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A study of empirical correlation for lateral deflections of diaphragm walls in deep excavations

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ABSTRACT: This paper presents a simplified procedure for prediction of maximum lateral deflections of concrete diaphragm walls in deep excavations with open cut method, based on the investigations of empirical correlation between maximum lateral deflections and factors affecting the behavior of walls in 52 case studies (excavation depth=10~42m). The following factors are taken into account for the proposed empirical correlation: 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).

1 INTRODUCTION

There have been many studies of lateral wall deflections and surface settlements associated with excavations by empirical, analytical, and numerical approaches (e.g., Peck (1969), Sugimoto(1986), Clough and O'Rourke (1990), Whittle and Hashash (1992), Hight and Higgins (1994).) Although the results of empirical study provide a useful guide for the approximate prediction of the magnitude of settlement and/or settlements, most of the data were obtained from excavations of less than 15 meters depth with relatively flexible retaining walls. In recent decades, the following measures are often implemented in deep excavations to mitigate the large amount of lateral deflections and surface settlement: 1) concrete diaphragm walls as the retaining walls; 2) preloading to struts; 3) top-down construction; and 4) soil improvement. Thus, what is wanted is a way to estimate the approximate deflections in deep excavations implemented with these mitigating construction methods.

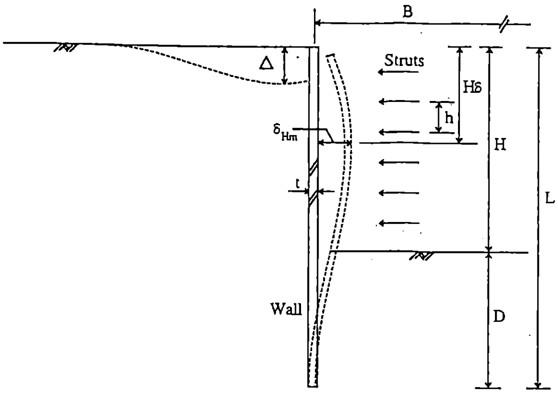
This paper presents a simplified procedure for prediction of maximum lateral deflections of concrete diaphragm walls in deep excavations with open cut method, based on the investigations of empirical correlation between maximum lateral deflections and factors affecting the behavior of walls in 52 case studies (excavation depth=10~42m). The following factors are taken into account for the proposed empirical correlation: 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).

Based on case studies of factors affecting the lateral deflections, consideration of the total excavation system stiffness including both the soil stiffness and support stiffness is required to distinguish the behavior of shallow excavations with flexible walls from the deep excavations with diaphragm walls. To meet the requirements for a coefficient correlating to the maximum lateral wall deflections, a new coefficient representing the excavation system stiffness of diaphragm walls is proposed. A new coefficient includes the factors mentioned above, and the empirical correlation between maximum lateral wall deflections and proposed coefficients is shown with ground classifications, i.e., " excavations in sand ", " excavations in mixed ground ", and " excavations in clay ", respectively.

2 CASE STUDIES OF LATERAL DEFLECTIONS OF DIAPHRAGM WALLS

2.1 Descriptions of Case Studies

The terms relating to excavations and used in the paper are shown in Fig.1. 52 case studies were collected from the literature on lateral deflections of diaphragm walls in deep excavations (Masuda (1993); Masuda, Einstein and Mitachi (1994).) The number of cases categorized by depth denoting " h (meter) " are : 1) 18 cases in $10 \leqq h < 15$; 2) 9 cases in $15 \leqq h < 20$; 3) 15 cases in $20 \leqq h < 25$; 4) 5 cases in $25 \leqq h < 30$;



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 the paper

5) 2 cases in 30≦h<35; 6) 2 cases in 35≦h<40; 7) 1 case in 40≦h<45. The classification of soil types in the excavations is determined as follows:

Excavations in sand: Hs / H≧60%, Hc / H≦40%

Excavations in clay: Hs / H≦40%, Hc / H≧60%

Excavations in mixed ground: 40% <Hs / H <60%, 40% <Hc / H <60%

where Hs=total thickness of sand layer above the base of excavation
Hc=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.

2.2 Measured Lateral Wall Deflections in the Case Studies

The lateral wall deflections measured in each excavation step were collected and the data on the maximum lateral wall deflections are used for the empirical correlation (See Table 1.) The plots of the maximum lateral wall deflection δ_{Hm} vs. excavation depth H are shown in Fig.2

Table 1 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		Soil type in excavation
				δ_{Hm} (mm)	δ_{Hm} / H (%)	
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 sand and mixed ground in the case Hs ≧ Hc, Case 1-14), and Fig. 3~5 (excavations in clay and mixed ground in the case Hs ≦ Hc, Case15-32, 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 lead to the following broad observations.

1) There is wide scatter of the ratio of maximum lateral wall deflections to excavations. However, the ratio (δ_{Hm}/H) tends to be in average 0.05~0.5%.

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

3) The closer the spacing of struts, the smaller the maximum lateral wall deflections.

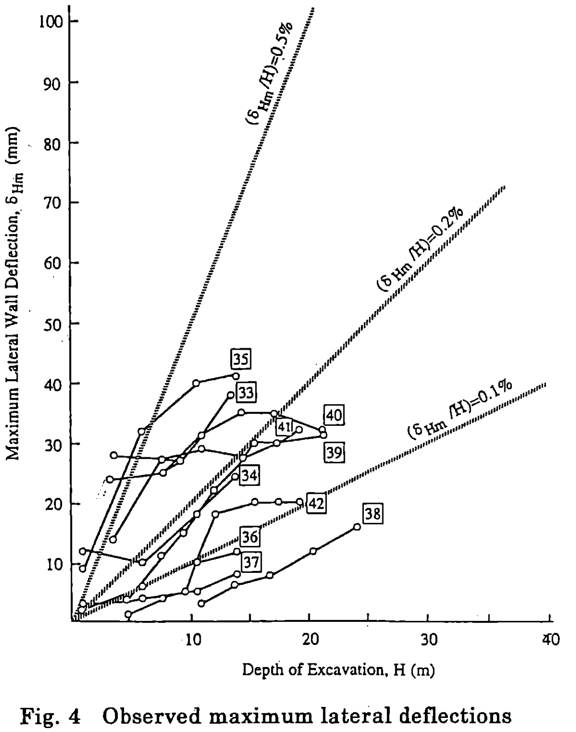


Fig. 4 Observed maximum lateral deflections of diaphragm walls vs. excavation depth, excavations in clay and mixed ground, Case 33-42

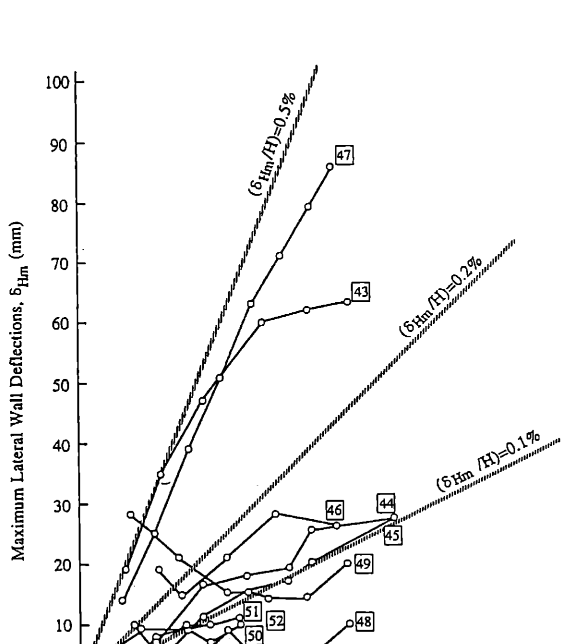


Fig. 5 Observed maximum lateral deflections of diaphragm walls vs. excavation depth, excavations in clay and mixed ground, Case 43-52

E_{sb} =average modulus of elasticity of soils below the base of excavation

$$=\left(\sum D_i \zeta E_{sbi}\right)/H \quad \left(tf/m^2\right)\left(\times 9.8 MPa\right) \qquad (8)$$

ζ =factor representing soil improvement

$H=\sum H_i$ =depth of excavation (m)

$D=\sum D_i$ =embedment depth of diaphragm wall (m)

A subscript " i " in Eqs.(6), (7), and (8) indicates each particular value of each ground stratum above/below the base of excavation. The coefficient " R " is used as an index parameter not intending to provide a direct amount of wall deflection. The factors of " α " and " λ " do not have a multiplicative effect on wall deflections in case studies, respectively, therefore they are treated as non-multiplicative factors. These factors are derived from the comparison of the case studies with/without the preloading to struts and the top-down method, and they are shown as in Table 2. The coefficients " β_u " and " β_b " adopt fourth root power to lead better empirical correlation. The values of the factor " ζ " are derived from the literature that illustrates the effects of improving the strength properties of soils (Masuda (1993)), and they are shown in Table 3. The moduli of elasticity of the soils are taken from the references (Masuda (1993)) which described the case studies, and it is assumed they were determined from the standard soil investigations.

3.2 Empirical Correlation between Maximum Lateral Deflections and the Proposed Coefficients

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 Fig. 6, 7, and 8 for " excavations in sand ", " excavations in mixed ground ", and " excavations in clay ", respectively. From the correlation lines in Fig. 6, 7, and 8, the following equation can be drawn:

$$\left(\delta_{Hm}/H\right)=A\left(R/R_1\right)^{1/2} \qquad (9)$$

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 (%)

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

R_1=value of the proposed coefficient R at left end of abscissa, as a reference value;

$$R_1=0.1 \ \left(\times 10^{-5} m^4/tf\right)\left(1/\left(9.8\times 10^3\right) m^4/N\right)$$

Table 2 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 3 Values of the factor representing soil improvement (ζ)

Method of soil improvement	Type of treated soil	
	Sand	Clay
Chemical grouting Quicklime pile	$\zeta = 1.5$	
Column Jet Grout	$\zeta = 3000/E_s$	$\zeta = 1000/E_s$
	Re: E_s is the modulus of soil. before treated. (tf/m^2)	

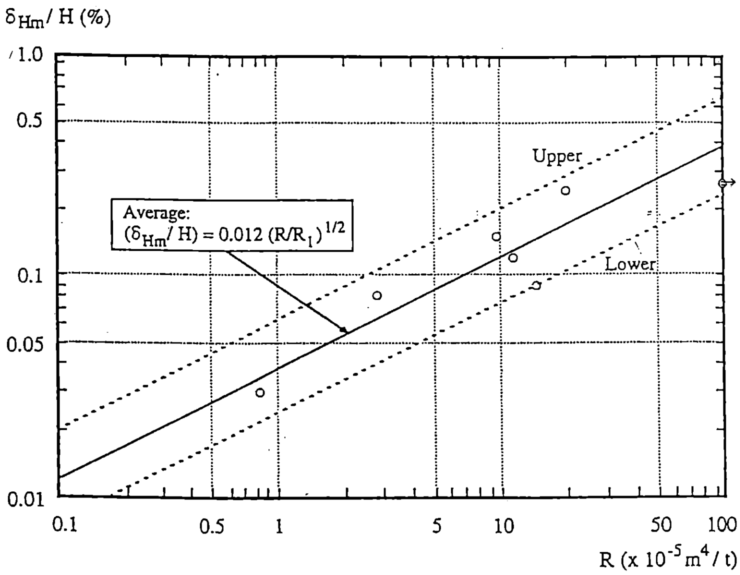


Fig. 6 Correlation between ratio of maximum lateral wall deflection (δ_{Hm}/H) and coefficient representing the excavation system stiffness (R), for " excavations in sand "

The average values of A and their bounds according to soil types, estimated from the figures, are shown in Table 4. Therefore, the equations for the prediction of the expected mean value of maximum lateral wall deflections are as follows:

Excavations in sand:

$$(\delta_{Hm}/H) = 0.012(R/R_1)^{1/2} \quad (10.1)$$

Excavations in mixed ground:

$$(\delta_{Hm}/H) = 0.03(R/R_1)^{1/2} \quad (10.2)$$

Excavations in clay:

$$(\delta_{Hm}/H) = 0.035(R/R_1)^{1/2} \quad (10.3)$$

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

4 CONCLUSIONS

A simple procedure for the prediction of maximum lateral deflections of concrete diaphragm walls in deep excavations is proposed, based on the empirical correlation. The proposed correlation, Eqs. (10.1), (10.2), and (10.3), include the following factors which will help designers 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.)

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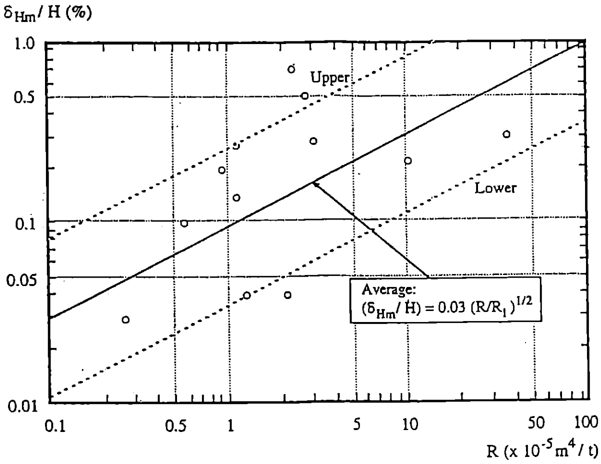

Fig. 7 Correlation between ratio of maximum lateral wall deflection (δ_{Hm} / H) and coefficient representing the excavation system stiffness (R), for " excavations in mixed ground "

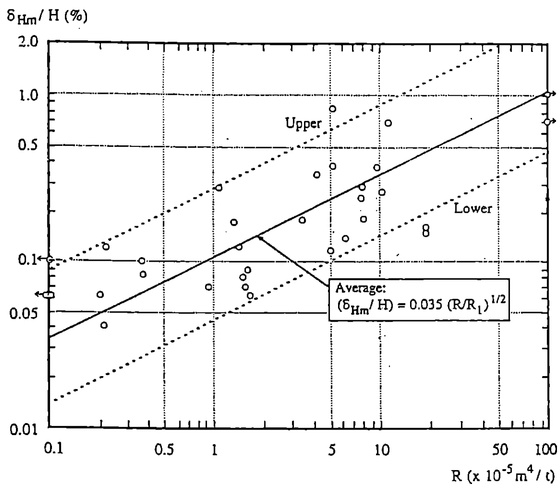

Fig. 8 Correlation between ratio of maximum lateral wall deflection (δ_{Hm} / H) and coefficient representing the excavation system stiffness (R), for " excavations in clay "

Table 4 Values of A in Eq.(9) 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

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