Journal of Geotechnical Engineering No. 505/III—29, pp. 19~29, December 1994

PREDICTION OF LATERAL DEFLECTION OF DIAPHRAGM WALL IN DEEP EXCAVATIONS

Toru MASUDA*, Herbert H.EINSTEIN** and Toshiyuki MITACHI***

In recent decades, the demand for underground space has been increased. Deep excavations are required to meet the demand, and, in many cases, excavation sites are in close proximity to existing structures. A major concern in these construction activities is to predict the lateral wall deflections and the ground surface settlements in the design stage. While numerical methods are often applied for the prediction of these movements, there are demerits because of the complexities of these methods, and it is desired to estimate the approximate deflections in a primary design stage. In this paper, a simplified procedure for the prediction of maximum lateral deflections of diaphragm walls is proposed, based on the research of empirical correlations concerning with factors affecting the behavior of walls in 52 case studies.

Key Words : *excavation, retaining structures, deformation, statistical analysis*

1. INTRODUCTION

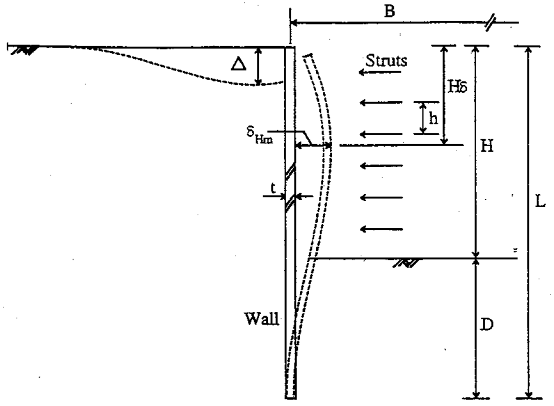
In recent decades, the demand for underground space has been increased. Deep excavations are required to meet the demand, and, in many cases, excavation sites are in close proximity to existing structures. Advanced techniques are needed in these excavations to mitigate the large amount of lateral wall deflections and surface settlements for the purpose of avoiding damage to the adjacent structures. For these reasons, the following measures are often implemented in deep excavations : 1) concrete diaphragm walls as the retaining walls; 2) preloading to struts; 3) the top-down construction method; and 4) soil improvement. A major concern in these construction activities is to predict the lateral wall deflections and the ground surface settlements in the design stage. While numerical methods are often applied for the prediction of these movements, there are demerits because of the complexities of these methods, and it is desired to estimate the approximate deflections in a primary design stage.

There have been many studies on lateral wall deflections and surface settlements in excavations with numerical and empirical approaches since the first practical study was published by Peck (1969)[1]. Sugimoto (1986)[2] proposed an empirical correlation for the maximum surface settlements adjacent to excavations, based on extensive case studies. Clough and O'Rourke (1990)[3] presented empirical correlation for the maximum lateral wall deflections with the factor of safety against basal heave and so called system stiffness. Although the results provide a useful guide for the approximate prediction of the magnitude of settlements/deflections, most of the existing data were obtained from excavations less than 15 meters depth with relatively flexible retaining walls. Therefore, there would be uncertainties in extrapolating these observations to much deeper excavations supported by concrete diaphragm walls. However, these observations are useful for the study to establish the empirical correlations for the prediction of the maximum lateral deflections of diaphragm wall.

Hata et al.[4] presented the numerical study about the performance of an anchored diaphragm wall in a deep excavation in soft clay, using a constitutive model of soil[5].Whittle and Hashash (1992)[6] and Hashash (1992)[7] presented the numerical study concerned with the lateral wall deflections supported with diaphragm walls, which summarize the numerical predictions of maximum lateral wall deflections for excavations in normally consolidated Boston Blue Clay as a function of the excavation depth and strut spacing using an advanced soil model (MIT-E3)[8] . While there are merits of this approach concerning the accuracy of the characterization of the soil behavior and the availability of procedures to model construction sequences, there are demerits in their complexities.

This paper presents a simplified procedure for the prediction of maximum lateral deflections of concrete diaphragm walls in deep excavations with the open cut method, based on the investigations of empirical correlations between the maximum

* Member of JSCE, M.S., East Japan Railway Company, 2-2-6, Yoyogi, Shibuya-ku, Tokyo, 151
** Sc.D., Professor, Department of Civil and Environmental Engineering,Mssachusetts Institute of Technology, M.A., U.S.A
*** Member of JSCE, Dr. Eng., Professor,Department of Civil Engineering, Hokkaido University



H= depth of excavation
B= width of excavation
D= embedment depth
L (= H +D)= length of wall
t = thickness of wall
h = spacing of struts
δ_{Hm} = maximum lateral wall deflection
Hδ = depth generating maximum lateral wall deflection
Δ = surface settlement
n = number of struts (supports)

Fig.1 Terms Relating to Excavations and Used in this Paper

lateral deflections and factors affecting the behavior of walls in 52 case studies (excavation depth $= 10 \sim 42$ m). The data of case studies were collected from the literature describing the behavior of diaphragm wall[9].

The following terms relating to excavations and used in this paper are shown in **Fig.1** : depth of excavation H; width of excavation B; embedment depth D; thickness of wall t; length of wall $L\ (=H+D)$; maximum lateral wall deflection δ_{Hm}; spacing of struts h; depth generating maximum lateral wall deflection H_δ; surface settlement Δ; and number of struts (supports) n.

2. CASE STUDIES OF LATERAL DEFLECTIONS OF DIAPHRAGM WALL

(1) Descriptions of Case Studies

52 case studies were collected from the literature on lateral deflections of diaphragm walls in deep excavations. The number of cases according to the depth of excavations is as shown in **Table 1**. The classification of soil types in excavations is determined as follows :

Excavations in sand : $Hs/H \geqq 60\%$, $Hc/H \leqq 40\%$

Excavations in clay : $Hs/H \leqq 40\%$, $Hc/H \geqq 60\%$

Table 1 Number of Cases Categorized by Depth Interval

Depth of excavations H (m)	Number of cases
10 ≦ H < 15	18
15 ≦ H < 20	9
20 ≦ H < 25	15
25 ≦ H < 30	5
30 ≦ H < 35	2
35 ≦ H < 40	2
40 ≦ H < 45	1
Total	52

Table 2 Maximum Lateral Wall Deflections and Their Ratio to Excavation Depth
The notation of ※ indicates that the value is estimated from the literature

No. of Case	H (m)	D (m)	H_s/H (H_c/H) (%)	Max. lateral wall deflections δ_{Hm} (mm)	δ_{Hm}/H (%)	Soil type in excavation
1	12.2	11.8	57.4	61	0.51	Mixed
2	10.5	4.7	100 ※	25	0.24	Sand
3	14.4	3.0	100 ※	22	0.15	Sand
4	10.2	6.3	100 ※	12	0.12	Sand
5	12.0	7.5	100 ※	10	0.08	Sand
6	17.68	4.32	100 ※	16	0.09	Sand
7	22.9	5.1	57.2	8.3	0.04	Mixed
8	33.2	3.0	56.9	10	0.03	Mixed
9	29.8	2.45	66.4	10	0.03	Sand
10	13.1	11.4	93.1	36	0.27	Sand
11	20.0	9.0	52.5	44	0.22	Mixed
12	15.1	4.9	51.0	45	0.30	Mixed
13	13.3	12.7	52.3	19	0.14	Mixed
14	13.3	12.7	52.3	26	0.20	Mixed
15	41.83	6.17	(86.9)	27	0.06	Clay
16	25.75	13.25	(50.5)	185	0.72	Mixed
17	25.1	3.9	(53.8)	10	0.04	Mixed
18	15.78	18.72	(100) ※	16	1.01	Clay
19	21.0	25.0	(100) ※	150	0.71	Clay
20	12.35	11.65	(100) ※	88	0.71	Clay
21	20.8	10.2	(100) ※	68	0.33	Clay
22	18.8	3.6	(100) ※	45	0.24	Clay
23	23.82	1.3	(100) ※	41	0.17	Clay
24	16.08	13.07	(100) ※	41	0.25	Clay
25	30.8	11.2	(80.8)	25	0.08	Clay
26	36.6	18.9	(61.2)	35	0.01	Clay
27	36.6	18.9	(69.1)	22	0.06	Clay
28	23.9	7.2	(87.4)	28	0.12	Clay
29	13.75	10.25	(100)	120	0.87	Clay
30	27.6	10.9	(83.3)	80	0.29	Clay
31	17.85	3.15	(88.2)	70	0.39	Clay
32	17.85	3.15	(88.2)	20	0.11	Clay
33	13.8	13.2	(50.0)	38	0.28	Mixed
34	13.9	6.1	(100)	24	0.17	Clay
35	13.9	6.1	(100)	41	0.29	Clay
36	13.9	6.1	(100)	12	0.09	Clay
37	13.9	6.1	(100)	8	0.06	Clay
38	26.0	2.0	(84.6)	16	0.06	Clay
39	21.3	4.8	(74.2)	31	0.15	Clay
40	21.3	4.8	(74.2)	35	0.16	Clay
41	19.1	7.9	(65.4)	32	0.17	Clay
42	19.1	7.9	(52.4)	20	0.10	Mixed
43	22.98	10.0	(54.3)	63	0.27	Mixed
44	26.2	2.5	(74.8)	27	0.10	Clay
45	26.2	2.5	(74.8)	27	0.10	Clay
46	21.6	24.4	(79.2)	28	0.13	Clay
47	21.6	15.4	(79.2)	85	0.39	Clay
48	22.65	3.0	(92.5)	10	0.04	Clay
49	22.65	3.0	(92.5)	28	0.12	Clay
50	13.55	2.3	(70.1)	10	0.07	Clay
51	13.73	2.25	(70.5)	11	0.08	Clay
52	13.55	2.32	(70.1)	10	0.07	Clay

Excavations in mixed ground :

$$40\% < H_S/H < 60\%$$
$$40\% < H_C/H < 60\%$$

where H_S = total thickness of sand layer above the base of excavation

H_C = total thickness of clay layer above the base of excavation

Classifications of sand and clay are as follows : sand layer : sand, gravel, sandstone; clay layer : clay, silt, hard clay deposit.

The number of cases according to the soil types is : 7 in sand, 33 in clay, and 12 in mixed ground. The most common soil properties described in the literature were the N values (standard penetration test), friction angles, unconfined compressive strength, and undrained shear strength. And the following construction conditions that will be used for the empirical correlations for the lateral wall deflections were collected : 1) soil improvement; 2) preloading to struts (the axial preloads are induced to struts by using hydraulic jacks immediately after the struts are placed at a certain depth); and 3) the top-down method (the method placing the permanent concrete floor/roof slabs from the top to the bottom as the excavation processes.)

The lateral wall deflections measured in each excavation step were collected and the data on the maximum lateral wall deflections will be used for the empirical correlations (See **Table 2**.)

(2) Measured Lateral Wall Deflections in the Case Studies

The plots of the maximum lateral wall deflection δ_{Hm} vs. excavation depth H are shown in **Fig.2** (excavations in sand and mixed ground in the case $Hs \geqq Hc$, Case 1-14), and **Fig.3~5** (excavations in clay and mixed ground in the case $Hs \leqq Hc$, Case 15-32, 33-42, 43-52.). In these figures, the deflections are plotted in each excavation step, and the lines of (δ_{Hm}/H)=0.05%, 0.1%, 0.2%, and 0.5% are drawn.

The plots of the maximum lateral wall deflections δ_{Hm} vs. excavation depth and the characteristics of excavation conditions[9] lead to the following rough observations. Note that following statements are quite general and will be examined in the later mentioned empirical correlations between the maximum lateral wall deflections and the factors affecting the behavior of diaphragm walls (See **Table 3** for the characteristics of construction conditions.)

1) There is ample scatter of the ratio of maximum lateral wall deflections to excavations. However, the ratio tends to be about 0.05~0.5%.

2) When some mitigating measures (the top-down method, preloading to struts, and soil improvement) are implemented, maximum lateral wall deflections can be reduced.

3) The smaller the spacing of struts, the smaller

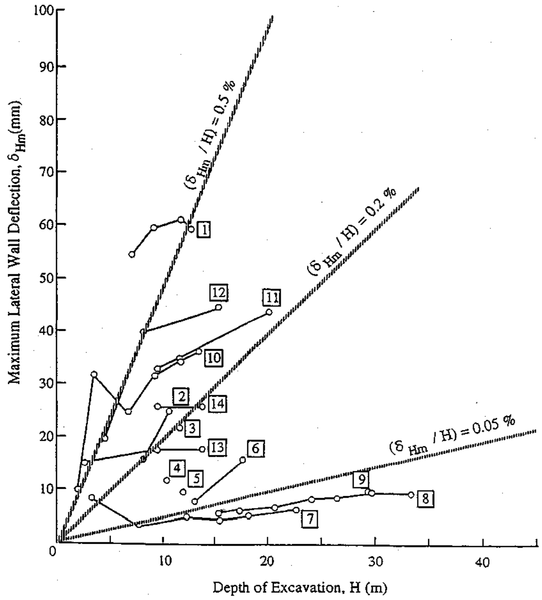


Fig.2 Observed Maximum Lateral Deflections of Diaphragm Walls vs. Excavation Depth, Excavations in Sand and Mixed Ground, Cases 1-14

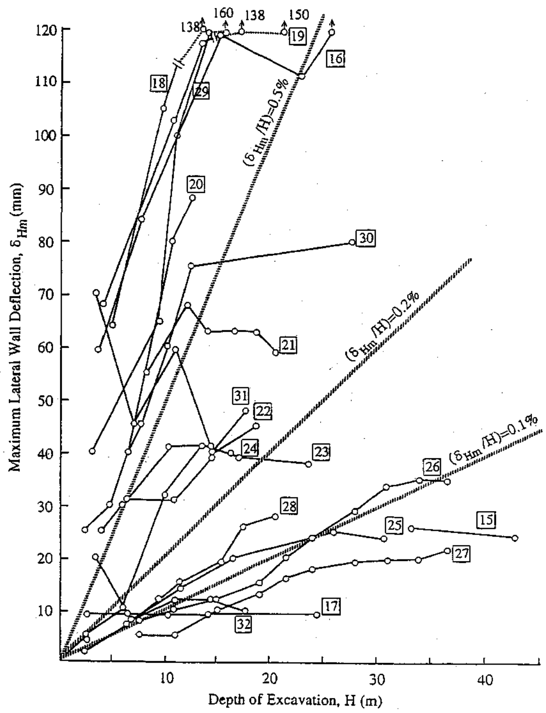


Fig.3 Observed Maximum Lateral Deflections Diaphragm Walls vs. Excavation Depth, Excavations in Clay and Mixed Ground, Cases 15-32

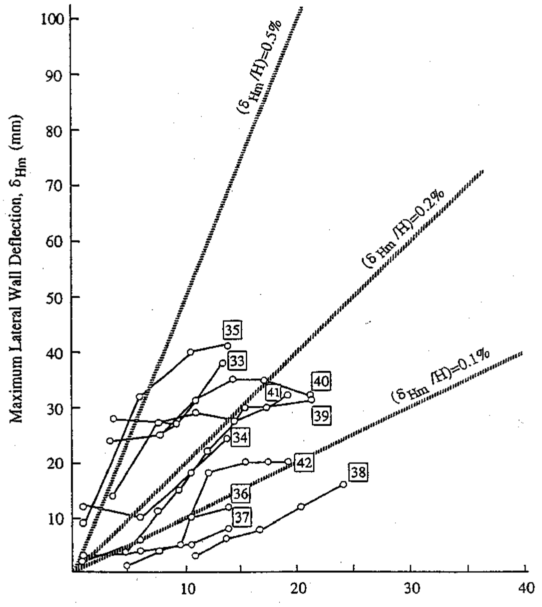


Fig.4 Observed Maximum Lateral Deflections of Diaphragm Walls vs. Excavation Depth, Excavations in Clay and Mixed Ground, Cases 33-42

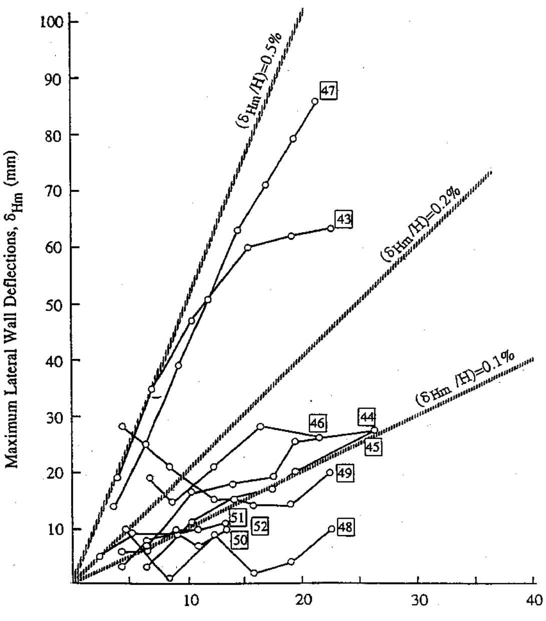


Fig.5 Observed Maximum Lateral Deflections of Diaphragm Walls vs. Excavation Depth, Excavations in Clay and Mixed Ground, Cases 43-52

the maximum lateral wall deflections.

4) When the walls are embedded into stiff deposits, the maximum lateral wall deflections are small.

Table 3 Characteristics of Construction Conditions
Note : W/O means with/without. P, T.D., and S.I. in the column of construction methods mean "preloading to struts", "top-down", and "soil improvement", respectively

No. of Case	No. of struts n	Construction methods W/O		
		P	T.D	S.I
1	4	W	0	0
2	2	0	0	0
3	3	0	0	0
4	3	0	0	0
5	3	0	0	0
6	3	0	0	0
7	5	W	0	0
8	12	0	W	0
9	6	0	W	0
10	5	0	0	0
11	7	0	0	0
12	6	0	0	0
13	5	0	W	W
14	6	0	W	W
15	12	0	0	0
16	4	0	W	0
17	5	W	0	0
18	4	0	0	0
19	5	0	W	W
20	3	0	0	0
21	6	0	0	W
22	4	W	0	0
23	5	0	W	0
24	4	0	0	0
25	11	W	W	W
26	11	W	W	0
27	11	W	W	0
28	7	0	W	0
29	2	0	W	0
30	10	W	0	0
31	4	W	0	0
32	4	W	0	0
33	5	0	W	0
34	6	0	0	W
35	6	0	0	W
36	6	0	0	W
37	6	0	0	W
38	8	W	0	W
39	5	W	0	0
40	5	W	0	0
41	6	0	W	0
42	6	0	W	0
43	7	0	W	W
44	6	W	W	W
45	6	W	W	W
46	3	0	W	0
47	7	0	0	0
48	5	W	W	0
49	5	W	W	0
50	4	W	0	0
51	4	W	0	0
52	4	W	0	0

3. FACTORS AFFECTING LATERAL DEFLECTIONS OF DIAPHRAGM WALLS IN DEEP EXCAVATIONS

(1) Factors Affecting Lateral Wall Deflections

Based on the observations of the behavior of lateral diaphragm wall deflections in the case studies and the previous studies[1)~8)], the following factors can be considered to affect the lateral wall deflections in deep excavations :

① Soil types in the excavations and embedments (i.e., sand, clay, and mixed ground)

② Soil properties in excavations and embedments (e.g., undrained shear strength and the modulus of elasticity)

③ Flexural stiffness of the diaphragm walls (i.e., EI of the wall, where E=Young's modulus, I= moment of inertia)

④ Spacing of struts/number of struts

⑤ With/without preloading to struts

⑥ Construction processes (i.e., the top-down method, the conventional down-top method)

⑦ Length of the walls ($L=H+D$, See **Fig.1**)

⑧ With/without soil improvement

⑨ Scale of excavations (depth and width of excavations)

⑩ Groundwater/pore water pressure conditions

⑪ Other construction activities (O'Rourke (1989)[10)])

I) Activities performed separately of the excavations and the supports

- Relocation of utilities
- Removal of existing basement/piles
- Installation of concrete diaphragm walls

II) Activities integral to the excavations and the supports

- Connections between supports and walls
- Excavation depth which the first level of supports installed
- Depth of excavation beneath the lowest support level
- Sequence of the excavation
- Time between the excavation and the installation of support
- Surcharge loads adjacent to the excavations

Since the above all factors were not mentioned in the previous case studies, this study uses the major soil properties described in the case studies, e.g., the N value (SPT), friction angles, and modulus of elasticity for sands; and the N values (SPT), unconfined compressive strength, undrained shear strength, and modulus of elasticity for clays.

(2) Discussion on Factors Affecting Lateral Wall Deflections

a) Review of Coefficients Correlating Lateral Wall Deflections and Ground Surface Settlements

Clough et al. (1989)[11)] proposed the design curves to obtain the maximum lateral wall deflections in excavations in soft to medium clays, using the factor of safety against basal heave and the so called system stiffness. The factor of safety, which is defined by Terzaghi (1943)[12)], is used as an index parameter intending not to provide a direct measure of base stability. The system stiffness was defined as follows

$$(\text{System stiffness}) = (EI)/(\gamma_w h_{ave}^4) \cdots\cdots\cdots (1)$$

where EI=flexural stiffness of walls
γ_w=unit weight of water
h_{ave}=average vertical spacing of struts

Sugimoto[2)] showed that the maximum settlements of the ground surface adjacent to the excavations were approximately predicted by using the so called the cutting factor. The cutting factor was defined as follows :

$$(\text{Cutting Factor}) = (BH)/(\beta_D D) \cdots\cdots\cdots\cdots (2)$$

$$\beta_D = [E_{sb}/(EI)]^{1/4}$$

where B=width of excavations
H=excavation depth
D=embedment depth
β_D=coefficient of embedment
E_{sb}=average modulus of elasticity of soils below the base of excavation (soils in embedment), which is estimated from the correlations between modulus, N value (SPT), and coefficient of subgrade reaction
EI=flexural stiffness of walls

Although these coefficients provide a guide on the expected magnitudes of the lateral wall deflections and the ground surface settlements, extrapolations of the use of these coefficients to the certain types of excavations of current interest are not effective due to following reasons :

1) The cutting factor can be used for the prediction only for the surface settlements adjacent to excavations with relatively flexible retaining walls, and was not applied for the index parameter of wall deflections.

2) The system stiffness can be effectively used for the prediction only for excavations in clay, i.e., the lateral wall deflections for excavations in sand can not be predicted using system stiffness in the design curves.

3) There have been many field data in the case studies which indicate that the maximum lateral wall deflections are less than 0.5% H in deep excavations, which are not effectively covered by the design curves using the system stiffness.

Therefore, there is a need to propose a new coefficient which will be related to the lateral wall deflections in deep excavations supported by diaphragm walls in order to set up the empirical correlations. The following factors will be considered in the proposed coefficients : ① depth of excavations, ② soil properties above and below the base of excavations, taking the modulus of elasticity as the representatives, ③ number of struts or spacing of struts (average) : n or h_{ave}, ④ flexural stiffness of the wall, ⑤ embedment depth, and length of the walls, and ⑥ construction methods (with/without preloading to struts, soil improvement, and the top-down method). Although other factors mentioned in last section 3. (1) (i.e., ⑨ width of excavations, ⑩ groundwater/pore water pressure conditions, ⑪ other construction activities) might be considered to affect the lateral wall deflections, they will not be taken as the factors in the proposed coefficients in this study since they were not precisely described in the literature.

b) Factors to Be Used in Proposed Coefficients

1) Flexural Stiffness of Diaphragm Walls

The flexural stiffness of diaphragm walls in situ is expressed as follows :

$$(EI)_{actual}=E_{eq}I_{eq} \qquad (3)$$

where

$(EI)_{actual}$ = flexural stiffness of diaphragm walls in situ

E_{eq} = equivalent Young's modulus of the concrete diaphragm walls after generation of tension cracks

I_{eq} = equivalent moment of inertia of the concrete diaphragm walls, assuming that the walls are in an uncracked state

The main concern is to decide the flexural stiffness of a concrete diaphragm wall in situ, since the flexural stiffness in situ would be decreased due to the generation of tension cracks.

According to a study[13], the flexural stiffness of the concrete diaphragm walls is expressed with the Young's modulus of the uncracked concrete as :

$$(EI)_{actual}=(E_cI_{eq})/3 \qquad (4)$$

In this paper, the stiffness will be based on Eq.(4).

2) Soil Properties Used in Empirical Correlations

The major properties described in the case studies in the literature were N value (STP), undrained shear strength, and modulus of elasticity. This paper treats the modulus of elasticity as the common property both for clay and sand. The modulus of elasticity of sand will be estimated from the correlations between N value (STP) in the case where there was no descriptions in the literature. According to a building code (1986)[14], modulus of elasticity of sand can be estimated as follows :

$$E_S=250N\,(\mathrm{tf/m^2}) \qquad (5)$$
$$(\times 0.98\ (\mathrm{MPa}))$$

where N = blow count of standard penetration test

Table 4 Characteristics of Soils Above and Below the Below the Base of Excavation, and Proposed Coefficient Representing the Excavation System Stiffness of Diaphragm Walls R
Esu, Esb, $Esub$ (tf/m^2) ($\times 0.98$ MPa), R($\times 10^{-5}$ m^4/tf) ($1/(9.8\times10^3)$ m^4/N)

No. of Case	Average modulus of elasticity			R
	E_{su}	E_{sb}	E_{sub}	
1	1302	10000	5579	2.824
2	1750	10000	4301	19.547
3	3750	10000	4828	9.862
4	5000	3146	4292	11.624
5	5000	18750	10288	2.888
6	5000	4078	4819	14.399
7	3279	15000	5414	1.274
8	13016	17009	13347	0.266
9	9354	15000	9783	0.839
10	910	2165	1494	137.665
11	1095	10171	3912	10.284
12	749	2500	1178	36.843
13	4177	12500	8242	1.127
14	4177	12500	8242	0.939
15	93552	106750	95248	0.102
16	5291	11366	7355	2.338
17	4824	12500	5856	2.161
18	699	1023	875	127.946
19	1282	2577	1986	11.435
20	466	855	655	197.646
21	875	6904	2859	4.108
22	699	18750	3600	7.955
23	466	18750	1412	3.479
24	4388	4921	4627	10.463
25	2851	14876	6058	0.374
26	3266	45500	17648	0.066
27	3170	42245	16477	0.073
28	3599	16497	6585	1.147
29	3413	7313	5079	5.256
30	3708	18107	7785	1.090
31	898	11500	2488	5.113
32	898	11500	2488	5.113
33	3385	10972	7094	3.055
34	1300	9385	3766	8.003
35	1300	9385	3766	8.003
36	1926	9385	4201	1.667
37	1926	9385	4201	1.667
38	12882	15000	13033	0.211
39	970	2214	1199	19.324
40	970	2214	1199	19.324
41	1525	19177	6690	1.344
42	1970	46946	15130	0.572
43	2681	19745	7855	1.141
44	7073	12500	7546	0.362
45	7073	12500	7546	0.362
46	812	10522	5963	6.477
47	812	10190	4715	9.640
48	1838	50421	7520	0.218
49	1838	50421	7520	0.218
50	3788	17475	5774	1.540
51	3763	17475	5694	1.558
52	3788	17475	5789	0.926

Terzaghi and Peck (1967)[15] proposed the correlations between the N value and unconfined compressive strength of clay q_u (note that undrained shear strength S_u is referred to as unconfined compressive strength q_u, using the relation, $S_u=q_u/2$), and the mean q_u can be estimated from the proposed correlations as follows :

$q_u \fallingdotseq N/7.5\,(\mathrm{kgf/cm^2})$ .... (6)

$(N/7.5 \times 0.098\ (\mathrm{MPa}))$

According to a design manual (1982)[16], the correlations are subdivided, depending on plasticity as follows :

Clays of low plasticity ($I_p<15$) and clayey silts

$q_u \fallingdotseq N/13.3\,(\mathrm{kgf/cm^2})$ .... (7.1)

$(N/13.3 \times 0.098\ (\mathrm{MPa}))$

Clays of medium plasticity ($15 \leqq I_P \leqq 30$)

$q_u \fallingdotseq N/6.7\,(\mathrm{kgf/cm^2})$ .... (7.2)

$(N/6.7 \times 0.098\ (\mathrm{MPa}))$

Clays of high plasticity ($I_P>30$)

$q_u \fallingdotseq N/4\,(\mathrm{kgf/cm^2})$ .... (7.3)

$(N/4 \times 0.098\ (\mathrm{MPa}))$

Bowles (1988)[17] presented the empirical correlations between undrained shear strength S_u and the modulus of elasticity for clay E_s as follows :

Normally consolidated sensitive clay

$E_s=(200-500) \times Su$

(mean value : $350 \times S_u$) .... (8.1)

Normally consolidated insensitive and lightly overconsolidated clay

$E_s=(750-1\,200) \times Su$

(mean value : $975 \times Su$) .... (8.2)

Heavily overconsolidated clay

$E_s=(1\,500-2\,000) \times Su$

(mean value : $1\,750 \times Su$) .... (8.3)

The soil above and below the base of excavations in the case studies are characterized by means of the modulus of elasticity. Average modulus of elasticity of soils above and/or below the base of excavations, Esu, Esb, and $Esub$, are described as shown in **Table 4**. The symbols of the elasticity are defined by Eqs.(9.5), (9.6), and (9.7).

In this paper, when the correlation is needed to estimate the modulus of elasticity of clay from the undrained shear strength and/or the N value, the correlation will be based on Eqs.(6) and (8) when the plasticity is unknown, and will be based on Eqs.(7) and (8) when the plasticity is known.

4. EMPIRICAL CORRELATIONS FOR MAXIMUM LATERAL DEFLECTIONS OF DIAPHRAGM WALLS

(1) Proposed Coefficients for the Empirical Correlations

Based on the previous discussions on the factors affecting the lateral deflections, the consideration of the total excavation system stiffness including both the soil stiffness and support stiffness is required to distinguish the behavior of conventional shallow excavations with relatively flexible walls from the deep excavations with diaphragm walls.

To meet the requirements for coefficients correlating to the maximum lateral wall deflections, the followings are proposed :

$R=[(\alpha+\lambda)\eta n Esub\beta u\beta b]^{-1}$ .... (9.1)

where R = coefficient representing the excavation system stiffness of diaphragm walls ($\times 10^{-5}\ \mathrm{m^4/t}$) ($1/(9.8 \times 10^2)\ \mathrm{m^4/N}$)

βu = coefficient representing the modulus of diaphragm walls and soils above the base of the excavation

$=[Esu/(EI)_{actual}]^{1/4}\ (\mathrm{m^{-1}})$ ..... (9.2)

βb = coefficient representing the modulus of diaphragm walls and soils below the base of the excavation (soils in embedment)

$=[Esb/(EI)_{actual}]^{1/4}\ (\mathrm{m^{-1}})$ ..... (9.3)

α = factor representing preloading to struts

λ = factor representing the top-down method

η = factor representing stiffness of soil in embedment

$=[Esb/Esub]^{1/4}$ .... (9.4)

n = number of struts

$(EI)_{actual}$ = flexural stiffness of concrete diaphragm walls based on Eqs.(3) and (4) ($\mathrm{tf \cdot m^2}$) ($\times 9.8\ \mathrm{kN \cdot m^2}$)

$Esub$ = average modulus of elasticity of soils above and below (in embedment) the base of excavation

$=(HEsu+DEsb)/(H+D)$ ($\mathrm{tf/m^2}$) ($\times 9.8$ MPa) .... (9.5)

Esu = average modulus of elasticity of soils above the base of excavation

$=(\Sigma Hi\zeta Esui)/H$ ($\mathrm{tf/m^2}$) ($\times 9.8$ MPa) .... (9.6)

Esb = average modulus of elasticity of soils below the base of excavation

$=(\Sigma Di\zeta Esbi)/H$ ($\mathrm{tf/m^2}$) ($\times 9.8$ MPa) .... (9.7)

ζ = factor representing soil improvement

$H=\Sigma Hi$ = depth of excavation (m)

$D=\Sigma Di$ = embedment depth of diaphragm wall (m)

A subscript "i" in Eq.(9) indicates each certain value of each ground stratification above/below the base of excavation.

As for the proposal of the new coefficient "R", following comments should be made; 1) The coefficient "R" is used as an index parameter intending not to provide a direct amount of wall deflection. In studying the empirical correlations,

Table 5 Values of the Factors Representing Preloading to Struts (α), and the Top-Down Method (λ)

Soil types in excavations		Sand	Mixed	Clay
α	No preload	1.0		
	Induced	$(1.5)^2=2.25$	$(1.75)^2=3.06$	$(2.0)^2=4.0$
λ	Conventional	1.0		
	the top-down	$(1.5)^2=2.25$	$(1.75)^2=3.06$	$(2.0)^2=4.0$

Table 6 Values of the Factor Representing Soil Improvement (ζ)

Method of soil improvement	Type of treated soil	
	Sand	Clay
Chemical grouting Quicklime pile	ζ = 1.5	
Column Jet Grout	ζ =3000/ E_s	ζ =1000/ E_s
	Re: E_s is the modulus of soil. before treated. (tf/m²)	

better correlations can be obtained when the "R" is inversely related to coefficients in a bracket in Eq.(9.1), therefore the dimension of "R" (i.e., m⁴/t) does not have physical measurement; 2) The factors representing preloading to struts (α), and the top-down method (λ) do not have the multiplicative effect to wall deflections in the case studies, respectively, therefore they are treated as non-multiplicative factors; 3) The coefficients βu and βb adopt fourth root power of the ratio between the wall stiffness and soil modulus above/below the base of excavation. The magnitude of fourth root power was hinted from Sugimoto[2] (See Eq.(2)) and this can lead to better empirical correlations.

The values of the factors representing preloading to struts and the top-down method are assumed as shown in **Table 5**. The values in the table are derived from the comparison of the case studies with/without the preloading to struts and the top-down method. The values of the factor representing soil improvement are assumed as shown in **Table 6**. The values in **Table 6** are derived from some literatures[18),19),20),21)] which illustrate the effects of improving the strength properties of soils, and the methods in the table are those treated in the case studies. The values of coefficient representing the excavation system R are shown in **Table 4**.

(2) Empirical Correlations Between Maximum Lateral Deflections and Proposed Coefficient

The ratio of maximum lateral wall deflections (δ_{Hm}/H) vs. the coefficient representing the excavation system stiffness R is plotted in a log-log plot as shown in **Figs.6**, **7**, and 8 for "excavations in sand", "excavations in mixed ground", and "excavations in clay", respectively.

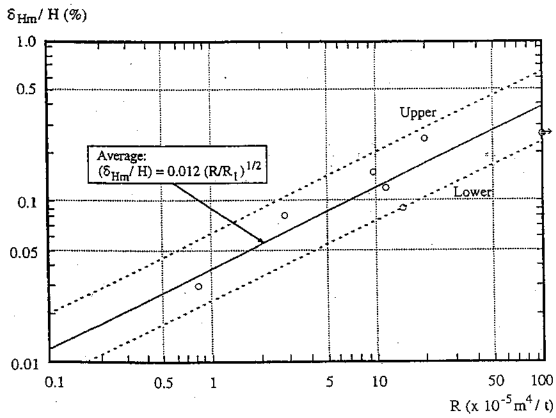


Fig.6 Correlation Between Ratio of Maximum Lateral Wall Deflection (δ_{Hm}/H) and Coefficient Representing the Excavation System Stiffness (R), for "Excavations in Sand"

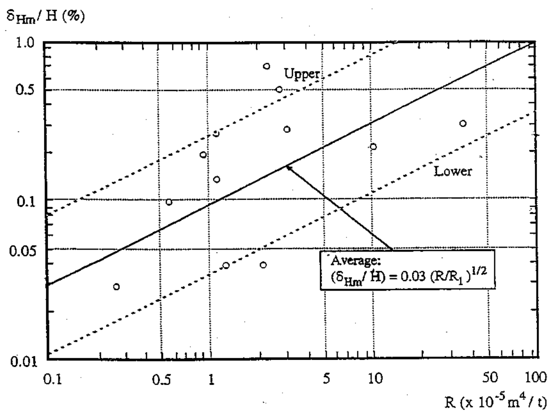


Fig.7 Correlation Between Ratio of Maximum Lateral Wall Deflection (δ_{Hm}/H) and Coefficient Representing the Excavation System Stiffness (R), for "Excavations in Mixed Ground"

From the correlation lines between the ratio of maximum lateral wall deflections and the proposed coefficient representing the excavation system stiffness in **Figs.6**, **7**, and 8, the following empirical correlations can be obtained :

$$\log(\delta_{Hm}/H) = \log A + K \log(R/R_1) \quad \cdots\cdots (10.1)$$

where

(δ_{Hm}/H) = value of the ratio of maximum lateral deflections of diaphragm walls to the excavation depth (%)

A = value of (δ_{Hm}/H) at left end of abscissa in coordinate system (%)

K = inclination of the correlation line

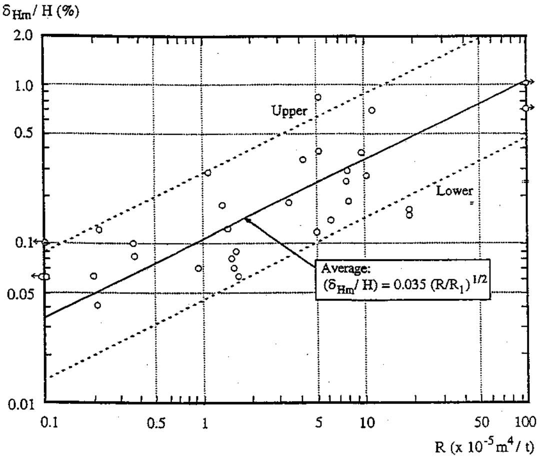


Fig.8 Correlation Between Ratio of Maximum Lateral Wall Deflection (δ_{Hm}/H) and Coefficient Representing the Excavation System Stiffness (R), for "Excavations in Clay"

Table 7 Values of A in Eq.(10) and Their Bounds (%)

Soil types in excavations	Sand	Mixed	Clay
Upper	0.02	0.08	0.09
Lower	0.0075	0.011	0.014
Average	0.012	0.03	0.035

$= [d\log(\delta_{Hm}/H)]/(d\log R)$

R_1 = value of the proposed coefficient R at left end of abscissa, as a reference value, $R_1=0.1$ ($\times 10^{-5}$ m^4/tf) ($1/(9.8\times10^3)$m^4/N)

R = value of the proposed coefficient at an excavation site ($\times 10^{-5}$ m^4/tf) ($1/(9.8\times10^3)$m^4/N)

Eq.(10.1) can be transformed to :

$$(\delta_{Hm}/H)=A(R/R_1)^K \quad \cdots\cdots (10.2)$$

From the correlation lines in **Figs.6**, **7**, and 8, the value of K becomes (1/2), and it can be assumed to be independent of the soil types. Therefore, Eq.(10.2) becomes :

$$(\delta_{Hm}/H)=A(R/R_1)^{1/2} \quad \cdots\cdots (10.3)$$

The value of A varies with the soil type as seen in the figures. The average values of A and their bounds according to soil types, estimated from the figures, are shown in **Table 7**. The maximum lateral wall deflections can be predicted from the empirical correlations based on Eq.(10.3) and **Table 7**. The equations for the prediction of the expected mean value of maximum lateral wall deflections are as follows :

Excavations in sand :

$$(\delta_{Hm}/H)=0.012(R/R_1)^{1/2} \quad \cdots\cdots (11.1)$$

Excavations in mixed ground :

$$(\delta_{Hm}/H)=0.03(R/R_1)^{1/2} \quad \cdots\cdots (11.2)$$

Excavations in clay :

$$(\delta_{Hm}/H)=0.035(R/R_1)^{1/2} \quad \cdots\cdots (11.3)$$

Note that the dimension of (δ_{Hm}/H) is percent (%).

The dimensions (length and thickness) of concrete diaphragm walls and the construction conditions (number of struts, necessity to preloading to struts, implementation of the top-down method and/or soil improvement) could be approximately obtained from Eqs.(9) and (11) if strength properties of ground and an allowable value of maximum lateral wall deflection are determined.

5. EVALUATION OF THE MEASURES TO MITIGATE LATERAL DEFLECTIONS OF DIAPHRAGM WALLS IN THE DESIGN STAGE

In design stage of deep excavations with diaphragm walls, the following can be evaluated to mitigate the lateral wall deflections based on the proposed empirical correlation.

(1) Soil improvement

The effect of soil improvement is taken into the proposed empirical correlation as the factor which increases the modulus of elasticity of soil as seen in Eqs.(9.6) and (9.7). It is important to properly select the soil improvement methods as well as the depth and the thickness of the treated soils since the improvement of the modulus varies with methods. Note that the behavior of walls during construction of soil improvement also should be paid attentions.

(2) Preloading to struts

The effect of preloading to struts is taken into the factor mitigating the lateral wall deflections in Eq.(9.1). The effects can be observed as follows[3] : (a) most importantly, preloading takes the slack out of a support system that otherwise would have to be taken up by movements of the walls; (b) preloading reduces the stress levels in the soil that are induced by the excavation process. This allows the soil to follow an unloading-reloading response instead of the softer primary loading response.

(3) The top-down method

The effect of the top-down method is taken into the factor mitigating the lateral wall deflections in Eq.(9.1). However, note that poor construction (e.g., larger slack of connections between slabs and walls) leads to less improved behavior of walls.

(4) Number of struts/spacing of struts

In the proposed empirical correlation in Eqs.(9) and (11), the number of struts have an direct effect on mitigation of maximum lateral wall deflections.

(5) Wall embedment

In the proposed empirical correlations, the stiffness of soil in embedment is taken into account as the average modulus of elasticity of soils below the base (in embedment) of excavation Esu and the factor representing stiffness of soil in embedment η in Eq.(9). It is recommended to increase the wall length into stiff deposits. However, note that it is not economical to extend the walls down to the stiff deposits where there are deep layers of soft ground, and that improving the soil in embedment is an alternative way.

6. CONCLUSIONS

The research presents a simple procedure for the prediction of maximum lateral deflections of concrete diaphragm walls in deep excavations, based on the empirical correlations. The proposed correlations include the following factors which will be helpful for designers to evaluate the behavior of deep excavations as a first approximation : ① soil properties (especially modulus of elasticity) above and below the base of excavations; ② dimensions of diaphragm walls; ③ spacing of struts/number of struts; and ④ construction conditions (with or without soil improvement/preloading to struts/the top-down method).

Future studies concerned with the deformation problems in excavations might be focused on the following issues : ① a collection of case studies, in which the ground conditions (e.g., modulus of elasticity, stress history, ground water) are much more precisely described; ② the effect of preloading to struts on wall behavior; ③ the effect of the top-construction considerations (e.g., time between excavation and installation of struts, and overexcavation prior to installation of struts) on wall behavior.

Authors would like to acknowledge : Professor Andrew J. Whittle at M.I.T., who provided the material and advice for this study; East Japan Railway Professor Joseph M. Sussman, Dr. Paul E. Brown, Director of Center for Advanced Engineering Study, and Mr. Carl A. Accardo, officer for J.R. East in Industrial Liaison Program, at M.I.T., who all assisted research activities for one of the authors.

REFERENCES

1) Peck, R.B. : Deep Excavations and Tunneling in Soft Ground, State-of-the-Art Report, Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico, pp.169~225, 1969.
2) Sugimoto, T. : Prediction for the Maximum Settlements of Ground Surface by Open Cut, Proceedings of Japan Society of Civil Engineers, No.373, Ⅵ-5, pp.113~120, 1986 (in Japanese).
3) Clough, G.W. and O'Rourke, T.D. : Construction Induced Movements of In Situ Walls, Proceedings of the 1990 Specialty Conference on Design and Performance of Earth Retaining Structures, American Society of Civil Engineers, New York, pp.439~470, 1990.
4) Hata, S., Ohta, H., Yoshida, S., Kitamura, H. and Honda, T. : A Deep Excavation in Soft Clay-Performance of an Anchored Diaphragm Wall, Proceedings of 5th International Conference on Numerical Methods in Geomechanics, Vol.2, pp.725~730. 1985.
5) Sekiguchi, H. and Ohta, H. : Induced Anisotropy and Time Dependency in Clays, Proceedings Specialty Session 9, 9th International Conference of Soil Mechanics and Foundation Engineering, pp.229~239, 1977
6) Whittle, A.J. and Hashash, M.A.Y. : Analysis of the Behavior of Propped Diaphragm Walls in a Deep Clay Deposit, Proceedings of International Conference on Retaining Structures, Cambridge, UK, 1992.
7) Hashash, M.A.Y. : Analysis of Deep Excavations in Clay, Ph.D. Thesis, Massachusetts Institute of Technology, U.S.A. 1992.
8) Whittle, A.J. : A Constitutive Model for Overconsolidated Clays with Applications to the Cyclic Loading of Friction Piles, Sc.D. Thesis, M.I.T., U.S.A. 1987.
9) Masuda, T. : Behavior of Deep Excavation with Diaphragm Wall, M.S. Thesis, M.I.T., U.S.A. 1993.
10) O'Rourke, T.D. : Predicting Displacements of Lateral Support Systems, Proceedings of the 1989 Seminar : Design, Construction, and Performance of Deep Excavation in Urban Areas, Boston Society of Civil Engineers, pp.1~36, 1989.
11) Clough, G.W., Smith, E.M. and Sweeney, B.P. : Movement Control of Excavation Support Systems by Iterative Design, Proceedings on Foundation Engineering : Current Principles and Practices, ASCE, pp.869~882, 1989.
12) Terzaghi, K. : Theoretical Soil Mechanics, Fourth Edition, John Wiley and Sons, New York, pp.189~194, 1947.
13) Japanese National Railways, Tokyo Daiichi Construction Office : Report on Studies of Design for Temporary Retaining Walls, No.1, pp.122~132, April 1981 (in Japanese)
14) Japanese National Railways : Building Code for Design of Foundation, Earth Retaining Structures, and Underground Structures, pp.71~79, March 1986 (in Japanese).
15) Terzaghi, K. and Peck, R.B. : Soil Mechanics in Engineering Practice, Second Edition, John Wiley & Sons, pp.346~352, 1967.
16) Department of the Navy, Navel Facilities Engineering Command, U.S.A. : Design Manual 7.1. Soil Mechanics, pp.7.1~88, May 1982.

17) Bowels, J.E. : Foundation Analysis and Design, Fourth Edition, MacGraw-Hill Publishing Company, pp.103, 1988.
18) Tokyo Metropolitan Highway Public Corporation : Construction Report on Mitsusawa Line of Yokohama-Haneda Route in Tokyo Metropolitan Highway, 1979 (in Japanese)
19) Tarumi, H. : Behavior of Braced Cuts, Quarterly Reports, Railway Technical Research Institute of Japanese National Railways, Vol.3, 1975.
20) Japanese National Railways : Design Manual for Chemical Grouting Method, pp.143～151, 1986 (in Japanese).
21) Shibazaki, M. : Remarks on Use of Jet Grouting Method and In Situ Mixing Method, The Foundation Engineering & Equipment, Vol.17, No.8, pp.9～15, 1989 (in Japanese).

(Received March 14, 1994)

深い掘削における地下連続壁の水平変位の予測

増田　達・ヘルベルト　アインシュタイン・三田地利之

既設構造物等に近接した深い掘削において，土留め壁の水平変位および周辺地盤における地表面沈下等がどの程度発生するかを影響解析するために土の構成則を考慮した数値解析などが行われるが，より簡便な手法による変位の概略値推定も望まれている。本論文では，既往計測結果等をもとに地盤および施工条件を勘案した係数の相関から，深い掘削における地下連続壁の最大水平変位を簡便に推定する手法を提案する.