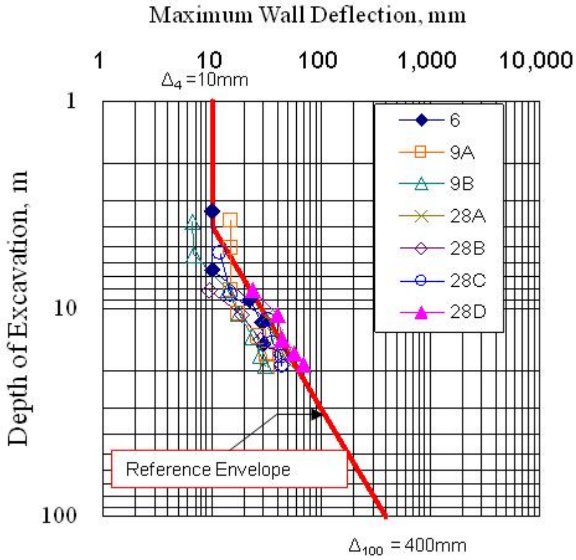


Figure 7 Wall deflection paths in the T2 Zone and reference envelope for 1m-thick diaphragm walls (Moh and Hwang, 2005)

In congested cities, there are most likely high-rise buildings with deep basements and large infrastructures such as underpasses, drainage boxes and common ducts, etc., alongside new excavations. This is particularly true for excavations for metro stations and cut-and-cover tunnels, Figure 8 as a typical example, which are normally constructed underneath major streets. These basements and large infrastructures normally have retaining structures left in-place after the completion of construction, hence, wall deflections in new excavations are very likely to be reduced as a result. Furthermore, there are always entrances, ventilation shaft, etc., as depicted in Figure 8, structurally connected to the station walls and, therefore, the rigidity of the walls is much increased and wall deflections are much reduced. Wall deflections are routinely monitored by using inclinometers. Some of the inclinometers may locate close to corners and their movements are restrained by the side walls. Since all these factors are not considered in back analyses which are normally carried out by two-dimensional numerical analyses, Figure 9 for example, comparison of the results obtained in back analyses with the observed performance of the walls is hence questionable and often leads to wrong conclusions. It is therefore desirable to have a means to quantify the influence of adjacent structures, and also many other factors which may affect wall deflections, so the performance of walls can be faithfully evaluated.

Since wall deflections are likely to have been reduced by the various factors mentioned above, the upper envelope of wall deflection paths would be a better tool to represent wall deflections without the influence from adjacent structures. In other words, the upper envelope of a family of wall deflection paths, instead of any single path, is closer to the wall deflection path for excavations in green field which is a scenario assumed in back analyses. This envelope is referred to as “reference envelope” hereinafter. Once the reference envelope is available for a particular site, the influence of many factors can be identified and evaluated by comparing the wall deflection paths observed with this reference envelope (Moh and Hwang, 2005).

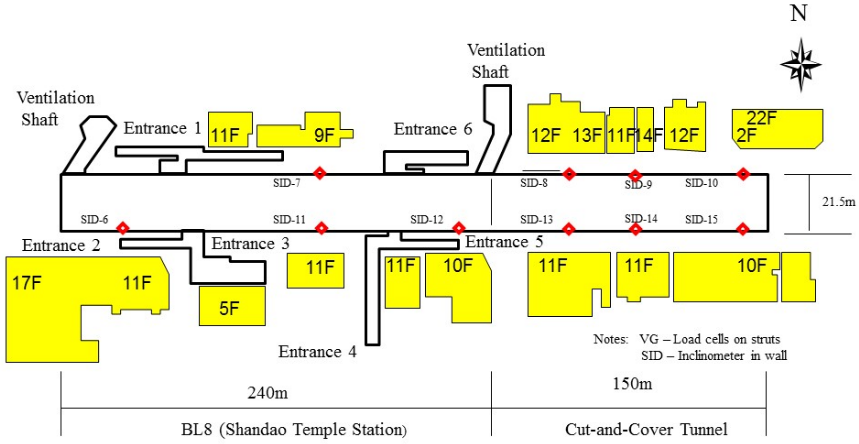


Figure 8 Setting of Shandao Temple Station (BL8 Station) of Taipei Metro and locations of inclinometers

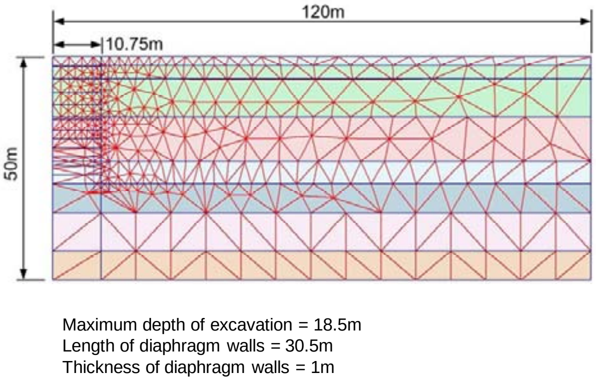


Figure 9 Finite element model adopted for Shandao Temple Station

The reference envelope for walls of 1m in thickness for the T2 Zone is shown in Figure 7. As suggested in Moh and Hwang (2005), reference envelopes are established by taking into account the data points in the range of excavation of 10m and 20m only and are defined by Δ_4 and Δ_{100} which are the maximum wall deflections for depths of excavation of 4m and the wall deflections projected to a depth of excavation of 100m, respectively. Accordingly, the reference envelope shown can be defined by Δ_4 = 10mm and Δ_{100} = 400mm.

5. CASE STUDY

The case of Shandao Temple Station has been extensively analysed to provide benchmark information for parametric studies (Hwang, et al., 2007; 2012). Figure 10 shows the excavation scheme adopted and Figure 11 shows the groundwater pressures acting on the outer face of diaphragm wall. Inside the pit, the groundwater table was maintained at 1m below the bottom of excavation. The soil properties adopted in the analyses are given in Table 4 and the Mohr-Coulomb model was adopted to simulate soil behaviour.

Table 4 Soil properties and soil parameters adopted

Depth (m)	Soil Type	γ_t (kN/m^3)	N (blows)	S_u (kPa)	c' (kPa)	Φ' (deg)	E' (MPa)
0-2	CL	18.6	3	20			10
2-13.5	SM	18.4	8	-	0	33	16
13.5-23.5	CL	18.8	6	40			20
23.5-28.5	SM	19.3	18	-	0	32	36
28.5-35	CL	19.4	17	150			75
35-43.5	CL	19.4		200			100
43.5-50	SM	21.6	30	-	0	35	60

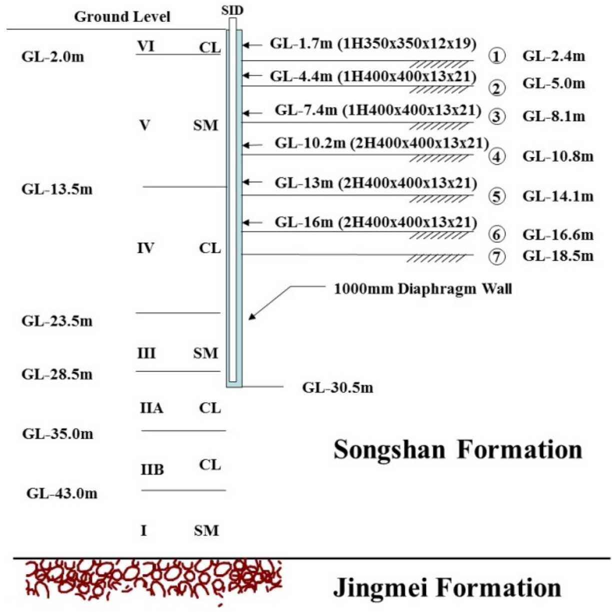


Figure 10 Excavation scheme for Shandao Temple Station

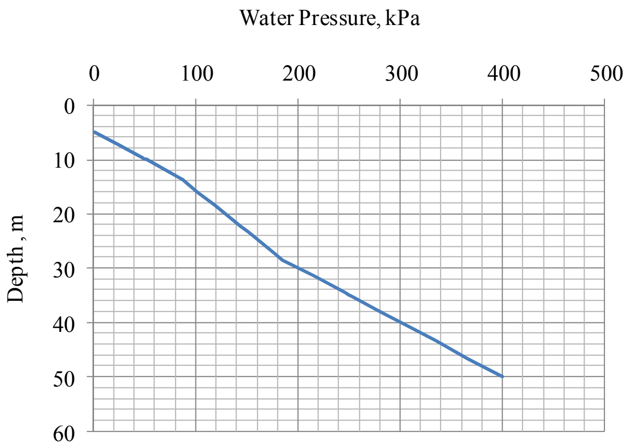


Figure 11 Groundwater pressures on the outer face of diaphragm wall

The computer program PLAXIS was adopted for the analyses and the finite element model is shown in Figure 9. The results of analyses for all the stages of excavation are shown in Figure 12. The computed wall deflections in Stage 4 to Stage 7 excavations are compared with those obtained by Inclinometer SID12 which recorded the largest wall deflections among all the inclinometers, in Figure 13. As can be noted, the deflection profiles in the two cases are the same at the end, but the analyses over-estimated wall deflections in the earlier stages of excavation due to the fact that soil moduli were under-estimated using the Mohr-Column model.

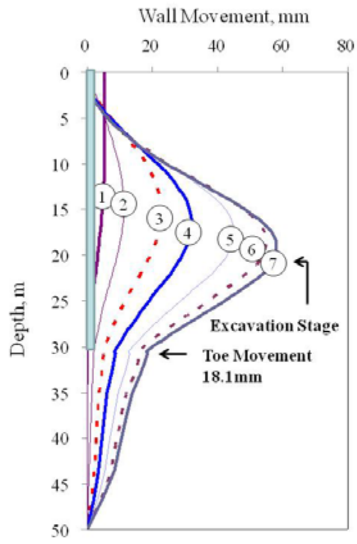


Figure 12 Wall deflection profiles obtained by PLAXIS analyses (Hwang, et al., 2012)

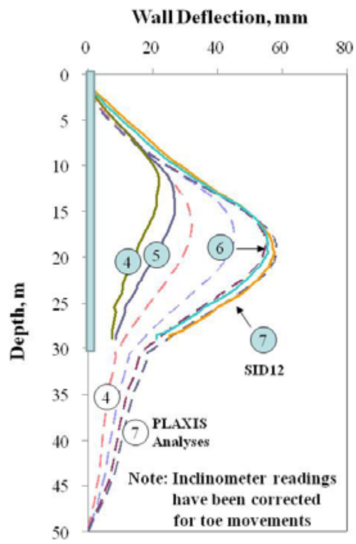


Figure 13 Comparison of results of PLAXIS analyses with inclinometer readings (Hwang, et al., 2012)

The results of analyses are compared with the reference envelope developed for T2 Zone in Figure 14. The idealized wall deflection path deduced from the results of PLAXIS analyses can be defined by Δ_4 = 10mm and Δ_{100} = 500mm which is quite close to the reference envelope defined by Δ_4 = 10mm and Δ_{100} = 400mm.

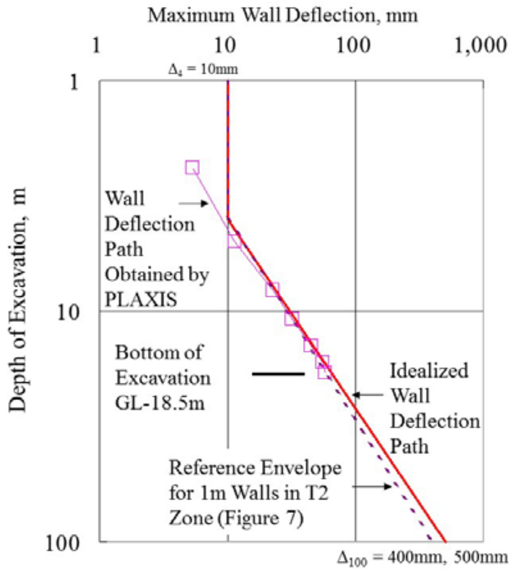


Figure 14 Wall deflection paths obtained by PLAXIS analyses (Hwang, et al., 2012)

6. TOE MOVEMENTS OF DIAPHRAGM WALLS

As can be noted from Figure 10, the diaphragm wall penetrated into Sublayer II of the Songshan Formation by 2m. It is therefore envisaged that the strength of this sublayer has dominating influence on toe movements of the diaphragm walls. This sublayer has been much consolidated as the piezometric level of groundwater in the Jingmei Formation was lowered by more than 40m in the 1970's, refer to Figure 15. As depicted in Table 5, the undrained shearing strength of this sublayer was increased by a factor of 2 in the 1990's as a result of consolidation using the SHANSEP relationship as follows (Ladd and Foott, 1974):

$$S_u/\sigma'_{vo} = S \times OCR^m \quad (1)$$

$$S = (S_u/\sigma'_{vo})_{nc} \quad (2)$$

and, for the case of interest, S = 0.32 and m = 0.8 (Chin, et al., 1994).

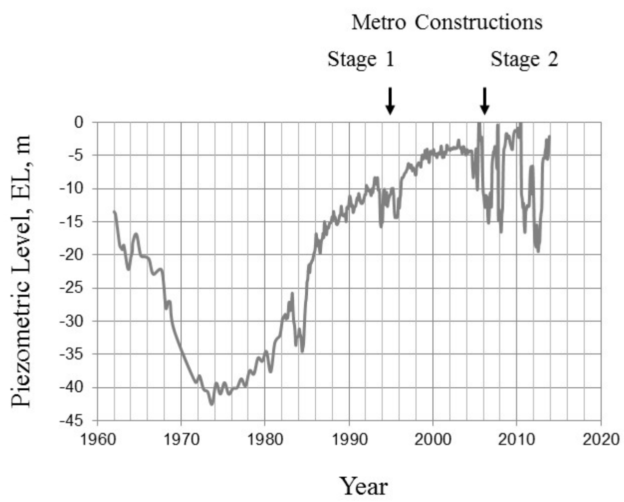


Figure 15 Piezometric levels of groundwater in the Jingmei Formation in T2 Zone

Table 5 Undrained shearing strengths of Sublayer II of Songshan Formation (Hwang, et al., 2013)

Period	Overburden Pressure (kPa)	Water Level GL	Porewater Pressure (kPa)	Effective Vertical Pressure (kPa)	OCR	Su (kPa)
Initial	756	+0m	400	356	1	114
70's	756	-40m	0	756	1	242
90's	756	-14m	260	496	1.52	224

Note: Depth considered = GL-40m, Refer to Table 4 and Figure 10

Excavation for Shandao Temple Station was carried out in 1993. It will be interesting to investigate how much the difference would have been if Sublayer II were not consolidated. Figure 16 shows the result of analyses with the Su and E' values for the CL layers between depths of 28.5m and 43.5m reduced by a half. Although the excavation was carried out to a depth of 18.5m in only 7 stages, analyses were proceeded further down to test the stability of the toe of diaphragm wall. As can be noted from the figure, the toe appears to be stable till Stage 8 excavation and subsequently the toe movement increases rapidly. Figure 17 compares the wall deflection paths for these two scenarios. As can be noted, the maximum wall deflections are about the same till Stage 8 excavation. Subsequently, the maximum wall deflection more or less remains constant for the scenario with Sublayer II over-consolidated while that for the scenario with Sublayer II normally consolidated increases rapidly.

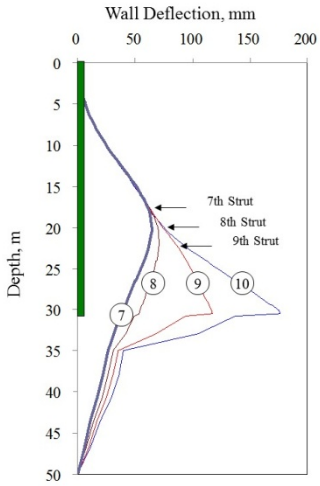


Figure 16 Computed wall deflection profiles for case with Sublayer II normally consolidated

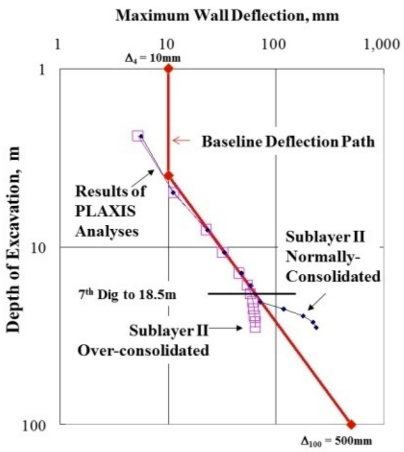


Figure 17 Wall deflection paths with and without Sublayer II over-consolidated

Notwithstanding the fact that the maximum wall deflections are the same for the two scenarios till Stage 8 excavation, as can be noted From Figure 18, the toe movements for the scenario with Sublayer II normally consolidated are larger than those for the scenario with Sublayer over-consolidated in all stages of excavation.

It is very difficult to obtain soil samples of good quality at great depth; therefore, the strengths of Sublayer II are often under-estimated due to sample disturbance. Undrained shearing strengths less than 100 kPa are frequently quoted in design reports. The agreement between the toe movement registered by inclinometer and that obtained from PAXIS analyses, refer to Figure 13, suggests that the strengths given in Table 4 are appropriate.

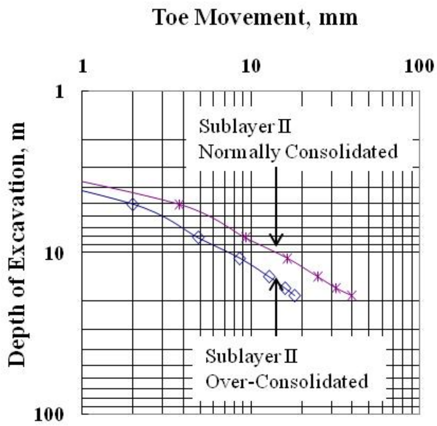


Figure 18 Movements at diaphragm wall toes with and without Sublayer II over-consolidated

7. ESTIMATION OF TOE MOVEMENTS

It is apparent from Figure 13 that the movements at the toe of diaphragm wall, i.e., 18.1mm at the completion of excavation, are too large to be ignored in back analyses. This is a very important fact to be recognized as it has become quite common nowadays to install inclinometers in diaphragm walls and stop at the toe levels, as was the case of interest. Since inclinometer readings are calculated by assuming the tip of the inclinometer as a fixed reference point, they will be misleading if the diaphragm wall toe does move. It is also frequent to specify a fixed length for all the inclinometers at the same site, instead of sufficient penetrations in the firm stratum in which the inclinometers are supposed to be anchored. As the top of the firm stratum may vary drastically, some of the inclinometers may stop short of the firm stratum and their tips may move as excavation proceeds. It is also vital to correct inclinometer readings in such cases.

In ideal cases, inclinometer readings can be calibrated by assuming that once the 1st or the 2nd levels of struts are installed and preloaded, the joints between these struts and the diaphragm walls would not move subsequently because of the high rigidity of struts. This assumption is proved by the results of numerical analyses as depicted in Figure 12. The movements at the toe can then be obtained accordingly and the results appear to be reasonable as depicted in Figure 13. More details are available in Hwang, et al., (2007).

Other than soil strengths, wall deflections, hence, toe movements, are affected by many factors. Figure 19 shows the toe movement paths for different widths of excavation obtained by PLAXIS analyses. It is readily apparent that the influence of width of excavation is very significant. Regarding the lengths of walls, Figure 20 is a chart previously proposed by Hwang, et al. (2007) based on the inclinometer readings obtained from this site and 2 other sites for correcting readings to account for toe movements. This chart can be replotted in the same way as wall deflection path, i.e., in a log-log scale, as shown in Figure 21. The 3 lines shown in the figure represent toe movement paths and can be defined by Δ_5 = 2mm, 3mm and 6mm for walls with lengths of 35m, 30m and 24m, respectively, and $\Delta_{20} = 15\Delta_5$. The toe movement paths for walls of 24m and 30m in length match those given in Figure 20 nearly perfectly. The path for walls of 35m in length was slightly modified so the three paths are now parallel and the paths for other wall lengths can easily be established by interpolation or extrapolation.

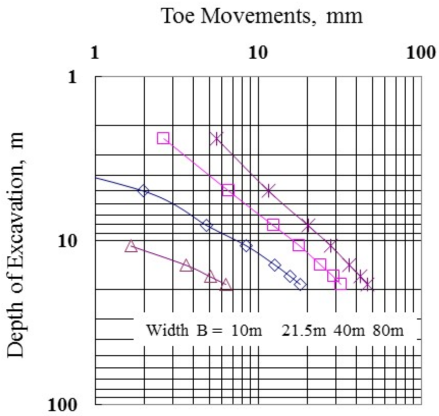
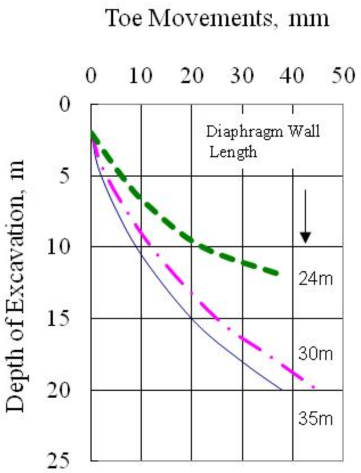


Figure 19 Influence of width of excavation on toe movements for walls of 30m in length



(Ref: Hwang, et al. 2007)

Figure 20 Potential movements at diaphragm wall toes

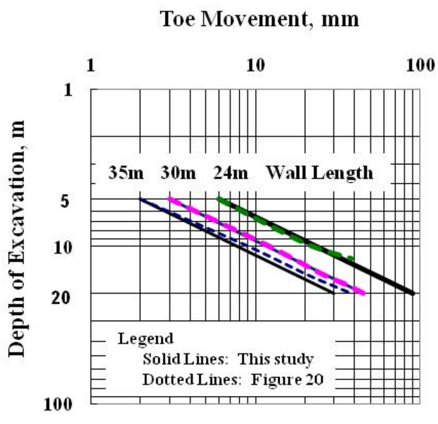


Figure 21 Influence of length of diaphragm walls on toe movements

Figure 19 and Figure 21 can be adopted together to estimate toe movements. The procedures are as follows:

1. Estimate toe movement based on the depth and the width of excavation using Figure 19. The results obtained are for walls of 30.5m in length but for practical purposes they can be deemed applicable to 30m walls.
2. Adjust the result based on the true length of the wall by proportioning in accordance with the ratios of Δ_5 values shown in Figure 21. For example, toe movements for 35m walls would be two-thirds of those for 30m walls and toe movements for 24m walls would be twice those for 30m walls.

These two figures are expected to have covered the practical ranges of lengths of walls and widths of excavations. For widths of excavation not shown in Figure 19 and for wall length not shown in Figure 21, the target values can be obtained by interpolation.

8. ESTIMATION OF REFERENCE ENVELOPES

Figure 22 shows the wall deflection paths for walls of different thickness obtained by PLAXIS analyses (Hwang, et al., 2012). The fact that the Δ_4 values are the same regardless of wall thickness supports the statement made in Section 4 that the rigidity of walls contributes very little in reducing wall deflections in the first stage of excavation. The Δ_{100} values increase as wall thicknesses reduce as expected and are 300mm, 500mm and 1000mm for walls of 1500mm, 1000mm and 600mm in thickness, respectively. For walls with other thicknesses, Figure 23 can be adopted to obtain the Δ_{100} values by interpolation and/or extrapolation.

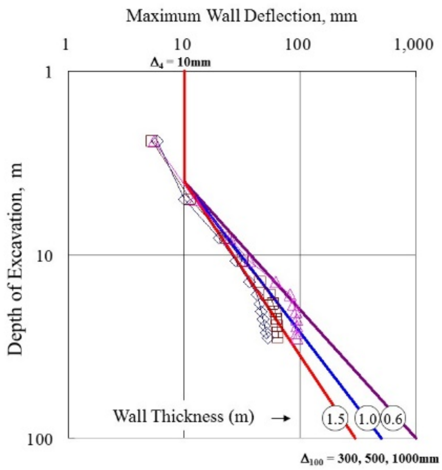


Figure 22 Influence of wall thickness on wall deflection paths (Hwang, et al., 2012)

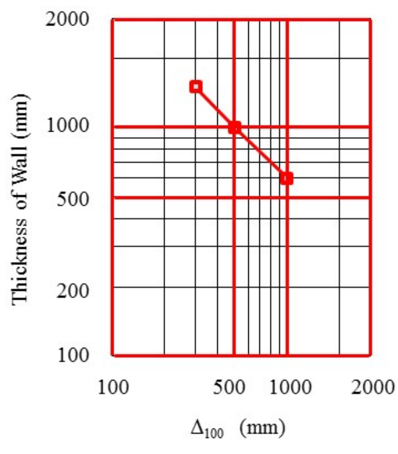


Figure 23 Influence of wall thickness on Δ_{100} values

Figure 24 shows the wall deflection paths for excavations of 10m, 21.5m, 40m and 80m in width for the case of interest (Hwang, et al., 2012). It is interesting to note that, the Δ_4 values are, roughly, proportional to the width of excavation while the Δ_{100} values appear to be unaffected. It should be emphasized herein that wall deflection paths are established by considering the deflections for depths of excavation in the range of 10m to 20m only.

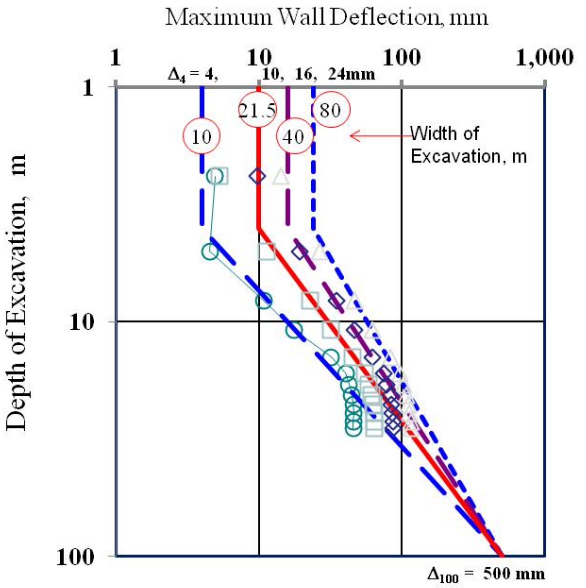


Figure 24 Influence of width of excavation on wall deflection paths (Hwang, et al., 2012)

Based on the inclinometer reading obtained at a limited number of sites, Hwang and Moh (2007) proposed the reference envelopes for the T2, TK2 and K1 (refer to Figure 1 for locations) Zones as depicted in Table 6. At that time, the dominating influence of width of excavation on the Δ_4 was not recognized. With the current finding, the validity of this table is dubious.

Table 6 Reference envelopes for T2, TK2 and K1 Zones (Hwang and Moh, 2007)

Wall Thickness t (mm)	Δ_4, mm			Δ_{100}, mm		
	T2	TK2	K1	T2	TK2	K1
600	10	12		1600	1600	
700		12			1200	
800	10	12	30	800	800	800
900		12	30		600	600
1000	10		30	400		400
1200	10			200		
Note: This table is superseded by Table 7						

A review of the data, which served as a basis for establishing the reference envelopes given in Table 6, reveals that the excavations quoted to in the T2 Zone were mainly excavations for metro constructions with widths ranging from 15m to 25m while those in the K1 Zone were mainly private developments with widths of excavations ranging from 40m to 100m. It is hence suspected that the differences between the Δ_4 values among the 3 zones shown in the table are due to the differences in widths of excavations, rather than ground conditions. Accordingly, Table 7 is proposed to replace Table 6. It is expected to be valid for excavations in the K1, TK2 and most of T2 Zones with thickness of the Songshan Formation in the range of 40m to 50m. As can be noted from Figure 3, below the Danshui River, and further to the west, the Songshan Formation reaches a depth of 60m, and wall deflection paths are expected to be different from what are given in the table. In any case, the validity of this table remains to be confirmed by further studies.

Table 7 Revised reference envelopes for T2, TK2 and K1 Zones

Wall Thickness t (mm)	Wall Deflections (mm)							
	B = 10m		B = 20m		B = 40m		B = 80m	
	Δ_4,	Δ_{100}	Δ_4,	Δ_{100}	Δ_4,	Δ_{100}	Δ_4,	Δ_{100}
600	4	1000	10	1000	16	1000	24	1000
1000	4	500	10	500	16	500	24	500
1500	4	300	10	300	16	300	24	300
Note: B = width of Excavation								

9. CONCLUSIONS

The foregoing discussions lead to the following conclusions:

1. For deep excavations in thick soft deposits, toe movements are significant if diaphragm walls are not long enough and/or not well anchored in a firm base stratum.
2. Inclinometer readings may be misleading if the tips of the inclinometers moved.
3. In most cases, inclinometer readings can be corrected by assuming the joints between the struts at the first level and the diaphragm walls will not move once these struts are preloaded.
4. Since the movements of diaphragm walls are reduced by the presence of existing underground structures in the vicinity of excavation, comparison of the observed wall deflections with the results obtained by using two-dimensional analyses may lead to erroneous conclusions.
5. Similarly, additions to diaphragm walls, such as buttresses, station entrances, ventilation shafts, etc., will also tend to reduce wall deflections. It is thus recommended to compare the results of two-dimensional analyses with the upper envelopes of a family of wall deflection paths of the same geometry of excavation and the same characteristics of the retaining system.
6. The consolidation of Sublayer II of the Songshan Formation due to the drawdown of groundwater in the past increased the shearing strength of this sublayer and reduces wall movements.
7. The width of excavation is one of the most important factors affecting wall deflections and should be taken into account in the assessment of wall deflections.

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