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Performance of deep excavations in the Taipei Basin

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ABSTRACT: The concept of wall deflection path and reference envelope is introduced herein for evaluating the performance of diaphragm walls. It has been found that, at a given site, wall deflection paths, which are plots of maximum wall deflections versus depths of excavation, converge to a narrow band as excavation goes beyond a depth of 10 m or so. The envelope of a family of wall deflection paths, i.e., the so-called reference envelope, characterizes performance of diaphragm walls with a specific set of ground conditions. Based on the data obtained for deep excavations carried out in recent years, reference envelopes are established for the T2, TK2 and K1 Geological Zones of the Taipei Basin and they can be used to evaluate the performance of individual walls. Furthermore, back analyses are performed to calibrate the soil parameters to be adopted in the numerical analyses.

1 INTRODUCTION

Because of the presence of a thick layer of young sediments to a depth of, up to, 60 m in the Taipei Basin, diaphragm walls are normally required for excavations exceeding 8 m in depth. An enormous quantity of field data have been collected in recent years and the performance of diaphragm walls in deep excavations has been analyzed systematically.

The performance of diaphragm walls will be most conveniently evaluated by studying the so-called wall deflection paths which are plots of maximum wall deflections versus depths of excavation in a logarithmic scale. Wall deflection paths at a certain site tend to converge to a narrow band as the excavation goes beyond a depth of 10 m or so. The envelope of a family of wall deflection paths thus characterizes the performance of retaining systems with similar configurations for excavations with similar ground conditions. Based on the data obtained, the so-called reference envelopes have been established for the T2, TK2 and the K1 Zones in the Taipei Basin (Moh & Hwang, 2005; Hwang & Moh, 2007).

The performance of diaphragm walls in the excavation for constructing Sandao Temple Station of the Taipei Metro is evaluated herein to illustrate the application of wall deflection paths and reference envelopes. Furthermore, back analyses are performed to calibrate the soil parameters to be adopted in the numerical analyses.

2 GEOLOGY OF THE TAIPEI BASIN

At the top of the Taipei Basin is the so-called Sungshan Formation of, up to, 60 m in thickness underlain by the Chingmei Gravels. Figures 1 and 2 show the north-south and east-west geological sections, respectively, of the basin. As can be noted, the Sungshan Formation comprises 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 Metro) is located. Toward the east and the north, the sandy sublayers diminish and clayey sublayers become dominating; and toward the west and the south, the stratigraphy of sublayers becomes rather complicated with silty sand and silty clay seams interbedded in these sublayers. Based on the information obtained in recent years, Lee (1996) proposed to divide the Basin into 22 geological zones as depicted in Figure 3 which is adopted herein for categorizing ground conditions.

Figure 4 shows the typical CPT profiles obtained in the T2 Zone. As can be noted that the six-sublayer sequence in the Sungshan Formation is clearly identifiable. The various soil sublayers can better be identified in the porewater pressure profile than tip resistance or local friction. In short, Sublayers I, III and V consist primarily of silty sands and Sublayers II, IV and VI consist primarily of silty clays. The sandy sublayers, i.e., Sublayers I, III and V, thin out toward the east and the north of the basin and become unidentifiable in the K1 Zone as can be noted in Figures 1 and 2. TK2 Zone is a transition between T2 and K1 Zones.

3 WALL DEFLECTION PATHS AND REFERENCE ENVELOPES

A large quantity of field data have been collected in recent years and it is therefore possible to conduct systematic analyses on the performance of retaining

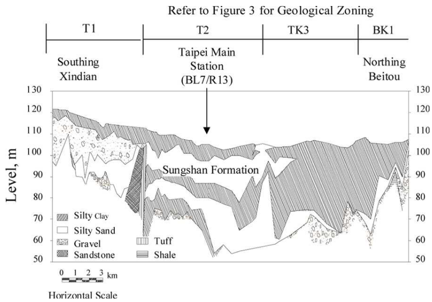

Figure 1. North-south geological section of the Taipei Basin.

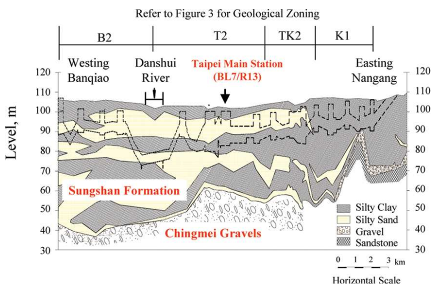

Figure 2. East-west geological section of the Taipei Basin.

systems. As illustrated in Figure 5(b), the maximum deflections in the deflection profiles in each stage are plotted versus depths of excavations in a log-log scale and such a plot is designated as "wall deflection path" (Moh & Hwang, 2005; Hwang, et al. 2006; Hwang, et al. 2007). The envelope, designated as "reference envelope" herein, of a family of wall deflection paths can be considered as a site characteristic curve for diaphragm walls and can be used for evaluating the performance of individual walls. Reference envelopes are defined by:

a. wall deflections for shallow excavations, represented by deflections at depths of excavation up to 4 m, i.e., Δ_4,
b. wall deflections projected to a depth of excavation of 100 m, i.e., Δ_{100}.

The depth of 4 m is chosen because the first digs are usually within 4 m and the depth of 100 m is chosen for convenience because Microsoft Excel only plots full log-cycles. Furthermore, the extension of reference envelopes to this depth amplifies the differences in reference envelopes among various cases and makes it easier to study the effects of various factors affecting the performance of walls.

The deflection paths for diaphragm walls with thicknesses of 600 mm, 800 mm, 1000 mm, and 1200 mm for excavations in the T2 Zone are shown

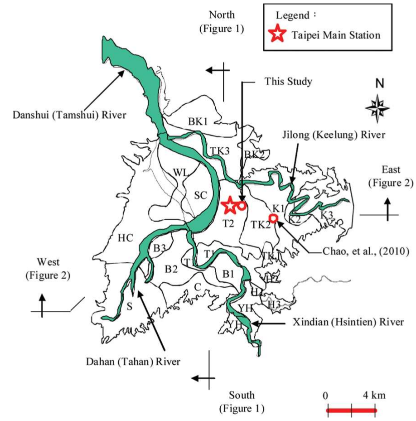

Figure 3. Geological zoning map of the Taipei Basin (Lee, 1996).

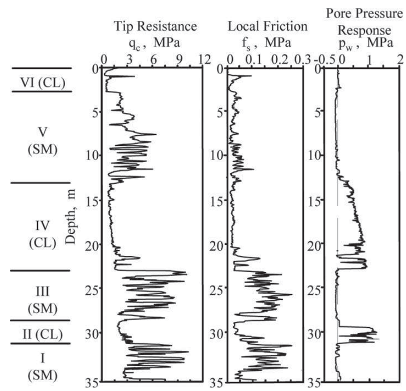

Figure 4. Typical results of CPT tests in the T2 Zone.

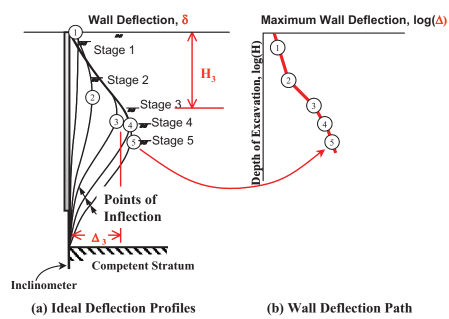

Figure 5. Ideal wall deflection profiles and wall deflection path.

in Figures 6 to 9. Individual inclinometers are identified by suffixes such as A, B, C, etc, affixed to the site numbers. Also shown in the figure are the reference envelopes which are the envelopes of respective deflection paths.

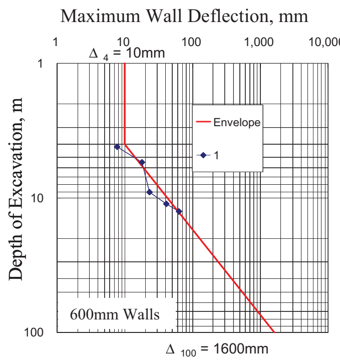

Figure 6. Wall deflection paths and reference envelopes for 600 mm walls in the T2 Zone.

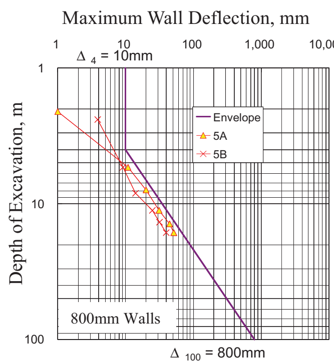

Figure 7. Wall deflection paths and reference envelopes for 800 mm walls in the T2 Zone.

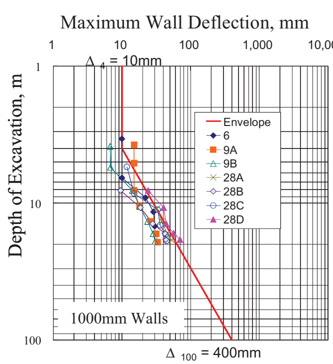

Figure 8. Wall deflection paths and reference envelopes for 1000 mm walls in the T2 Zone.

There are numerous ways to draw reference envelopes based on the data presented and the decisions are inevitably subjective. The reference envelopes shown in Figures 6 to 9 were so drawn that, as shown in Table 1, deflections for depths

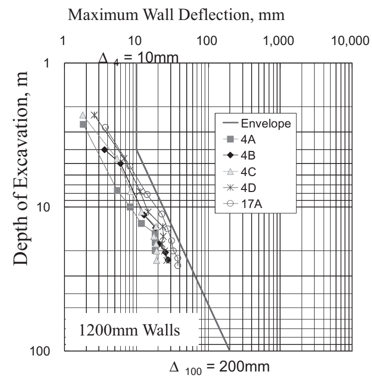

Figure 9. Wall deflection paths and reference envelopes for 1200 mm walls in the T2 Zone.

Table 1. Comparison of reference envelopes for the T2, TK2 and K1 Zones.

Wall thickness, mm	Δ_4, mm			Δ_{100}, mm		
	T2	TK2	K1	T2	TK2	K1
600	10	12		1,600	1600	
700		12			1200	
800	10	12	30	800	800	800
900		12	30		600	600
1000	10*		30	400*		400
1200	10			200		

* for the case of interest

of excavation of 4 m or less, i.e., Δ_4, remain to be the same regardless of wall thickness while wall deflections for depths of excavation of 100 m, i.e., Δ_{100} decrease by a factor of 2 as wall thickness increases from 600 mm to 800 mm, from 800 mm to 1000 mm, and from 1000 mm to 1200 mm.

To illustrate the application of the concept of wall deflection path in evaluating the performance of diaphragm walls, the performance of diaphragm wall during excavation for constructing Shandao Temple Station (BL8 Station) of the Taipei Metro is studied herein. Figure 10 shows the layout of the station and the cut-and-cover tunnels connected to the east end of the station. The station is located in the T2 Zone and, as shown in Figure 11, the six-sublayer sequence is clearly identifiable.

Inclinometers were installed in 5 sections for monitoring wall deflections as shown in Figure 10. The readings obtained for Section B, for example, are shown in Figure 12. As can be noted, significant outward wall movements were reported for both Inclinometers SID-7 and SID-11 which stopped at the same depth as the toe of diaphragm walls. Such outward wall movements were not reasonable

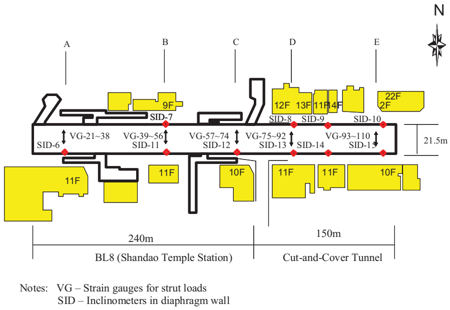

Figure 10. Layout of Shandao Temple Station and locations of instrumented sections.

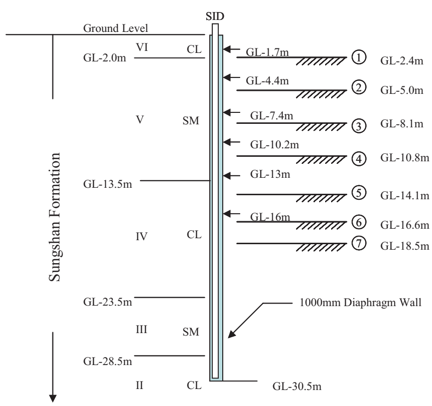

Figure 11. Ground conditions and excavation scheme.

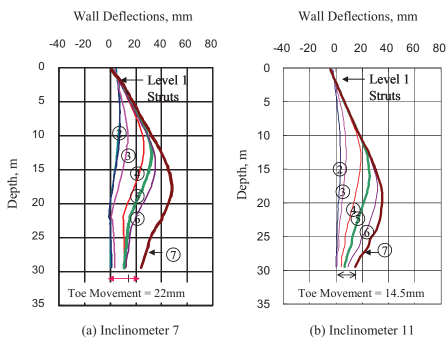

Figure 12. Inclinometer readings before correction.

because they imply significant elongation of struts. They were obviously caused by the movements at the toes which were assumed to be fixed in computing wall deflections. As depicted in Figure 5, the subsequent wall movements at the each strut level should be very small once the struts at this level is preloaded. Inclinometer readings can thus be corrected accordingly (Hwang, et al. 2007). The readings duly corrected by taking the end points of Level 1 struts as reference points are shown in Figure 13 and the toe movements were found to be 22 mm for Inclinometer 7 and 14.5 mm for Inclinometer 11.

The hypothesis that wall movements at the two ends are minimum once struts are preloaded has been verified by studying the changes in strut loads in the case of interest (Hwang, et al. 2007). Figure 14 shows the strut loads recorded at the upper 4 levels by strain gauges in Section B. Take Level 1 for example, the maximum increase in loads was 23.3 tonnes after preloading, corresponding to a shortening of the strut of only 1.4 mm for a cross-sectional area of 173.9 cm^2 and a length of 21.5 m, assuming an E value of 200,000 N/mm^2. Wall movements at the two ends of the strut would only be a half of this magnitude. Wall movements of such small magnitudes are indeed negligible for practical purposes.

The toe movements for all the inclinometers computed by following the same procedure are plotted versus depth of excavation in Figure 15. The final toe movements varied from 5 mm to 31 mm. The movements of Inclinometers SID-10 and SID-15 were smaller than those of others because these two inclinometers were very close to the eastern wall which helped to reduce wall movements. Although Inclinometer SID-6 was located at the west end of the excavation, grouting was once carried out to

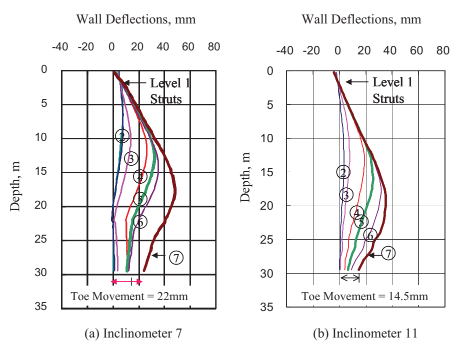

Figure 13. Inclinometer readings after correction.

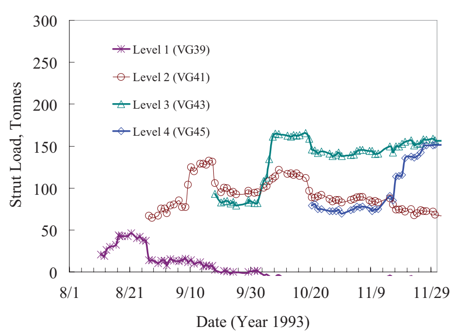

Figure 14. Strut loads in Section B.

stop leakage on the diaphragm wall at this location and presumably increased the movement at the toe.

The final wall deflections, with the toe movements duly accounted for, for the northern and the southern walls are shown in Figures 16 and 17 respectively.

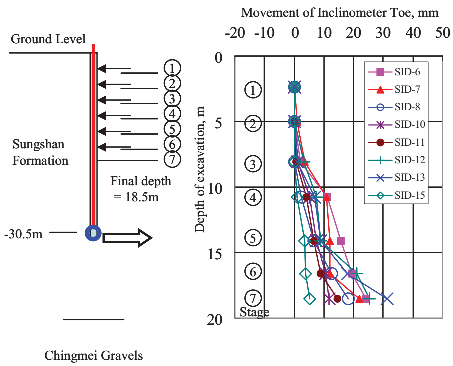

Figure 15. Progressive toe movements of inclinometers.

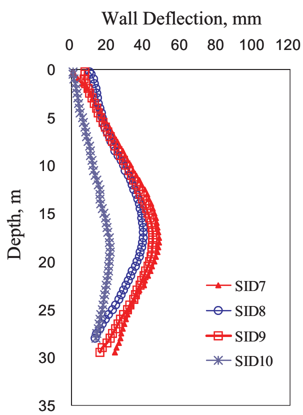

Figure 16. Final deflections of the northern wall.

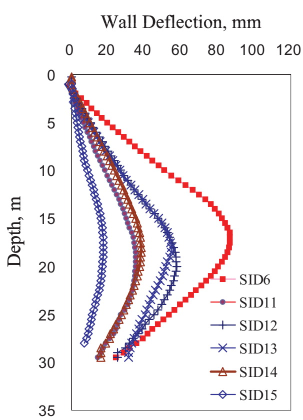

Figure 17. Final deflections of the southern wall.

Even with SID-6, SID-10 and SID-15 excluded, the readings for other inclinometers are far from being consistent. The maximum deflections varied from 35.2 mm (SID-11) to 57.6 mm (SID-12).

4 BACK ANALYSES

The purpose of back analyses is to calibrate soil parameters to be used in numerical analyses for predicting the performance of future excavations in similar ground conditions by comparing the results obtained with the observations. The cases chosen for calibration must be compatible with the numerical schemes adopted for the calibration to be meaningful. However, with the diversity in the observed wall deflections as depicted in Figures 16 and 17, the key question to ask is "Which curve is representative of the case studied?".

Back analyses nowadays are most commonly conducted by performing two-dimensional finite element analyses and so are predictions of performance of excavations. In theses analyses, structures adjacent to the excavations are normally ignored except for research purposes. Therefore, the observed wall deflections chosen should be free of the influences of adjacent structures for the comparison to be fair.

In well developed cities in which deep excavations are normally carried out, there are always tall buildings with deep basements along major roads. Besides, there are also likely large underground structures, such as culverts, subways, underpasses, etc. These structures inevitably affect the performance of walls during excavations. Therefore, the wall deflections to be adopted for calibration must be selected with care.

Since the presence of adjacent underground structures can only reduce wall deflections, the envelope of a family of wall deflection paths would approach to the path representing the behavior of walls free of the influences of adjacent structures as more and more cases are included. Therefore, the reference envelope would be more appropriate than individual wall deflection curves, or individual wall deflection paths, to be used as the basis for comparison in back analyses.

In the case of interest, there are many highrise buildings varying from 9 to 22 stories in height right next to these two walls as depicted in Figure 10. There are presumably deep basements under these buildings as well. These basement together with the retaining walls which were left in place after construction provided much resistance to ground movements and hence reduced wall deflections during excavation for constructing the station. The situation is further complicated by the presence of auxiliary facilities, such as entrances/exits, ventilation shafts, etc. as depicted in Figure 10, which also tended to reduce wall deflections. This well explains why the wall deflection paths shown in Figures 18 an 19 are below the reference envelope established for the T2 Zone, refer to Figure 8, with the only exception of SID-6 of which the readings were affected by grouting. It thus becomes clear that none of the wall deflection curves shown in Figures 16 and 17, and nor of the wall deflection paths shown in Figures 18 and 19, represents the true behavior of walls in free-field excavations.

The reference envelopes proposed in Figures 6 to 9 were established based on the observations made in many excavations in the T2 Zone. They were established with duly consideration given to walls in different geological zones, refer to Table 1. For the reasons given above, the envelope shown in Figure 8 is the envelope for walls of 1 m in thickness and is the one to be adopted in back analyses.

The computer program PLAXIS V8, released by PLAXIS BV of Amsterdam, the Netherlands

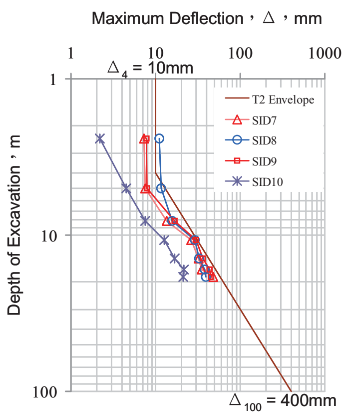

Figure 18. Deflection paths for the northern wall.

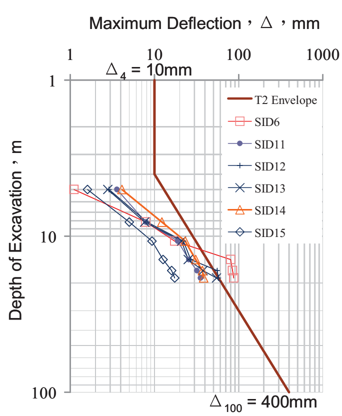

Figure 19. Deflection paths for the southern wall.

(PLAXIS, 2002), was used and the mesh adopted in the back analyses is shown in Figure 20. The soil properties are given in Table 2. As a first attempt, the Young's moduli were determined as follows:

for clayey soils

$$E = 800\ Su \tag{1}$$

in which Su = undrained shearing strength, and for sandy soils

$$E = 4000\ N\ (kPa) \tag{2}$$

where N = blow counts in standard penetration tests. For the purpose of illustration, the readings obtained by Inclinometer SID-12 which gave larger wall deflections than others are chosen for comparison. The wall deflections obtained in the last 3 stages of excavation are compared with the results of the analyses in Figure 21. The toe movements obtained from the analyses are in a fair agreement with what was observed after correction were made. However, the maximum wall deflections appear to have been under-estimated in the back analyses.

The wall deflection path obtained in the back analyses is compared with the reference envelope for 1 m walls in the T2 Zone, i.e., the one shown in Figure 8, in Figure 22. It can be represented by

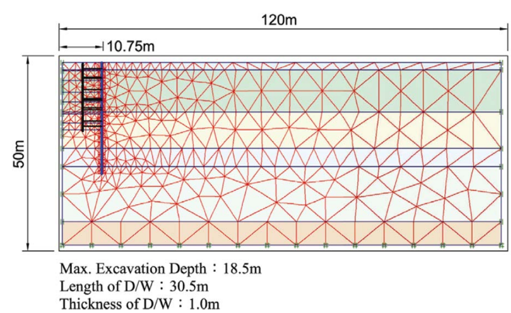

Figure 20. Finite element model adopted in PLAXIS analyses.

Table 2. Soil properties adopted in PLAXIS analyses.

Depth (m)	Soil type	γ_t (kN/m^3)	N	S_u (kPa)	c′ (kPa)	Φ′ (deg)	E (MN/m^2)	ν
0–2	CL	18.6	3	20	0	30	16	0.45
2–13.5	SM	18.4	8	–	0	33	32	0.35
13.5–23.5	CL	18.8	6	40	0	32	32	0.45
23.5–28.5	SM	19.3	18	–	0	32	72	0.35
28.5–43.5	CL	19.4	17	80	0	33	64	0.40
43.5–50	SM	21.6	30	–	0	35	120	0.30

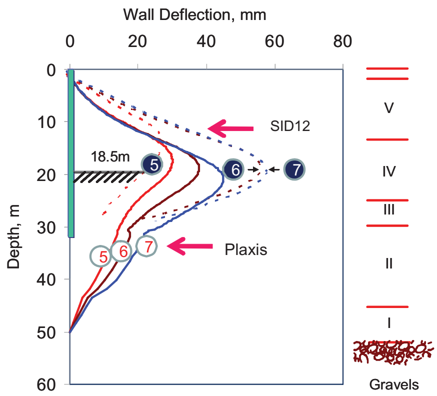

Figure 21. Comparison of wall deflections obtained in back analyses with corrected inclinometer readings.

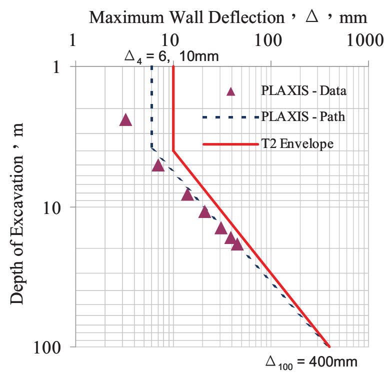

Figure 22. Comparison of wall deflections path obtained in back analyses with the reference envelope for the T2 Zone.

Δ_4 = 6 mm, Δ_{100} = 400 mm. The Δ_{100} value obtained is the same as that for the reference envelope shown in Figure 8 but the Δ_4 value is only 60% of that for this reference envelope.

Figure 23 shows the results of finite element analyses using PLAXIS in a previous study carried out for an excavation for Kaohsiung Metro (Hsiung and Hwang, 2009). A Δ_4 of 13 mm was obtained In Set A analyses in which soil moduli were obtained as follows:

$$E = 500\ Su \qquad (3)$$

and, for sandy soils

$$E = 2000\ N\ (kPa) \qquad (4)$$

In Set B analysis, the Young's moduli of soils were halves of what were used in Set A analyses

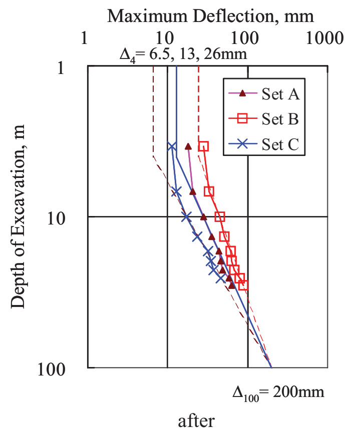

Figure 23. Influence of Young's moduli on wall deflections paths (Hsiung and Hwang, 2009).

and the Δ_4 was doubled to 26 mm. In Set C analysis, the Young's moduli were twice what were used in Set A analyses and the Δ_4 were halved to 6.5 mm. It becomes evident that the Δ_4 values are inversely proportional to the soil moduli. The changes in soil moduli, however, did not affect the Δ_{100} value.

In the case of interest, the soil moduli appear to have been over-estimated so the Δ_4 value obtained was smaller than what it should be. The computed wall deflection path would well match the reference envelope if soil moduli were reduced to 60% of the values given in Equations 1 and 2. That means, It then appears, Equations (3) and (4) would be suitable for the soils in the Sungshan formation.

To verify whether Equations (3) and (4) can indeed be used for soils in other geological zones in the basin, the results of a previous study conducted by Chao, et al., (2010) are referred to herein. Finite element analyses were performed using PLAXIS for an excavation carried out at a site which is right at the boundary between TK2 and K1 Zones as shown in Figure 3. As shown in Figure 2, sandy soils are absent at the TK2/K1 boundary and the ground is dominated by clayey soils. This greatly reduces the complicity of the problem. Equation (3) was adopted for the clayey soils and the wall deflection path obtained is shown in Figure 24. Although the Δ_{100} value obtained, i.e., 300 mm, is slightly smaller than that for walls of 1 m in thickness, the wall deflection path obtained in the range of excavation depths of 10 m to 30 m which is of primary interest falls in-between the reference envelopes for the TK2 and the K1 Zones as expected. It is thus concluded that Equation 3 can indeed be used for clayey soils in back analyses.

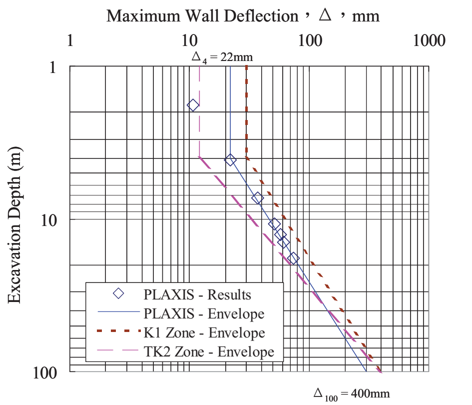

Figure 24. Wall deflections path for clayey soils (Chao, et al., 2010).

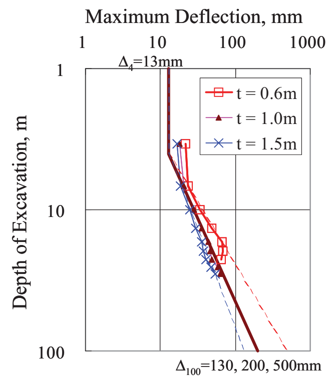

Figure 25. Influence of wall stiffness on deflection paths (Hsiung and Hwang, 2009).

Regarding Equation (4), more analyses are desired to be conducted for excavations at sites where sandy soils dominate before its applicability can be generalized.

The results of PLAXIS analyses depicted in Figure 23 confirm that Δ_{100} values are rather insensitive to soil moduli. Therefore, the adoption of the same Δ_{100} values for T2, TK2 and K1 Zones appears to be valid. On the other hand, it is interesting to note that the Δ_4 values are insensitive to wall stiffness as depicted in Figure 25 (Hsiung & Hwang, 2009). In the first stage of excavation, walls behave as cantilevers offer little resistance to ground movements because of the great depths of soft deposits.

5 CONCLUDING REMARKS

Inclinometer readings should be interpreted with care. Readings can be calibrated to account for toe movements by assuming wall movements at the first strut level are insignificant once struts at this level are installed and preloaded.

Performance of diaphragm walls can be evaluated by studying their wall deflection paths. Wall deflection paths are linear in the range of 10 m to 20 m, if plotted in a log scale, for excavations in thick soft sediments.

Reference envelopes of a family of wall deflection paths can be defined by Δ_4 and Δ_{100}. The Δ_4 values are insensitive to the stiffness of walls and the Δ_{100} values are a function of the stiffness of walls.

Wall deflection paths of individual walls can be compared with reference envelopes for studying the influences of various factors on wall deflections.

Instead of individual walls, reference envelopes should be used for calibrating soil parameters to be used in back analyses.

In back analyses and in analyses for predicting wall deflections, the Young's moduli for clayey soils can be estimated by assuming E = 500 Su. For sandy soils, E moduli equal to 2000 N (in kPa) appear to be reasonable, however, more case studies are required for confirmation.

REFERENCES

Chao, H.C., Chang, J.F. & Hwang, R.N. (2010). Evaluation of performance of diaphragm walls in deep Excavations by using deflection path method, *Proc., 17th Southeast Asian Geotechnical Conference*, Taipei, Taiwan, vol I, pp. 390–393.

Lee, S.H. (1996). Engineering Geological Zonation for the Taipei City, *Sino-Geotechnics*, vol. 54, April, pp. 25–34 (in Chinese).

Hsiung, B.C. & Hwang, R.N. (2009). Evaluating performance of diaphragm walls by wall deflection path, *Special Issue on Excavation and Tunneling in Geotechnical Engineering Journal of SEAGS*, pp. 81–90.

Hwang, R.N. & Moh, Z.C. (2007). Deflection paths and reference envelopes for diaphragm walls in the Taipei Basin, *J. of GeoEngineering*, v2, no. 1, April, Taipei, Taiwan, pp. 1–12.

Hwang, R.N., Moh, Z.C. & Kao, C.C. (2006). Design and construction of deep excavations in Taiwan, *Seminar on "The State-of-the-Practice of Geotechnical Engineering in Taiwan and Hong Kong*", 20 January, Hong Kong.

Hwang, R.N., Moh, Z.C. & Wang, C.H. (2007). Toe movements of diaphragm walls and correction of inclinometer readings, *J. of GeoEngineering*, v2, no. 2, August, Taipei, Taiwan pp. 61–72.

Moh, Z.C. & Hwang, R.N. (2005). Geotechnical considerations in the design and construction of subways in urban areas, *Seminar on Recent Developments on Mitigation of Natural Disasters, Urban Transportation and Construction Industry*, 30 November–2 December, Jakarta Indonesia.

PLAXIS (2002). *Reference Manual*, PLAXIS BV, Amsterdam, the Netherlands.