DEFLECTION PATHS AND REFERENCE ENVELOPES FOR DIAPHRAGM WALLS IN THE TAIPEI BASIN

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

ABSTRACT

The concept of wall deflection path and reference envelope is introduced herein for evaluating 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 reference envelope of wall deflection paths characterizes performance of diaphragm walls. It, however, should be noted that inclinometer readings must be interpreted with care and corrections must be made to account for toe movements, if any. Based on the data obtained for deep excavations carried out in recent years, reference envelopes are established for the T2, TK2, and K1 zones and they can be used to evaluate the performance of individual walls.

Key words: Diaphragm wall, deflection path, reference envelope, deep excavation, toe movement.

1. INTRODUCTION

With the rapid economic growth in the past decades, Taiwan has undergone drastic social reform with construction industry playing a leading role. As more and more high-rise buildings are constructed, basements tend to go deeper and deeper. Furthermore, the majority of stations in the Taipei Rapid Transit Systems (TRTS) and the Kaohsiung Mass Rapid Transit System (KMRTS) are underground. As a result, there is significant advancement in both design concept and construction practice of underground works.

For deep excavations in soft ground, diaphragm walls were exclusively used with other types of retaining structures used in very rare occasions. Presented herein are the concepts of wall deflection path and reference envelope for evaluating performance of diaphragm walls in deep excavations. In order for the professionals to have a common understanding, in the lack of precedents, the authors propose the following definitions (Hwang, *et al*., 2006):

- shallow excavations: up to 5 m in depth, or 1-level basement
- mid-depth excavations: 5 m to 10 m in depth, or 2-level to 3-level basements
- deep excavations: 10 m to 20 m in depth, or 4-level to 5-level basements
- very deep excavations: 20 m to 30 m in depth, or 6-level or more basements
- extremely deep excavations: 30 m or greater in depth

Accordingly, the performance of walls in excavations deeper than 10 m is of primary interest.

2. CONCEPT OF PERFORMANCE-BASED DESIGN

Prior to TRTS constructions (say, 1990 and earlier), diaphragm walls were generally designed in consideration of their structural capacity and the stability of the ground below the formation levels without due consideration given to their lateral deflections. As deep excavations are normally carried out in densely populated areas and people have become more and more aware of their own rights, protection of adjacent buildings and properties is a serious concern nowadays for underground constructions.

Experience indicates that rectification of buildings and/or structures which have been affected by ground movements is both costly and ineffective and it will be much better to minimize ground movements at source. The old saying that "An ounce of prevention is worth of a pound of cure" certainly holds true for underground constructions. As it is obvious that ground movements are primarily caused by wall deflections, the concept of performance-based design, instead of capacity-based design, has thus been adopted since the early 90's for the purpose of limiting wall deflections, hence, ground movements behind walls.

In the early stage of the TRTS constructions, ground settlements were limited to 25 mm by specifications and wall deflections were limited to a similar magnitude. This was found to be impractical and specifications were later revised so that designers have to evaluate the conditions of adjacent buildings and properties, determine allowable ground settlements and wall deflections, and design walls accordingly. In most cases, wall deflections were limited to 30 mm to 60 mm. To achieve this, thicker walls, generally 200 mm to 300 mm thicker in comparison with those designed based on their structural capacities, were used, and struts were preloaded to 50% to 60% of their design loads. These precautionary measures indeed paid off as damages to adjacent buildings and properties due to wall movements were greatly minimized.

For deep excavations in soft ground, Fig. 1(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

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

[2] President, Moh and Associate, Inc., Taipei, Taiwan, R.O.C. (e-mail: zachieh.moh@maaconsultants.com)

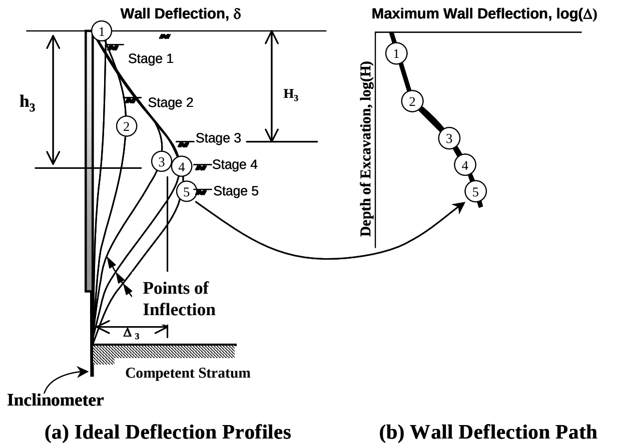


Fig. 1 Ideal wall deflection profiles and wall deflection path

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.

The factors affecting wall deflections can be summarized as follows:

(1) depth of excavation
(2) width of excavation
(3) ground conditions, *e.g.*, soil stiffness, groundwater table
(4) depth to competent base stratum
(5) method of construction, *e.g.*, top-down, bottom-up, or semi top-down
(6) rigidity of wall system, represented by wall thickness, including buttress, if any
(7) length of wall
(8) stiffness of the strutting system, including spacing and member size
(9) preloading of struts
(10) corner effects, *i.e.*, proximity to boundaries of pits (3D effects)
(11) ground treatment, *i.e.*, grouting
(12) foundation piles (or tension piles)
(13) adjacent structures, *e.g.*, surcharge loads and basement effects
(14) workmanship, *e.g.*, over-excavation, promptness of strutting and preloading

To account for all these factors, sophisticated 3D numerical analyses have to be performed. Even so, the nonlinearity of soil properties often becomes a difficult problem for most of engineers to handle. Furthermore, depending on the algorithm adopted and the skill of the engineers who perform the analyses, the results obtained by different numerical schemes are inconsistent and can be drastically different from what is observed in field. Therefore, it is desirable to have simple empirical tools to give approximate results which can be used as the basis of judgment.

As illustrated in Fig. 1(b), the maximum deflections in the deflection profiles are plotted versus depths of excavations in a log-log scale and such a plot is designated as "wall deflection path" (Moh and Hwang, 2005; Hwang, *et al.*, 2006: Hwang, *et al.*, 2007). The envelope, designated as "reference envelope" herein, of the wall deflection paths can be considered as site characteristic curves for diaphragm walls and can be used for evaluating the performance of individual walls. Based on experience, the performance of a diaphragm wall can be judged by comparing its deflection path with relevant reference envelope for the site as illustrated in Fig. 2:

Path A: The presence of basements, retaining walls and foundation piles in the vicinity is likely to reduce wall deflections in the early stage of excavation.

Path B: On the other hand, surcharge loads in the vicinity of excavation, if any, will increase wall deflections in the early stage of excavation.

Path C: Because the influence of adjacent structures and/or surcharges diminishes as depth of excavation increases, deflection paths tends to converge toward the reference envelope.

Path D: As excavation exceeds a certain depth, the performance of the wall is affected by the stability of the toe of the wall. For walls with sufficient lengths beyond the formation levels and/or with their toes properly embedded in competent strata, wall deflections will increase at diminishing rates (in a log-log scale) and their deflection paths are expected to bend downward. Ground treatment below the formation level will have similar effects.

Path E: On the other hand, if the deflection path for a certain wall becomes flatter than the reference envelope, it is most likely that the toe of the wall has become unstable. Soft strutting system and poor workmanship will have similar effects.

As shown in Fig. 2, reference envelopes can be 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.

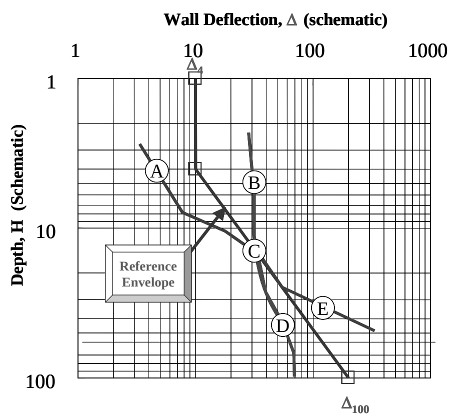


Fig. 2 Evaluation of performance of walls by studying deflection paths

3. GEOLOGY OF THE TAIPEI BASIN

The Taipei Basin was formed by tectonic movements about 180,000 years ago; and young deposits subsequently accumulated all the way to the surface with a maximum thickness exceeding 500 m. At the top is the so-called Sungshan Formation of, up to, 60 m in thickness underlain by the Chingmei Gravels of about 60 m in thickness, followed by the Hsinchung Formation all the way to the bottom of the basin. Figures 3 and 4 show the north-south and the east-west sections, respectively, of the basin. As can be noted, the Sungshan Formation contains 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. 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.

The Chingmei Gravels contains gravels, cobbles and boulders of various sizes and is extremely permeable. This gravelly layer is practically an underground reservoir and was responsible for several major failures during the first stage construction of TRTS. As can be noted from Fig. 5 that the piezometric levels in the Chingmei Gravels were lowered by as much as 40 m in the 70's as a result of excessive pumping of groundwater for industrial and domestic usages. The accompanying ground subsidence exceeded 2 m. As pumping was banned in the late 70's, the piezometric levels in the Chingmei Gravels recovered rapidly. The recovery of the piezometric levels in the Chingmei Gravels, however, has been slowed down as a result of dewatering for constructing the rapid transit systems starting from the early 90's.

The development of Taipei City started centuries ago along the Tamshui River (with a new translation of the Danshui River), which was then the major waterway for cargo ships. As economy on the island boomed in the 70's and 80's, the city expanded rapidly and numerous highrise buildings were erected. Most of these buildings have 3 to 5-level basements and numerous boreholes were sunk for revealing ground conditions. Based on the information obtained, Lee (1996) proposed to divide the Basin into 22 zones as depicted in Fig. 6 which is adopted herein for categorizing ground conditions.

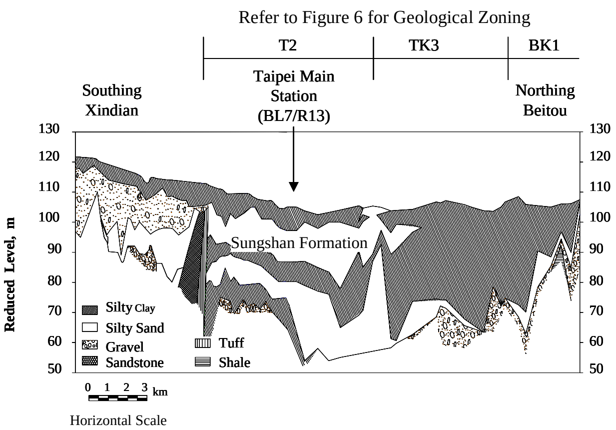


Fig. 3 North-south geological section of the Taipei Basin

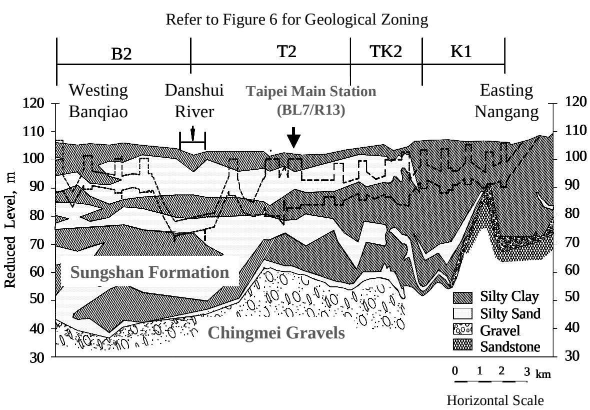


Fig. 4 East-west geological section of the Taipei Basin

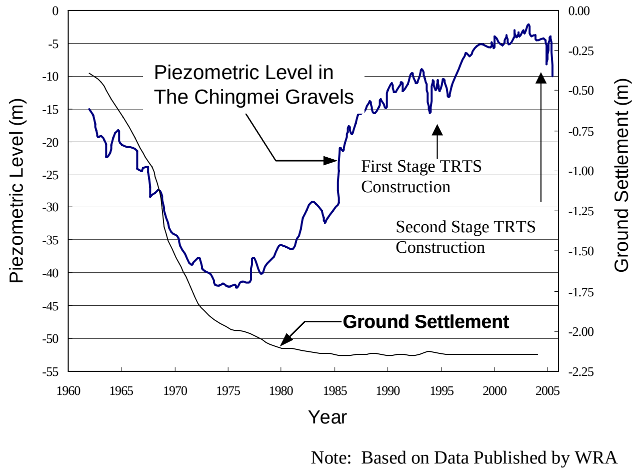


Fig. 5 Piezometric levels in the Chingmei Gravels and ground settlements induced by the lowering of water heads

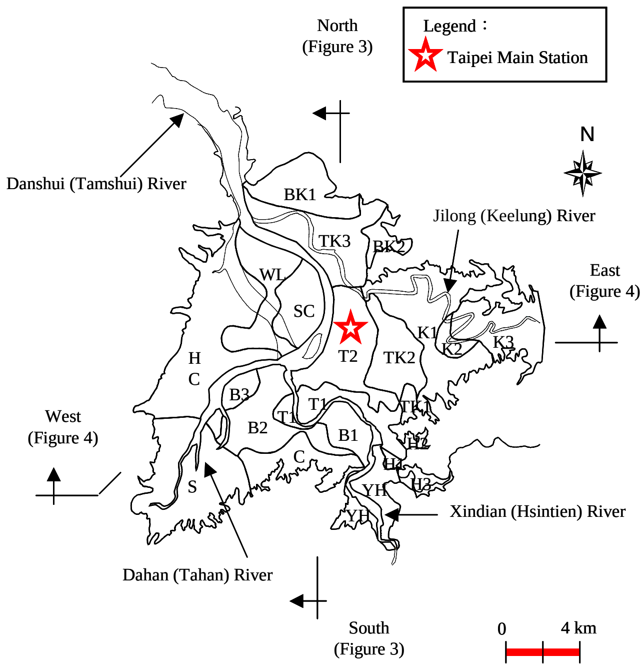


Fig. 6 Geological map of the Taipei Basin by Lee (1996)

3.1 Ground Conditions in the T2 Zone

Figure 7 shows a typical CPT profile obtained at a location which is very close to the Taipei Main Station. 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. Representative properties of these sublayers are summarized in Table 1. In short, Sublayers I, III, and V consist primarily of silty sands and Sublayers II, IV, and VI consist primarily of silty clays. As the piezometric levels in the Chingmei Gravels were once lowered by as much as 40 m, all these sublayers have experienced consolidation to various degrees.

3.2 Ground Conditions in the K1 zone

In the K1 zone, subsoils consist of predominantly clays with only thin seams of silty sands. Figure 8 shows the results of a cone penetration test carried out in the K1 zone and what is shown can be considered to be representative of the strength characteristics of soft deposits in the entire K1 zone. Unlike other zones in which the Sungshan Formation is underlain by the Chingmei Gravels, the underlying base strata in the K1 zone include both gravels and sandstone with erratic rock heads as depicted in Fig. 4.

Because the K1 zone was under-developed till the early 80's and groundwater has not been lowered, the subsoils are normally consolidated, or even under-consolidated. In fact, in many places, the clays are very soft and very weak in strength with water contents equal to or even greater than liquid limits. There were a few failures associated with deep excavations in the 70's as retaining structures were under-designed. As design of retaining system has been improved, there were in fact less failures in the K1 zone than other zones because of the fact that subsoils are clayey and impervious and also because of the absence of water bearing strata.

3.3 Ground Conditions in the TK2 Zone

The TK2 zone is a transition zone between the T2 zone and the K1 zone. In fact, the western half of the TK2 zone was part of the T2 zone and the eastern half of the TK2 zone was part of the K1 zone in the geological map of the basin proposed by Woo and Moh (1991). For this reason, the soil profiles in the TK2 zone are thus expected to vary between what is shown in Fig. 7 and what is shown in Fig. 8.

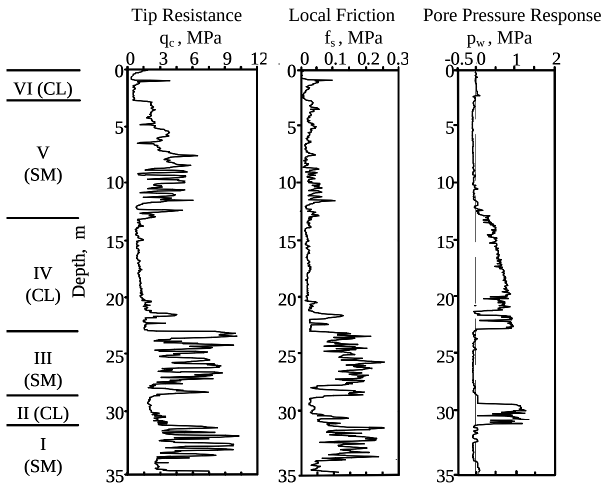


Fig. 7 Typical results of CPT tests in the T2 zone

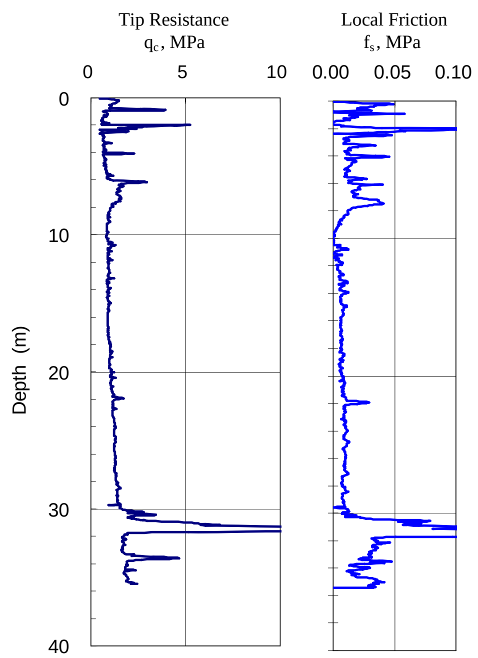


Fig. 8 Typical results of CPT tests in the K1 zone

Table 1 Representative properties of sublayers in the Sungshan Formation in the T2 zone

(after Woo and Moh (1991))

Sublayer	Dry unit weight, kN/m^3	Water content, %	Specific gravity	Liquid limit	Plasticity index	Particle size percentage, %			
						Gravel	Sand	Silt	Clay
VI	14.5	31.2	2.72	35.8	12.9	0	10	58	32
V	15.4	26.3	2.68			1	75	19	4
IV	14.3	32.1	2.72	34.3	12.0	0	8	61	31
III	16.1	23.9	2.69			0	60	34	7
II	15.5	27.2	2.72	30.3	9.2	0	9	67	25
I	17.0	20.3	2.69			1	62	29	7

4. ILLUSTRATING EXAMPLE

To illustrate the applications of the concept of wall deflection path and reference envelope, the performance of diaphragm walls observed at a construction site at the junction of Jian Guo N. Road and Chang An E. Road in the Taipei City is discussed herein as an example.

As shown in Fig. 9, excavations were carried out in 3 blocks for constructing 6 highrise buildings, 2 in each block, with 4-level basements. The dimensions of the pits were 108 m by 33 m for the North Block, 132 m by 40 m for the Central Block and 109 m by 37 m for the South Block. Excavations were carried out to a depth of 17.5 m, consecutively, in the sequence of North, Central and South Block. All the 3 pits were retained by 900 mm diaphragm walls installed to a depth of 35 m as depicted in Fig. 10.

4.1 Monitoring of Wall Deflections & Interpretation of Data

Lateral deflections of walls are nowadays routinely monitored by using inclinometers which are amazingly accurate and can be considered as one of the most reliable types of geotechnical instruments. However, this does not necessarily lead to the conclusion that the readings obtained always faithfully represent the behavior of walls. They can easily be mis-interpreted and misjudgments are by no means rare.

Wall deflections were monitored by 20 inclinometers at this site, of which 15 (SID1 ~ SID15) were installed in the wall panels and 5 (SIS1 ~ SIS5) were installed in soil immediately next to the walls to pair with those in the wall panels so the difference in performance can be studied. As a normal practice, the toes of inclinometers were assumed to be fixed and the movements at all other depths were computed in relation to the toes. Because diaphragm walls usually are not designed to have zero movements at their toes, the toes of inclinometers are expected to move if inclinometers stop at the same levels as the walls. In such cases, the readings obtained may become misleading and have to be corrected. It is a good practice to check the movements of the top of casing by precision survey for calibrating readings at other depths. However, this sometimes may become difficult to carry out because of site constraints or difficult to enforce because of lack of supervision. Therefore, it will be a good idea to specify that toes of inclinometers should be buried in competent strata, as depicted in Fig. 1, or extended to sufficient depths so the toe movements will be insignificant.

The readings obtained by inclinometers SIS2 which was installed in soil next to the walls are shown in Fig. 11(a) for illustration. Significant outward movements of walls, as much as 20 mm, were recorded by inclinometers at shallow depths in the later stages of excavation. Such outward movements are unlikely to be realistic because of the lack of mechanism for this to happen in reality. It is thus suspected that the toes of these inclinometers have moved. As all of these inclinometers were installed to a predetermined depth of 52 m while the top of the Chingmei Gravels was supposed to be at a depth of 51 m, the penetrations into the gravel layer were supposed to be 1 m. However, the penetrations were not confirmed during the installation and could be unachieved because of the erratic top of the Chingmei Gravels.

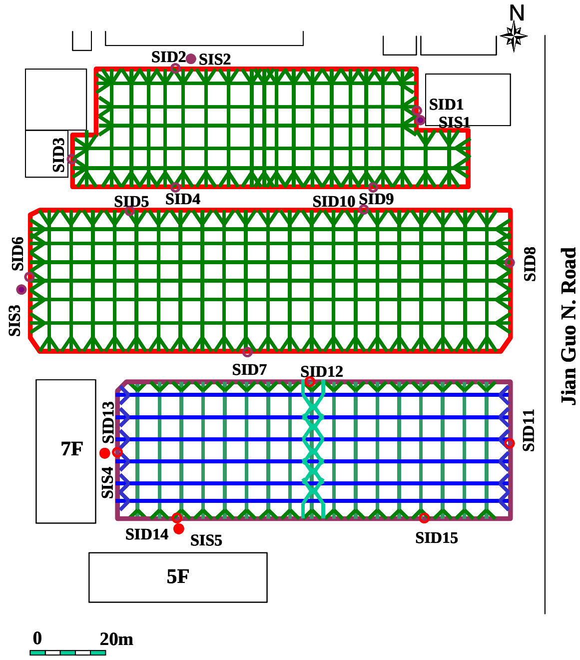
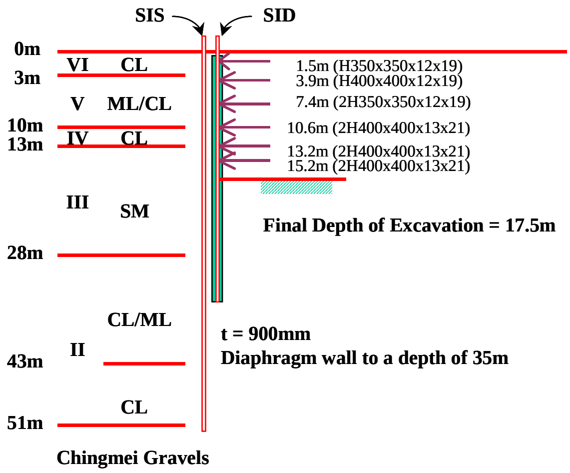


Fig. 9 Site plan for the illustrating example



Notes: SIS = slope indicator in soil (to a depth of 52m)
SID = slope indicator in diaphragm wall (to the same depth of the walls)

Fig. 10 Soil profile and retaining system for the illustrating example

Figure 12(a) shows the movements of the walls at the first level of struts, *i.e.*, at a depth of 1.5 m as depicted in Fig. 10, at the end of various stages of excavation. The struts at the first level were installed at the end of the 1st dig and before the 2nd dig. While some outward movements of these connections are expected due to the preloading of the struts at the 2nd level and due to excavation toward the 3rd level, there is no reason for the wall to move outward subsequently. That means, the time-plots of wall deflections must be "increasing functions" with only positive increments (*i.e.*, inward movements). Accordingly, the readings indicating outward movements of the walls in subsequent stages of excavation were thus deemed to be caused by the movements of the toes of inclinometers and have to be corrected.

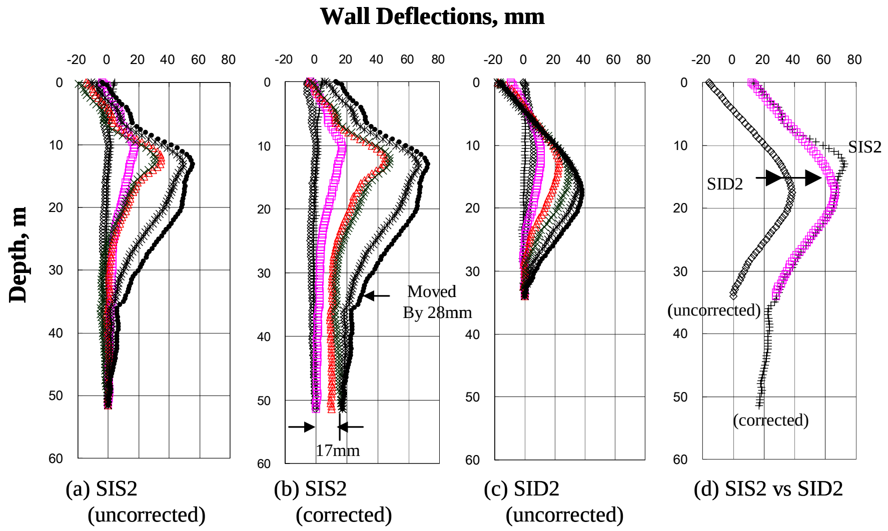


Fig. 11 Readings of inclinometers SIS2 and SID2 with and without corrections for toe movements

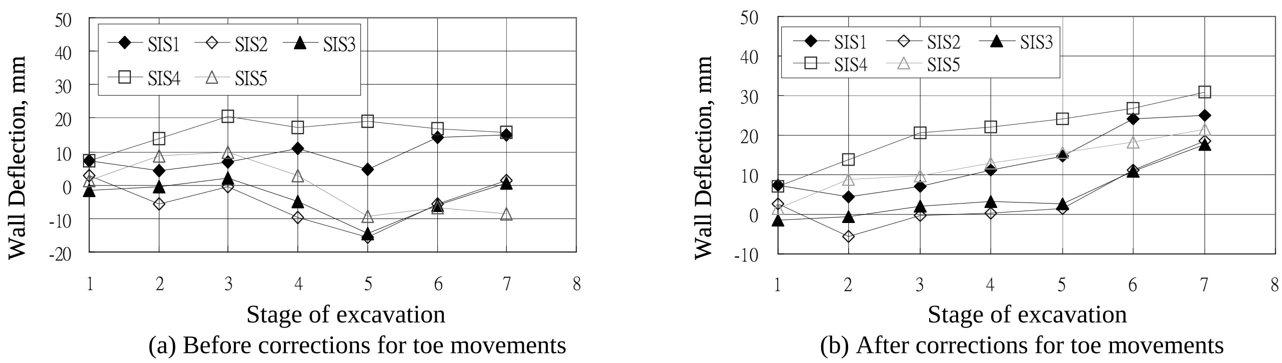


Fig. 12 Movements of wall at the first strut level

Figure 12(b) shows the results obtained by replacing the readings which show outward movements between two consecutive stages of excavation by small inward movements, say, 2 mm or so to give smoothly rising curves. The net movements between the 3rd dig and the final dig were 10 mm to 20 mm and were due to the shortening of struts. These magnitudes correspond to axial strains of 0.008% to 0.02% for struts of 109 m to 132 m in length and are considered to be reasonable. The profiles of wall deflections after the corrections for toe movements are shown in Fig. 11(b) and are apparently more reasonable. The corrections made for the final stage are 10 mm, 17 mm, 17 mm, 15 mm, and 30 mm for SIS1 to SIS5, respectively, and these magnitudes correspond to the toe movements of inclinometers.

The deflection profiles of inclinometer SID2 which is right next to SIS2 are shown in Fig. 11(c). The toe movements of this inclinometer at the final stage of excavation can be read directly from the readings at a depth of 35 m of inclinometer SIS2 and is 28 mm. The corrected readings are compared with those obtained by SIS2 in Fig. 11(d). The two sets of readings appear to be very close. Also shown in the figure are the uncorrected readings for comparison.

4.2 Wall Deflection Paths and Reference Envelope

The wall deflection paths of the five inclinometers installed next to the walls are shown in Fig. 13. As can be noted that, the data points for depths of excavation shallower than 10 m do scatter widely (but are small in magnitude). After a depth of excavation of 10 m, wall deflection paths, except that for SIS1, do converge to a narrow band. Inclinometer SIS1 is located at the east end of North Block where the diaphragm wall retreated by 15 m or so. The east-west segment of the diaphragm wall, *i.e.*, the web of the Z-section, appeared to work as a buttress and reduce wall deflections. The reference envelope which is the envelope of deflection paths, can be defined by Δ_4 = 12 mm and Δ_{100} = 600 mm.

5. REFERENCE ENVELOPES FOR THE T2 ZONE

The locations of the sites to be referred to are shown in Fig. 14 and relevant information regarding the excavations carried out at these sites is given in Table 2. As can be noted from Figs. 3 and 4 that, the Sungshan Formation in the T2 zone reaches a maximum of 60 m toward the western boundary. At the sites of interest, however, the Sungshan Formation is much shallower. All these excavations were carried out by using the bottom-up construction method without ground improvement other than localized treatment behind diaphragm walls for stopping leakage.

Table 2 Configurations of excavations in the case studies in the T2 zone

Site number	Thickness of Sungshan Formation, m	Depth of excavation, m	Type of excavation	Wall thickness, mm	Wall length, m
1	48	12.7	Basement, 3300m^2	600	20
4	45	23.4	MRT station	1200	41
5	48	17.5	Cut-and-cover tunnels	800	34
6	40	16.3	MRT station	1000	31
9	44	19.0	MRT Pedestrian Mall	1000	36
17	44	24.5	MRT station	1200	45
28	43	19.0	MRT station	1000	31

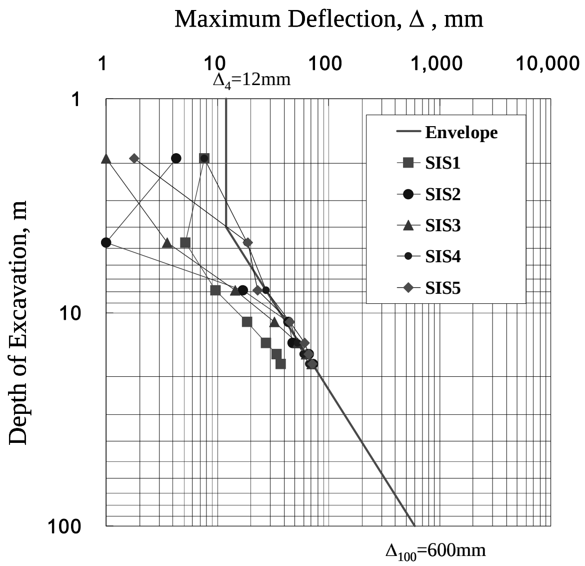


Fig. 13 Wall deflection paths and reference envelope for the illustrating example

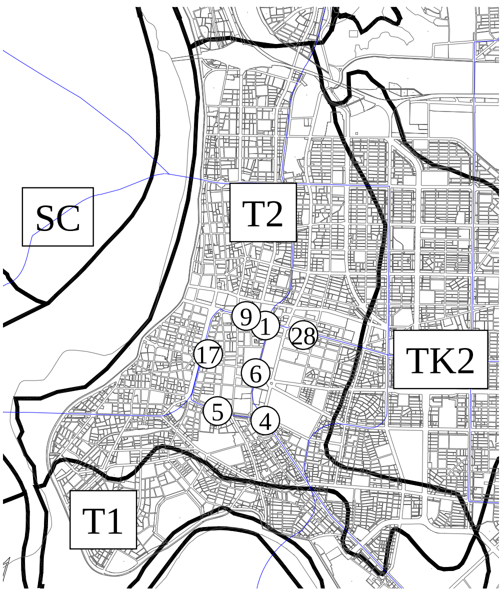


Fig. 14 Case studies in the T2 Zone

The deflection paths, which are plots of the maximum wall deflections versus depths of excavation at various stages of excavation for diaphragm walls with thicknesses of 600 mm, 800 mm, 1,000 mm, and 1,200 mm are shown in Fig. 15. Also shown in the figure are the reference envelopes which are the envelopes of respective deflection paths. Individual inclinometers are identified by suffixes such as A, B, C, *etc*, affixed to the site numbers.

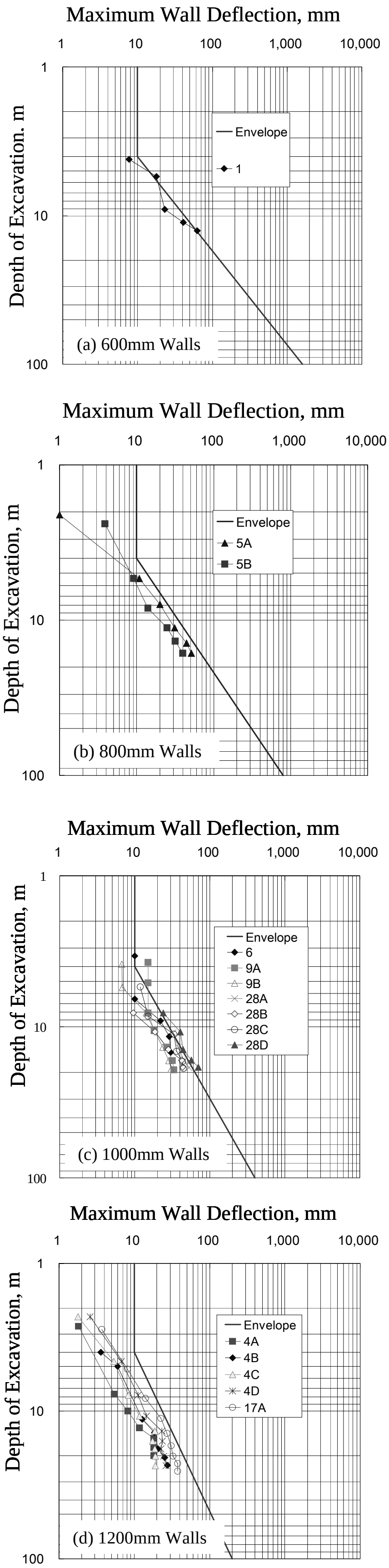
There are numerous ways to draw reference envelopes based on the data presented and the decisions are inevitably subjective. The reference envelopes shown in Fig. 15 were so drawn that, as shown in Table 3, deflections for depths of excavation of 4 m or less, *i.e.*, Δ_4, remain to be the same regardless 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 1,000 mm, and from 1,000 mm to 1,200 mm.

Wall deflections for shallow depths of excavations are of little interest so the fact that some of the data points of inclinometer 9A for excavations up to 5 m go beyond the reference envelope for 1000 mm walls in Fig. 15(c) is of little concern. The fact that the data points for inclinometer 28D in the range of 10 m to 20 m going beyond the reference envelope in the same figure is rather a disappointment but is considered to be an acceptable exception.

As can be noted from Fig. 15(d) that deflection paths tend to bend downward as excavations exceed 12 m or so as the excavations approached the Chingmei Gravels which is located at a maximum depth of 60 m or so and is considered to be a rigid base. The reference envelopes below a depth of 20 m, instead of 12 m just to be conservative, are simulated by arcs which are tangent to the upper portion of the envelopes and are perpendicular to the rigid base as shown in Fig. 16. The envelopes so revised are shown in Fig. 17 which can be used as a preliminary guide for deciding the thicknesses of diaphragm walls. For example, if wall deflections are limited to, say, 40 mm, than walls

Table 3 Parameters defining reference envelopes for the T2 zone

Wall thickness, mm	Δ_4, mm	Δ_{100}, mm	Δ_{30}, mm
600	10	1,600	240
800	10	800	155
1000	10	400	100
1200	10	200	65



Note: The numerals in the inclinometer numbers are sites numbers shown in Fig. 14

Fig. 15 Wall deflection paths and reference envelopes for case studies in the T2 zone

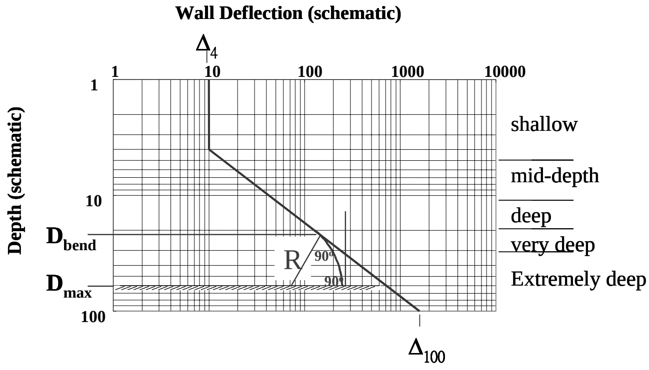


Fig. 16 Correction to reference envelope to account for the effects of rigid base

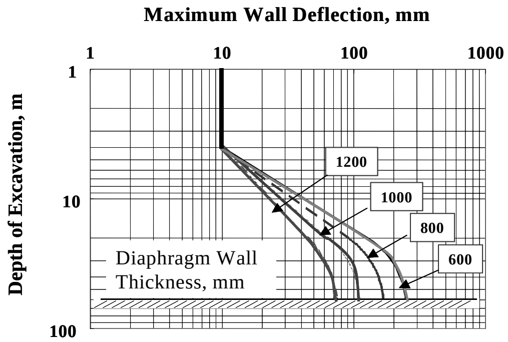


Fig. 17 Reference envelopes proposed for the T2 zone

of 1,200 mm in thickness are definitely appropriate for excavations of, up to, 18 m. Similarly, walls of 600 mm in thickness will be appropriate for excavations of, up to, 10 m only and thicker walls have to be considered if excavations do go deeper. Readers are advised to refer to Section 8.2 for more details regarding the effects of thickness of soft deposits on wall deflection paths.

6. REFERENCE ENVELOPES FOR THE TK2 ZONE

The locations of the sites to be referred to hereinafter are shown in Fig. 18 and relevant information regarding the excavations carried out at these sites is given in Table 4. All these excavations were carried out by using the bottom-up construction method without ground improvement works other than local treatment behind diaphragm walls for stopping leakages. The wall deflection paths and reference envelopes for all the sites listed in Table 4 are shown in Fig. 19. The wall deflection paths shown in Fig. 19(b) bend downward at a depth of excavation of 12 m or so, and those shown in Fig. 19(d) bend at a depth of excavation of 15 m or so. This phenomenon is similar to what is shown in Fig. 15(d) for 1,000 mm walls and further confirms the influence of rigid base on wall deflections. It should be noted, as depicted in Table 4, the thickness of the Sungshan Formation is only 34 m at Site 34 while it varies from 41 m to 51 m at other sites.

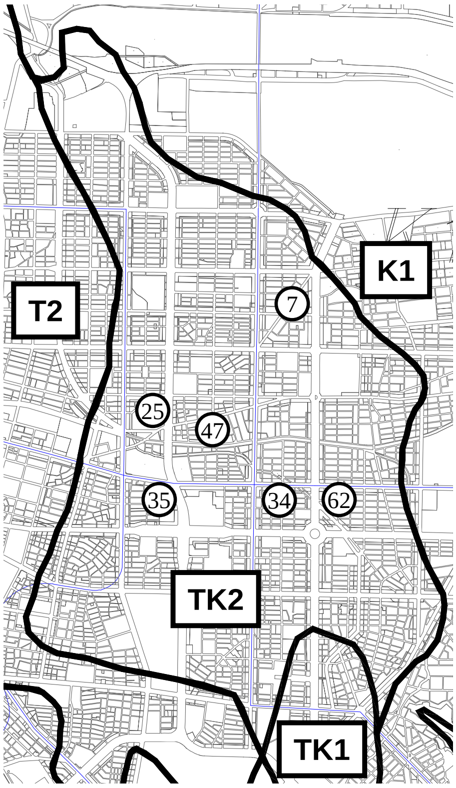
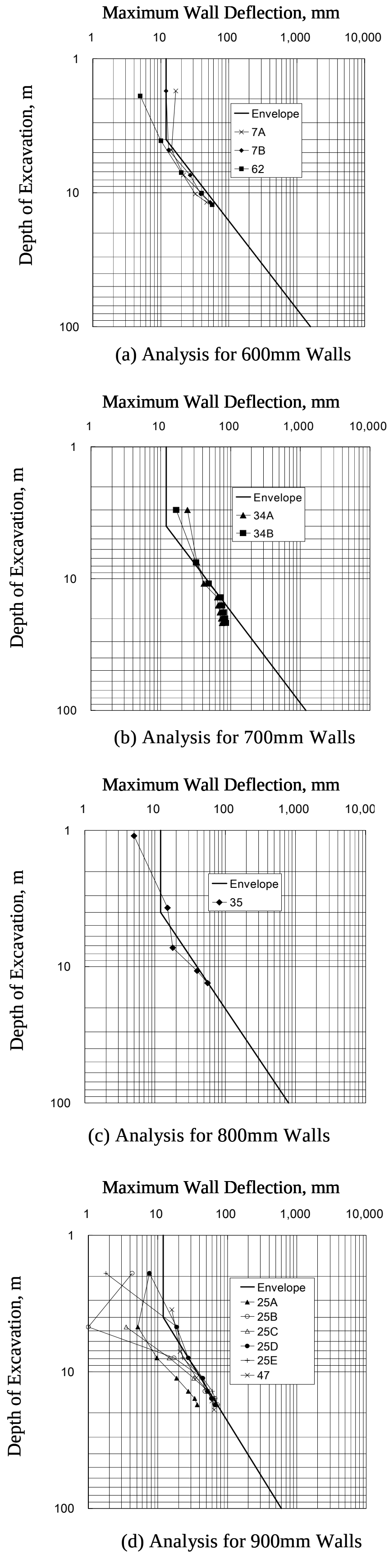


Fig. 18 Case studies in the TK2 zone

7. REFERENCE ENVELOPES FOR THE K1 ZONE

The locations of the sites to be referred to hereinafter are shown in Fig. 20 and relevant information regarding the excavations carried out at these sites is given in Table 5. Excavations at all these sites were carried out by using the bottom-up construction method without ground improvement works other than local treatments behind diaphragm walls for stopping leakages. As the development of the city started from the central area of the basin and mushroomed outward, the construction activities in the K1 zone lag behind the T2 zone. Therefore there are fewer deep basements in the K1 zone in comparison. Furthermore, because of the weak strengths of the clays, auxiliary measures, such as buttresses, grouted slab, *etc*., were frequently adopted in the K1 zone to limit wall deflections. For this reason, the number of cases available for analyses is rather limited and only 3 sites fit in the category.

The wall deflection paths and reference envelopes for diaphragm walls adopted at all the sites listed in Table 5 are shown in Fig. 21. The envelopes were drawn with due considerations given to the reference envelopes proposed for the T2 and TK2 zones and may not be the true envelopes of corresponding sets of data. Furthermore, although the top of the base strata, as depicted in Fig. 3, is erratic with differences of, as much as, 40 m in elevation, the thicknesses of the Sungshan Formation are rather similar at these 3 sites. For this reason, the reference envelopes shown in Fig. 21 may not be representative of the entire zone and local variation in ground conditions may lead to considerably different results.



Note: The numerals in the inclinometer numbers are sites numbers in Fig. 18

Fig. 19 Wall deflection paths and reference envelopes for case studies in the TK2 zone

Table 4 Configurations of excavations in the case studies in the TK2 zone

Site number	Thickness of Sungshan Formation, m	Depth of excavation, m	Type of excavation	Wall thickness, mm	Wall length, m
7	46	12.0	Basement 32 m × 33 m	600	24
25	51	17.5	3 Blocks, 132 m × 40 m largest	900	34
34	34	21.8	Basement 144 m × 45 m	700	34
35	48	13.2	Basement 72 m × 35 m	800	25
47	48	19.0		900	35
62	41	12.3	Basement 1,080 m^2	600	23

Table 5 Configurations of excavations in the case studies in the K1 zone

Site number	Thickness of Sungshan Formation, m	Depth of excavation, m	Type of excavation	Wall thickness, mm	Wall length, m
10	45	12.1	Basement 11,500 m^2	900	28.0
32	38	14.5	Basement 43.5 m × 43.5 m	800	33.0
33	46	18.1	Basement 2,854 m^2	1000	50.0

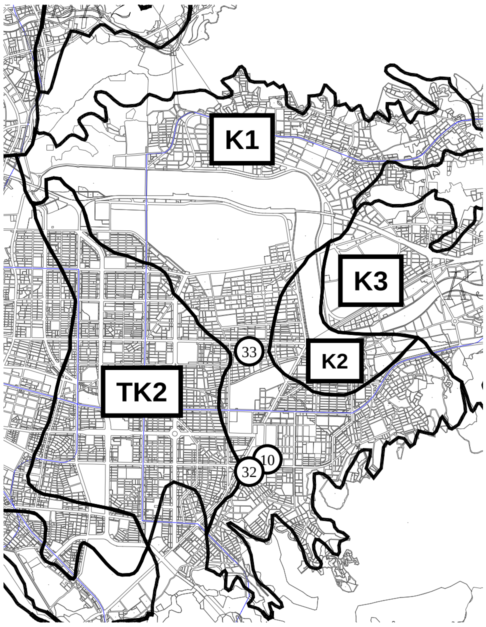


Fig. 20 Case studies in the K1 zone

8. APPLICATIONS OF REFERENCE ENVELOPES

As discussed in Section 2, deflections of diaphragm walls are affected by many factors and the influences of these factors can be evaluated by studying the deflection paths of diaphragm walls and reference envelopes. The reference envelopes proposed herein are for excavations carried out by using the bottom-up construction method without ground improvement other than local treatment for stopping leakage on walls. They can be used as a basis for evaluating performance of diaphragm walls in other situations. For example, it has been found in an on-going study that the adoption of the top-down construction method leads to much larger wall deflections in comparison and this fact is clearly identifiable by studying wall deflection paths.

The following are a few examples to illustrate how reference envelopes can be utilized to study the performance of diaphragm walls in soft ground.

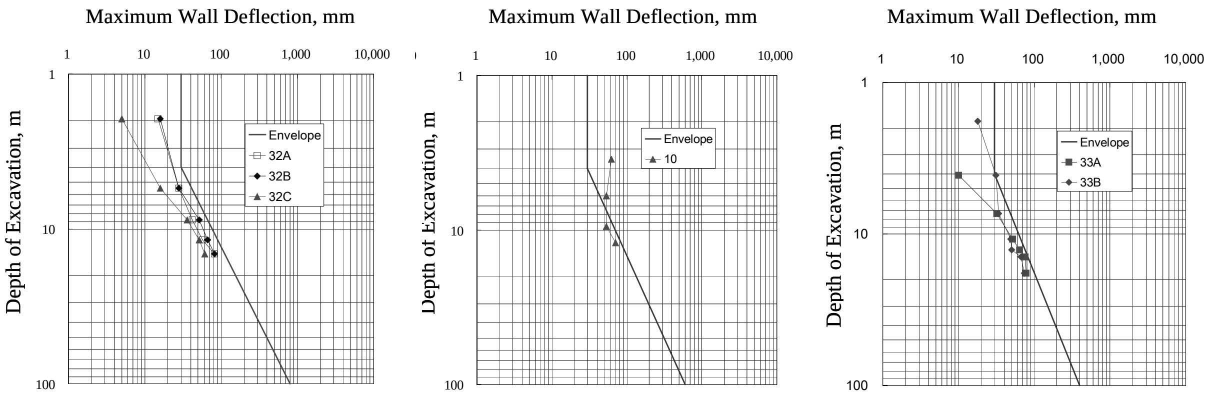
8.1 Effects of Soil Properties

Figure 22 compares the results of CPT tests carried out in the T2 and K1 zones and it can be noted that ground conditions in these two zones are significantly different. The subsoils in the T2 zone are predominantly silty sands while subsoils in K1 zone are predominantly silty clays. The TK2 zone is a transition zone with ground conditions falling in-between those for the T2 and K1 zones. It will thus be interesting to see how soil properties will influence the behavior of walls.

Reference envelopes can conveniently be defined by Δ_4 and Δ_{100}. Table 6 compares the reference envelopes for walls in the T2, TK2, and the K1 zones. Although data are rather limited, the trend that wall deflections decrease systematically as wall thicknesses increase is clear. The values of Δ_4 are 10 mm, 12 mm, and 30 mm for the T2, TK2, and K1 zones, respectively, regardless of wall thickness and the values of Δ_{100} for walls with the same thickness are the same for the three zones. This finding is very encouraging as it greatly simplifies the procedure of constructing reference envelopes for cases without sufficient data. It, however, should be confessed that these values were determined not without prejudice as reference envelopes were purposely drawn so the Δ_4 and Δ_{100} values vary in the desired way to make the results simple and useful for practical applications. After all, geotechnical engineering is a practical science and judgment is highly encouraged.

8.2 Effects of Thickness of Soft Deposits

As can be noted from Figs. 15(d), 19(b), and 21(c), it is convincing that wall deflection paths will bend downward at certain depths of excavation as excavations proceed further down and the bottoms of excavation approach the competent base strata



(a) for 800mm Walls (b) for 900mm Walls (c) for 1000mm Walls

Note: The numerals in the inclinometer numbers are sites numbers shown in Fig. 20

Fig. 21 Wall deflection paths and reference envelopes for case studies in the K1 zone

which are presumably unaffected by the excavations. This phenomenon has been briefly discussed in Section 5 and a procedure for modifying reference envelopes to account for this effect is proposed in Fig. 16.

To further study how the thickness of soft deposits will affect the reference envelopes in different situations, analyses have been performed for two conditions: (1) the real thicknesses of the Sungshan Formation at the sites corresponding to the data shown in these figures, and (2) the maximum thickness of the Sungshan Formation in the T2, TK2, and K1 zone. The latter corresponds to the worst condition possible and shall be the most conservative condition to consider.

For the T2 zone, the reference envelopes corresponding to the above-mentioned conditions are compared with the wall deflection paths shown in Fig. 15(d) in Fig. 23. The Sungshan Formation is about 45 m in thickness at Site 4 and Site 17. Although individual wall deflection paths are widely apart, the trend of bending downward is quite consistent. The reference envelope for the real thickness of the Sungshan Formation of 45 m, *i.e.*, Curve (1), with its lower portion below a depth of excavation of 12 m modified by following the procedure outlined in Fig. 16, agrees with the data very well.

Data are unavailable for determining the depth of excavation at which the reference envelope starts to bend for the case corresponding to the maximum thickness of the Sungshan Formation. It is believed that it will be sufficiently conservative to assume the envelope starts to bend at a depth of 20 m. As can be noted from Fig. 23, at a depth of excavation of 30 m, which is a practical limit for building basements, the reference wall deflection, which is the wall deflection on the reference envelope, will increase from 45 mm to 60 mm as the thickness of the Sungshan Formation increases from 45 m to 60 m.

A similar comparison is given in Fig. 24 for the same sets of data given in Fig. 19(b) for the TK2 zone. The reference envelope is also assumed to start to bend at a depth of excavation of 12 m and, as can be noted, it is quite consistent with the data obtained at Sites 34 where the Sungshan Formation is 35 m in thickness. At a depth of excavation of 30 m, the reference wall deflections will increase from 100 mm to 180 mm as the thickness of the Sungshan Formation increases from 35 m to 60 m.

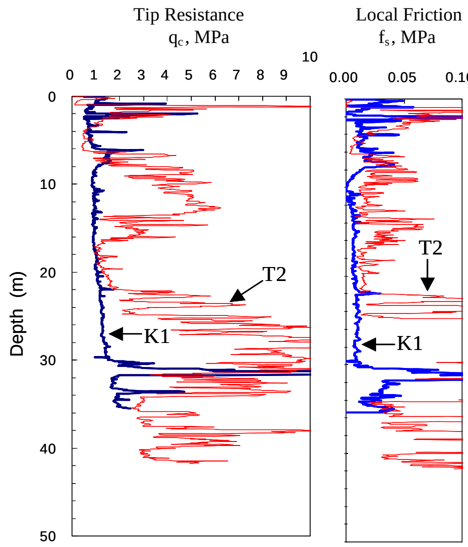


Fig. 22 Comparison of results of CPT tests obtained in the T2 and K1 zones

Table 6 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	1,600	
700		12			1,200	
800	10	12	30	800	800	800
900		12	30		600	600
1000	10		30	400		400
1200	10			200		

The analysis is repeated in Fig. 25 with the same sets of data given in Fig. 21(c) for the K1 zone. The assumption that the reference envelope starts to bend at a depth of 12 m is again valid as evidenced by the fact that the envelope agree with the data quite well. Reference wall deflection at a depth of excavation of 30 m increases from 110 mm to 140 mm as the thickness of the Sungshan Formation increases from 45 m to 60 m.

All the reference envelopes in the 3 cases shown in Figs. 23, 24, and 25 bend at the same depth of excavation of 12 m. Whether this is coincidental or it is supposed to be so remains to be investigated. Since the thicknesses of the Sungshan Formation in the cases listed in Table 6 vary in a rather narrow range as follows:

T2 zone: 7 sites – 40 m to 48 m
TK2 zone : 6 sites – 41 m to 51 m, except Site 34 (34 m)
K1 zone: 3 sites – 45 m to 46 m, except Site 32 (38 m)

it is uncertain whether these values of Δ_4 and Δ_{100} are still applicable should the Sungshan Formation be much thicker or much thinner.

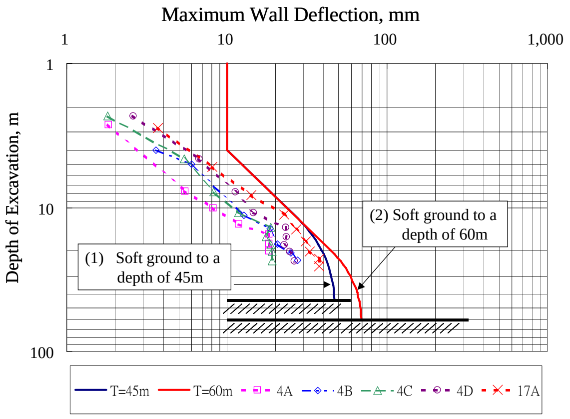


Fig. 23 Deflections of 1,200 mm walls in the T2 zone

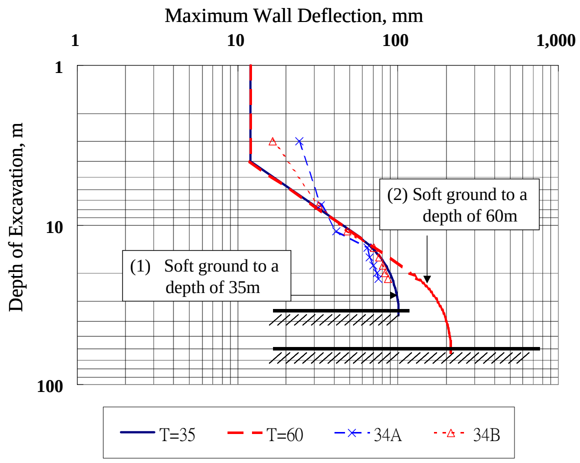


Fig. 24 Deflections of 700 mm walls in the TK2 zone

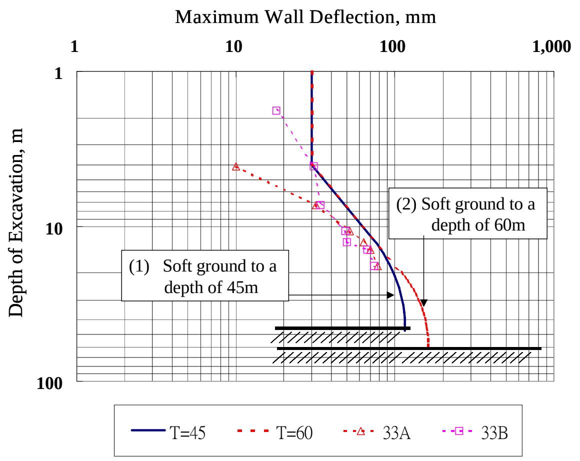


Fig. 25 Deflections of 1,000 mm walls in the K1 zone

8.3 Effects of Ground Treatment

There are a few cases in which grouted slabs were used below the formation levels in the K1 zone to reduce wall deflections. It is expected that these grouted slabs served a similar function as rigid base and wall deflection paths will bend downward as excavation approach these grouted slabs. Lateral boundaries will also reduce wall deflections. The so-called corner effects have been well recognized and the use of cross walls has been proved very effective in reducing wall deflections. The influences of these boundaries can be quantified by using the concept of wall deflection paths. This, however, is the subject of on- going studies and will be discussed in the forthcoming papers in due time.

9. CONCLUSIONS

The foregoing discussions lead to the following conclusions:

(1) The toes of inclinometers may move if inclinometers do not have sufficient penetrations in the rigid base strata and it is very important to correct inclinometer readings for toe movements for the readings to be interpreted correctly.
(2) Wall deflection paths which are plots of maximum wall deflections versus depths of excavation in a log-log scale can be used to evaluate the performance of diaphragm walls in deep excavations carried out in soft ground.
(3) Reference envelope which is the envelope of wall deflection paths can be considered as a site characteristic curve and can be used for estimating maximum wall deflections for a specific retaining system.
(4) The reference envelope can be defined by Δ_4 and Δ_{100} which are the wall deflections for depths of excavation of 4 m and 100 m, respectively.
(5) The Δ_4 values are 10 mm for the T2 zone, 12 mm for the TK2 zone and 30 mm for K1 zone.
(6) The Δ_{100} values vary from 1,600 mm for 600 mm walls to 200 mm for 1,200 mm walls.

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