Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48475-6

A study on loads from complex support system using simple 2D models

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ABSTRACT: In deep pit engineering, spatial displacements are readily available, commonly along horizontal or vertical lines. It's traditionally difficult to get strut loads from complex concrete strut system due to limited scale of instrumentation and uncertainties in field measurements. This results in problem in predicting wall deformation where not instrumented. This paper proposes to utilize spatial wall displacements measured to back-analyze supporting loads on the wall from concrete struts through modeling wall-soil system. The analysis can be applied to each strut layer to obtain loads between wailing and wall in horizontal plane. The obtained support loads at different levels are then used as input in a vertical section model, from which deformation profile of wall can be predicted. The application is verified in project case and shows close correlation to field measurements.

1 INTRODUCTION

Reinforced concrete strut system is widely adopted with diaphragm wall for support of deep foundation pits in soft soil ground. During excavation, the diaphragm wall is supported by concrete struts from inside and subject to soil pressure on the other side. It is typical for deep foundation pits to have a few layers of concrete struts at different excavation depths. The interaction between diaphragm wall and concrete struts (through wailing), which is one of the most important factors in analyzing deep foundation pits, presents a very complicated scenario under loads from soil.

Because wailing is in continuous direct contact with diaphragm wall, it is difficult to measure the internal loads between them. By direct method, the internal force of struts is commonly measured by embedded load cells. This measurement is usually insufficient to estimate support loads on diaphragm wall because:

1 The scale of field measurements of strut force is limited; and the geometry of strut system is complex. Therefore, it is difficult to derive reliable support loads on diaphragm wall or through complex strut system by mechanical analysis with limited strut force measurements.
2 Field measurement of strut force could be deviated by other factors such as creep, contraction and thermal stress of concrete material (Xia & Li, 1999). Zhao (1996) reported significant thermal stress measured in concrete struts.

Therefore, indirect methods are widely used for analyzing the support loads. Back-analysis from displacement is one of the commonly used. By indirect method, there have been numerous 2D and 3D studies on the analysis of such support system (Li & Hu, 1995; Zhao, et. al., 1996).

In contrary to the difficulty of direct measurement of support force, spatial displacement information of diaphragm wall is more readily available and more reliable by field measurement. Therefore, wall displacement measurements, for example in plan section at a strut level, can be used to back-analyze loads on diaphragm wall by a simple wall-soil model.

During excavation, the diaphragm wall deforms subject to the soil pressure on one side and support loads on the other side. The soil pressure can be estimated by empirical method. Therefore, for a system consisting of supports, diaphragm wall and soil, the measured displacement pattern of diaphragm wall on the plan can be used to back-analyze supporting loads on the wall from concrete struts. It is recommended to carry out the back-analysis in plan section since the vertical sections normally involve much more complexity associated with construction sequence etc. In plan of each strut layer, a simple 2D model can easily represent such case scenario. This can be repeated for each layer of strut. Therefore, support loads at a section can be back-analyzed from spatial displacement information from field.

Based on a case history, this paper presents a simple method of estimating support loads on diaphragm wall by wailings. The estimated support loads are then verified in models for vertical cross section.

2 ANALYSIS OF SUPPORT LOADS IN PLAN

2.1 *Assumptions and simplifications*

On the plan section of each strut layer, the system of diaphragm wall and soil resembles a plain strain scenario at the center elevation of wailing. The diaphragm wall deforms under the support loads and soil pressure after excavation. The sidelines of pit, which in most cases are straight, can be simplified as an elastic continuous wall, i.e. a continuous beam on plan. The deflection pattern of the beam can be easily defined by displacement measurement along the side and is taken as target deformation in back-analysis. The two ends of the sideline can normally be deemed as pinned ends, as shown in Figure 1.

For simplicity, following assumptions are made in the analysis:

- On plan section, the diaphragm wall is modeled as elastic continuous beam.
- The loads between the wailing and diaphragm wall are evenly distributed along vertical direction but vary along horizontal direction for each strut layer.
- On plan of each strut layer, the support loads from wailing are simplified as point loads along the pit side.
- In vertical plan, the support loads of each strut layer are invariable during construction.
- The initial stress level of soil in the model is calculated from its depth following Rankin's active earth pressure formula.

In the plan model, point loads equivalent to the initial stress level prior to excavation are applied onto the beam (diaphragm wall) so that the model is in initial balance with zero displacement in diaphragm wall. In back-analysis, the applied point loads are adjusted from initial values in a controlled manner till that the diaphragm wall deforms approximately to the target displacement pattern, which is defined from field measurements. The result point loads can be converted to internal stress between the diaphragm wall and wailing (Fig. 1 (d)) along the length of sideline. This can be repeated for each strut layer without major changes to the model. In this way, the support loads of each strut layer can be found.

In the model for a vertical cross section, analysis can be carried out to simulate the construction cases corresponding to plan models. The predicted deformation pattern of diaphragm wall can checked against field measurements and the quality of estimated support loads can be verified.

A history case of a deep foundation pit in soft clay in Shanghai area is selected for the application of the method. The program used in the study is the FLAC by Itasca CG (Itasca, 1997).

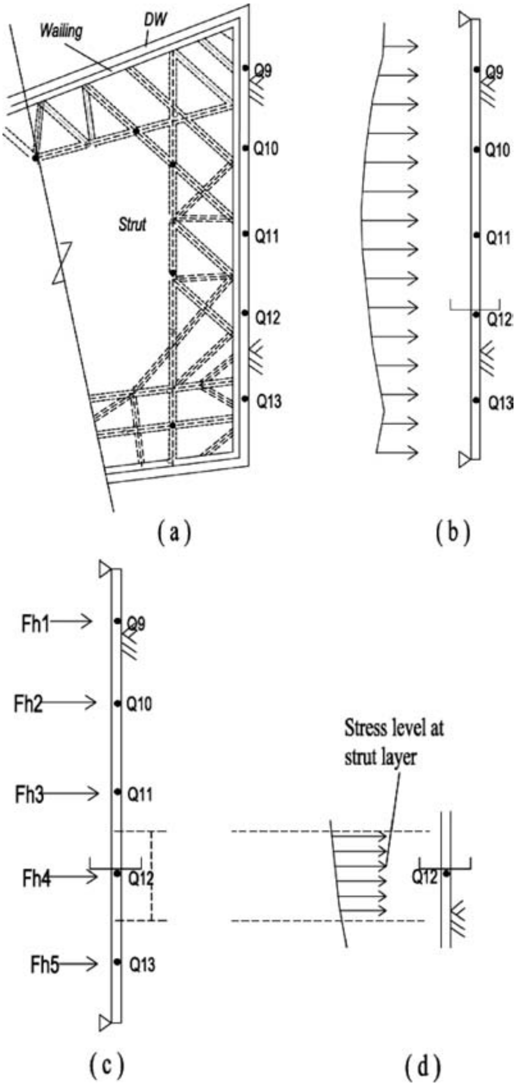
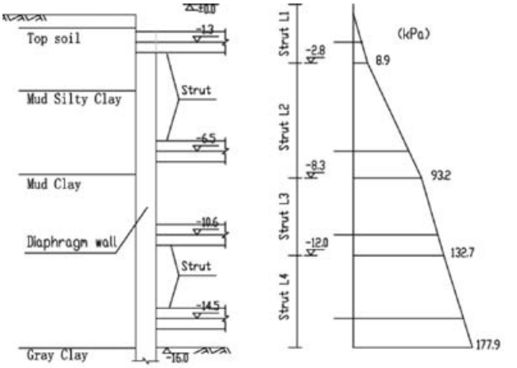


Figure 1. Plan section: (a) Plan of strut layout; (b) Line loads on diaphragm wall from wailing; (c) Converted point loads; (d) Calculated support stress on diaphragm wall.

2.2 *Model conditions and material properties*

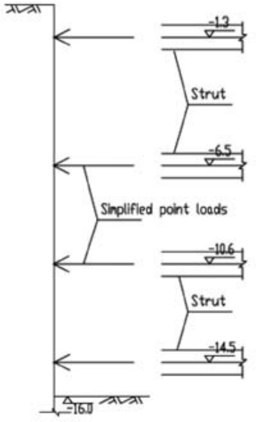
In the case history, one sideline of the pit with a length of about 100m is selected for application (Fig. 1 (a)).

The initial stress level is calculated according to Rankin's active pressure with a surcharge of 20 kPa, as shown in Figure 2 (b). The excavation process is divided into four steps equaling to the number of strut layers (Fig. 2 (b)).



(a) Vertical section

(b) Exc depth for each strut layer and stress levels



(c) Model of vertical section

Figure 2. Vertical section and simulation conditions.

On each plan section, the loads from wailing on diaphragm wall are simplified as five point loads ($F_{h1} \sim F_{h5}$) at the elevation of each strut layer (Fig. 1 (c)). The target displacements for each support layer ($S_{1\sim} \sim S_i$) are taken at the end of excavation at time t_k. The back-analyzed support forces ($F_{h1\sim} \sim F_{h5}$) represent the site condition at the end of excavation.

The geometry of the plan model is shown in Figure 3. The soil layers are listed in Table 1 with material properties. The soil is modeled as elasto-plastic material with Mohr-Coulomb strength criteria.

The reinforced concrete diaphragm wall reaches 41 m from ground surface, modeled as elastic continuous beam.

2.3 *Analysis of support loads at strut layers*

There are five monitoring points available for each layer with field measurement except for the first layer as listed in Table 2. Due to availability of field data, there are measurements for three monitoring points for the first strut layer.

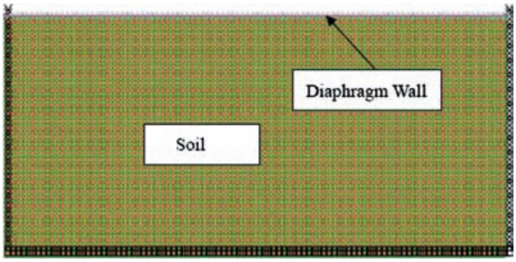


Figure 3. Model mesh and set up for plan sections.

According to excavation history, the corresponding excavation steps for each strut layer are defined as: up to 2.8 m for the first layer; 6.3 m (2.8 m ~ 8.3 m) for the second layer; 3.7 m (8.3 m ~ 12.0 m) for the third layer; and 4.0 m (12.0 m ~ 16.0 m) for the fourth layer. The initial stress condition for each strut layer is determined in the same way as above (Fig. 2 (b)).

To reduce noise during back-analysis, only the field measurements of the center three points (Q10~Q12) are set as target deformation because the other two monitoring points (Q9 and Q13) could be easily affected by fixed ends of diaphragm wall. The matching criteria for model prediction is set as within 5% of field measurement, i.e. the model reaches its target condition when the model predictions at each selected points are within 5% difference from field measurements. Under this condition, the point loads on wall are measured from the model.

The result deformations of back-analysis are shown in Table 3 with corresponding calculated point loads of support in Table 4.

3 VERIFICATION OF CALCULATED SUPPORT LOADS IN VERTICAL SECTION

3.1 *Models of vertical section*

Two vertical cross sections intersecting the diaphragm wall at Q10 and Q12 are selected to verify the calculated support loads.

The vertical section model has a total width of 120 m with 40 m on the side of the pit as shown in Figure 4. The height of model is 80 m from the ground surface.

The strut levels and excavation steps are shown in Figure 2. The model is prescribed with initial lateral stress conditions as calculated above. The two sides are fixed only in horizontal direction. The bottom is fixed in both directions.

Considering the high stiffness and limited height of wailing, the loads of wailing are assumed evenly distributed along its height at each strut layer. Therefore in plan model, the support loads can be represented

Table 1. Material properties of soil and diaphragm wall.

No	Soil Layer	Thickness (m)	Unit Weight (kN/m3)	Modulus (MPa)	Poisson's ratio	Cohesion (kPa)	Friction (°)
1～2	Top Soil	3.5	18.3	11.25	0.35	24	15.5
3	Mud Silty Clay	3	17.4	5	0.35	15	20
4	Mud Clay	9.9	16.6	2.75	0.4	12	11.0
5_{1a}	Grey Clay	4.2	17.5	5	0.35	18	11.5
5_{1b}	Grey Silty Clay	7.2	17.9	12.5	0.35	17	20.5
5_{1c}	Sanded Silty Clay	10.4	17.9	25	0.3	16	23.5
6	Silty Clay	2.4	19.9	36	0.35	51	24.5
	Diaphragm Wall	1.0	20.0	30000	0.17	–	–

Table 2. Field measurements of deformation at strut layers (mm).

	Q9	Q10	Q11	Q12	Q13
Layer 1	–	0.1	0.3	0.2	–
Layer 2	15.9	24.3	23.7	19.6	13.2
Layer 3	32.3	52.4	49.0	43.5	23.3
Layer 4	42.0	62.7	59.9	48.0	33.2

Table 3. Calculated deformations at strut layers (mm).

	Q9	Q10	Q11	Q12	Q13
Layer 1		0.1	0.3	0.1	
Layer 2		24.3	24.0	19.6	
Layer 3		52.7	50.1	44.1	
Layer 4		63.0	59.1	48.8	

Table 4. Calculated support point loads at strut layers (kN/m).

	Q9	Q10	Q11	Q12	Q13
Layer 1	150	106	120	136	108
Layer 2	89	34	80	39	170
Layer 3	220	50	220	70	382
Layer 4	310	150	320	200	540

by point loads at the center elevation of wailings as illustrated in Figure 2 (c).

The calculated point loads from plan models are converted to line loads along horizontal direction at all strut layers, where the values at Q10 and Q12 can be obtained (Fig. 1 (d)) for use in vertical model. The values of point load are listed in Table 5.

In correspondence to the calculated support loads, the following construction cases are simulated in the plan model:

Case 1: Initial condition before excavation; installation of diaphragm wall;

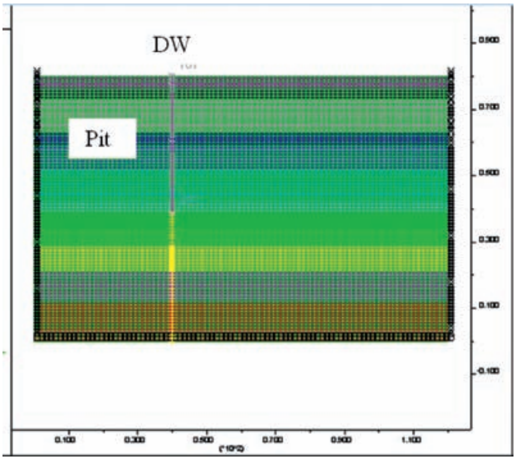


Figure 4. Overview of model for vertical sections.

Table 5. Converted support loads for vertical model (kN/m).

	Layer 1	Layer 2	Layer 3	Layer 4
Section (Q10)	318	136	200	300
Section (Q12)	408	156	280	400

Case 2: Excavate to −2.8 m; apply support load at first strut layer;

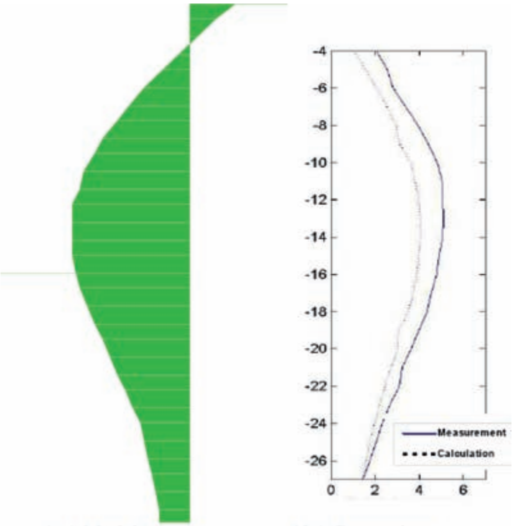
Case 3: Excavate to −8.3 m; apply support load at second strut layer;

Case 4: Excavate to −12.0 m; apply support load at third strut layer;

Case 5: Excavate to −16.0 m; apply support load at fourth strut layer.

3.2 *Results of vertical section models*

The deformation patterns of diaphragm wall at target points are very similar as Q12 shown in are shown in Figure 5.



(a) Model output (b) Comparison

Figure 5. Horizontal deformation pattern (mm) of diaphragm wall along depth (m) in vertical section through Q12.

The calculated deformations of diaphragm wall are compared with field measurements in Figure 5. The maximum calculated displacement is 40.5 mm while 51.1 mm in field measurement on vertical section through Q12. It is noted that all cases show good correlation of deformation pattern between model calculation and field measurement as shown in Figure 5(b).

4 DISCUSSIONS AND CONCLUSIONS

By using spatial displacement measurements in simple 2D models, the difficulties associated with complex support system and uncertainties in load measurement are avoided with reasonable correlation to field data in vertical sections.

However, the displacement in vertical section shows notable discrepancies on magnitude, which is partly a result of simplifications made in the analysis. In the system of diaphragm wall and soil, the calculated support loads are considerably affected by the stress conditions in the model. The influence from stress can be minimized if soil stress measurements are incorporated in the back analysis.

The discrepancies in prediction of vertical model could also result from the assumption that the stress release due to an excavation step is undertaken entirely by a specific strut layer. Therefore the support loads can only be calculated for limited cases in the same number of excavation steps as strut layers.

However, the method produces reasonable estimation of support loads that lead to acceptable prediction of deformation pattern of diaphragm wall. This would be helpful in many engineering cases.

ACKNOWLEDGEMENT

The Author would like to acknowledge great assistance and suggestion in preparation of this paper from Dr Dongmei Zhang from Tongji University.

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