Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)
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Informational construction approach for deep excavation

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ABSTRACT: An informational construction system for the safety evaluation of deep excavation in soft soil formation is presented. The optimization procedure using simplex method for numerical calculation was incorporated into a finite element program with Mohr-Coulomb plasticity model. It allows the optimization of "numerical soil parameters" from the measured diaphragm wall deflection by simulating the construction procedures. With the back analyzed soil parameters, prediction analysis can be carried out to predict the performance or potential problems in the later stages of construction. A case history is given to demonstrate the application of the method proposed.

1 INTRODUCTION

In the design of support work for deep excavation in soft ground, very limited information are generally available, and simplified models are often being used. The design parameters for the model selected are hence highly dependent on the local experience and subjectivity of the design engineer. Therefore, field monitoring is an integral part for such kind of project to ensure the safety of excavation and to take necessary remedial measure if required. However, in practice, the monitoring data are seldom being analyzed from the viewpoint of improving the prediction of construction performance as well as the rationality of design.

Optimization techniques had been used for identifying the system parameters in numerical analyses and geomechanics since 1980's. Arai et al. (1983) proposed a simple optimization method for evaluating the deformation moduli of linearly elastic soil from field observations. Estimation of nonlinear constitutive parameters based on monitored movement had been performed by similar procedure (Arai et al. 1987). Gioda & Sakurai (1987) summarized the numerical techniques for back analysis in the field of geomechanics, with particular reference to tunnelling problems. Lee et al. (1997) combined field measurement and prior information to develop a feedback system for underground structures. The system was proved to be highly effective in actual field problem.

The purpose of informational construction approach is to use the field measurements of construction stages and the techniques of optimization to calibrate the parameters of the in-situ soils. The "optimal" soil parameters obtained from the construction stages which possess the factors of uncertainties during excavation can be used to predict the performance or potential problems in the next construction stage with better reliability.

2 FORMATION OF INFORMATIONAL SYSTEM

2.1 *Objective function of optimization procedure*

The wall deflection is a good indication of the stability of an excavation since the measurements can be obtained with relatively good quality and accuracy. Therefore, the soil constants are obtained based on the measured wall deflection through back analysis. The objective function of optimization procedure could be presented as follows:

$$F = \sum_{k=1}^{N_s} \left\{ \mathbf{U}^{*k} - \mathbf{U}^{k} \right\}^{T}_{1\times N_d} \left\{ \mathbf{U}^{*k} - \mathbf{U}^{k} \right\}_{N_d\times 1} \qquad (1)$$

where N_s is the number of stages; N_d is the number of measured points of the wall deflection; $\mathbf{U}^{*k}$ is the vector of measured wall deflection in kth stage; and $\mathbf{U}^{k}$ is the vector of calculated wall deflection.

2.2 *Numerical procedures*

Finite element analysis was adopted to simulate the staged construction behavior of retaining system and surrounding soils. The back analysis program was developed by incorporating the optimization procedure into the finite element program originally developed by Britto & Gunn (1987) and modified by Chi and Chern (1997) with hyperbolic stress-strain relationship and Mohr-Coulomb plasticity for soil model.

Since calculations are carried out through finite element analysis, the optimized soil parameters in current construction stage become implicit functions of wall deflection. It is a highly nonlinear problem and numerical techniques were adopted to find the solutions. From Gioda & Sakurai's (1987) work, the direct search approaches can be developed on the basis of standard computer codes for nonlinear function minimization in which the finite element program for stress analysis is introduced as a subroutine. Simplex method (Nelder & Mead 1965) was used as the direct search algorithm in the back analysis system.

In most practical cases some limiting values exist for the unknown parameters. For instance, the modulus of elasticity and the parameters of Mohr-Coulomb failure criterion cannot reach negative values. These limits can be introduced into a direct search algorithm by means of a penalization procedure to convert the constrained minimization into unconstrained problem.

3 APPLICATION

The code developed in this study is applied to the case history studied by Ou et al. (1998) to investigate the adaptation of proposed method.

3.1 *Site description*

The field case study is the Taipei National Enterprise Center excavation project (TNEC), which was completed using the top-down construction method. The TNEC building is an 18-story above and 5-story below ground surface. The construction site is approximately trapezoid in shape with an area of about 3500 m^2, as shown in Figure 1. A 0.9-m-thick and 35-m-deep diaphragm wall was used as the earth-retaining structure supported by the concrete floor slab.

Figure 1 also shows the location of inclinometer I-1 to monitor the wall deflection during excavation. The excavation was proceeded to a final elevation of 19.7m below ground surface, as shown in Figure 2. As indicated in Figure2, the subsurface strata at this site consist of six layers of alternating silty clay and silty sand overlaying a thick gravel formation. The third layer is a 25 m thick silty clay, which dominated the excavation behavior in this case. Therefore, the properties of silty clay in this layer were the

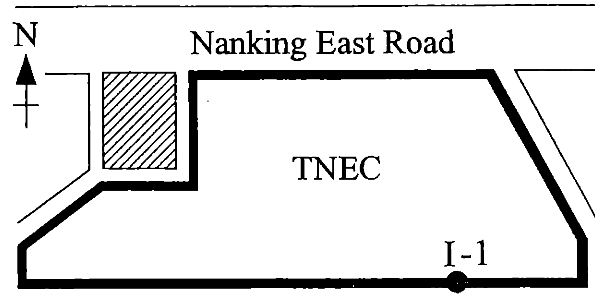

Figure 1. Plan view of the TNEC site.

main concern in the back analyses. Oedometer tests showed that this clay layer was normally consolidated to slightly overconsolidated. The ratio of undrained shear strength to effective overburden pressure (s_u/σ'_v) is about 0.36 from K_0-consolidated triaxial tests. Figure 3 shows the finite element mesh used for analysis.

3.2 *Construction sequence*

Top-down construction method was used for the TNEC project and the excavation sequence was listed in Table 1.

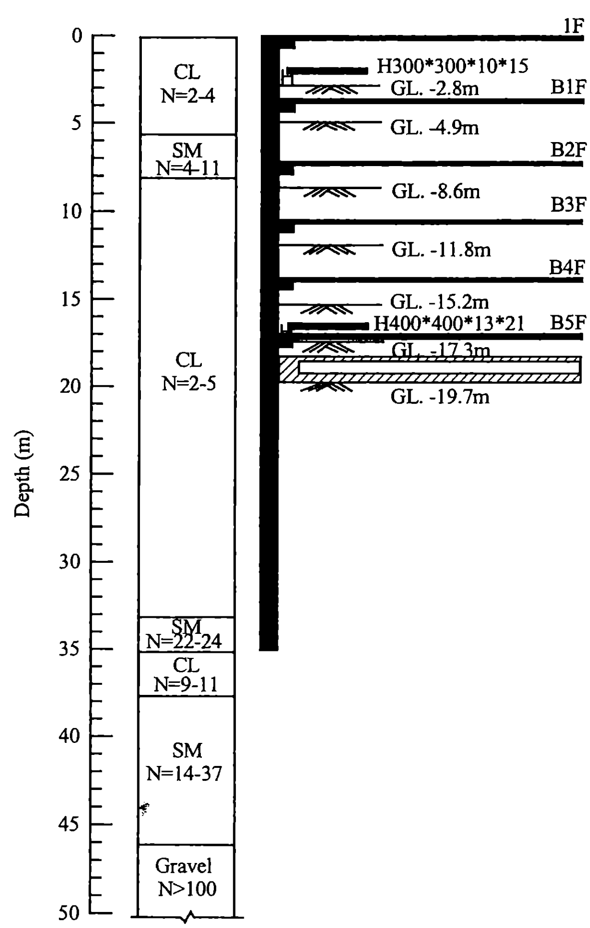

Figure 2. Analyzed section.

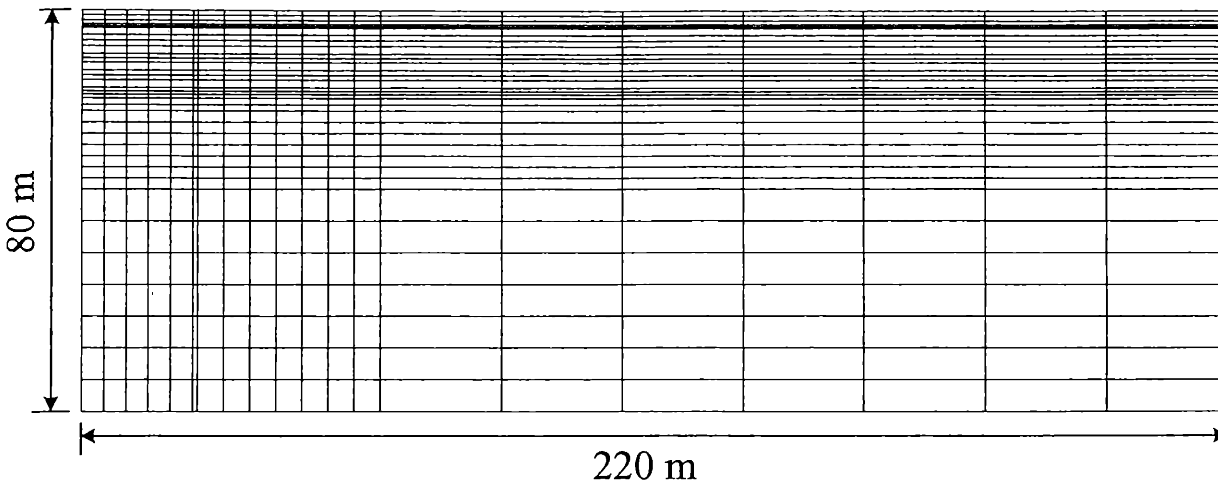

Figure 3. Finite element mesh for analysis

Table 1. Excavation sequence of TNEC case history.

Stage	Construction activities
1	Excavation to elevation of –2.8m
2	Install H300x300x10x15 at –2m, preload 785kN per strut
3	Excavation to elevation of –4.9m
4	Cast floor slab (B1F) at elevation of –3.5m
5	Remove first level of the strut and cast ground level of slab
6	Excavation to elevation of –8.6m
7	Cast floor slab (B2F) at elevation of –7.1m
8	Excavation to elevation of –11.8m
9	Cast floor slab (B3F) at elevation of –10.3m
10	Excavation to elevation of –15.2m
11	Cast floor slab (B4F) at elevation of –13.7m
12	Excavation to elevation of –17.3m
13	Install H400x400x13x21 at –16.5m, preload 1177kN per strut
14	Excavation to elevation of –19.7m
15	Cast the foundation slab
16	Cast floor slab (B5F) at elevation of –17.1m
17	Remove second level of the strut

3.3 *Additional considerations of material constants*

The hyperbolic stress-strain relationship and Mohr-Coulomb plasticity are adopted for the soil model in the finite element analysis. The total stress analysis ($c = s_u, \phi = 0$) was used for clayey layer while the effective stress analysis ($c = 0, \phi = \phi'$) for sandy layer. The most important parameters that may affect the excavation behavior and could not be determined readily are modulus of elasticity E and cohesion c of Mohr-Coulomb yield criterion. Therefore, the E and c values of each soil layer need to be estimated through back analysis.

For simplicity and convergence of optimization procedure, the empirical soil characteristics of Taipei basin were adopted and the modulus of elasticity was expressed as the function of undrained shear strength s_u and standard penetration test value N for clayey layer and sandy layer, respectively.

$$E = m_{su} s_u \tag{2}$$

$$E = m_N \mathrm{N} \tag{3}$$

where m_{su} and m_N are the ratios of Young's modulus over undrained shear strength and SPT N-value, respectively. The undrained shear strength is assumed to increase with depth and could be expressed as follow:

$$s_u = m_c D + s_{u0} \tag{4}$$

where m_c is the variation slope; s_{u0} is the undrained shear strength at ground level; and D is the depth below ground surface. Therefore, the four unknowns of optimization procedure are s_{u0}, m_c, m_{su}, and m_N.

Usually, the initial value of the variable has a large effect on the convergence during the optimization process. However, they can be empirically estimated from correlations with local experience of Taipei basin. The undrained shear strength at ground level was about to be 3 kPa, and the variation slope of undrained shear strength was selected to be 5kPa per meter. The ratios of Young's modulus over undrained shear strength and SPT N-value were 500 and 2000, respectively.

3.4 *Results of back analyses and further predictions*

The main purpose of informational construction method is to use the parameters obtained from back analysis to predict the response of the retaining structure and soil for next excavation stage. In this study, two kinds of the utilization of field measurement were incorporated into optimization precess. One is the use of the field measurement from all constructed stages including current stage (method 1), and the other is the use of the field measurement only from current construction stage (method 2).

Table 2 and Table 3 list the results of back analysis by the two methods of the utilization of field measurement, respectively. It shows that the variation slope of undrained shear strength decreases as the excavation proceeded in both methods except for stage 6 of method 2. The results show the disturbance of silty clay due to construction and that reduced the undrained shear strength. The ratio of Young's modulus over undrained shear strength ranges from 450 to 650 excluding stage 6 of method 1, stage 5 and stage 6 of method 2. The range of Young's modulus for sand was found to be much larger than that of clay. That is because of insignificatant influence on the wall deflection for sandy layer. Since the silty clay dominated the excavation behavior in this case history.

To compare the methods of the utilization of measured data, the parameters listed in Table 2 and Table 3 were used to predict the behavior of retaining system in the next excavation stage. The wall deflection profiles against depth between different prediction methods and field monitoring data are shown in Figure 4. The difference of predicted wall deflection between method 1 and method 2 in stage 2 to stage 4 is insignificant, but that is relatively large in stage 5 to stage 7. According to the constrained conditions of the parameters of soil layers, the predicted deflection at the bottom of the wall in stage 3 to stage 6 is always larger than measured data and the maximum wall deflection obtained from prediction is always smaller than that of measurement. Method 2 gave the wall deflection profile closer to the field measurement in last three stages.

The parameters obtained from back analysis by method 1 stand for overall behavior during excavation. The variability of parameters between individual stage is equalized in optimization process. On the contrary, the parameters obtained from method 2 stand for the behavior of individual stage during excavation. However, method 2 is preferable to be used to predict the movement of retaining system from the viewpoint of engineering practice.

Table 2. Results of back analysis by all constructed stages.

Stages	s_{u0} (kPa)	m_c (kPa/m)	m_{su}	m_N (kPa)	Objective function
initial	3	5	500	2000	-
1	1.803	4.910	536	1823	1.55e-4
2	1.616	4.515	478	2095	2.05e-3
3	0.822	3.335	558	2356	4.35e-3
4	0.836	3.172	561	2282	8.07e-3
5	3.357	2.799	625	3302	1.07e-2
6	0.156	2.189	1130	5540	8.86e-3

Table 3. Results of back analysis by current stages.

Stages	s_{u0} (kPa)	m_c (kPa/m)	m_{su}	m_N (kPa)	Objective Function
initial	3	5	500	2000	-
1	1.803	4.910	536	1823	1.55e-4
2	1.138	4.380	462	2043	1.79e-3
3	0.218	3.236	607	2201	2.40e-3
4	2.453	2.708	653	3394	2.42e-3
5	3.961	2.242	927	4532	1.81e-3
6	1.879	8.564	104	5449	7.35e-4

4 CONCLUSIONS

The informational construction method for the prediction of retaining system and the safety evaluation of construction during deep excavation is presented. The optimization techniques in back calculation through finite element analysis were used for evaluating the soil parameters.

From the preliminary application of the method to the case history studied, the conclusions can be summarized as follows:

1. The informational construction approach presented in this paper can be used for deep excavation in engineering practice to assess the safety of retaining system during construction.

2. The relatively simple material model parameters obtained from back analysis contain the factors of uncertainty including construction quality, and, therefore, can reflect the complicated behavior of deep excavation better.

3. Back analysis is not only to identify the parameters which lead to the best description of the actual behavior of soil-support system, but also to obtain the parameters that obey the natural characteristics. In order to avoid the unreasonable results, some limitations of material constants should be introduced in the optimization process and will lead to more reasonable results from numerical analysis.

4. For the safety of construction, the back calculation and forward prediction processes should be carried out during the entire excavation process. This is especially important when the excavation reaches the later stage of construction. In the back analysis, measured data from the current construction stage, which have better reflection of deeper soil strata on the construction, would give a better estimation of soil parameters and, therefore, a better forward prediction of construction performance.

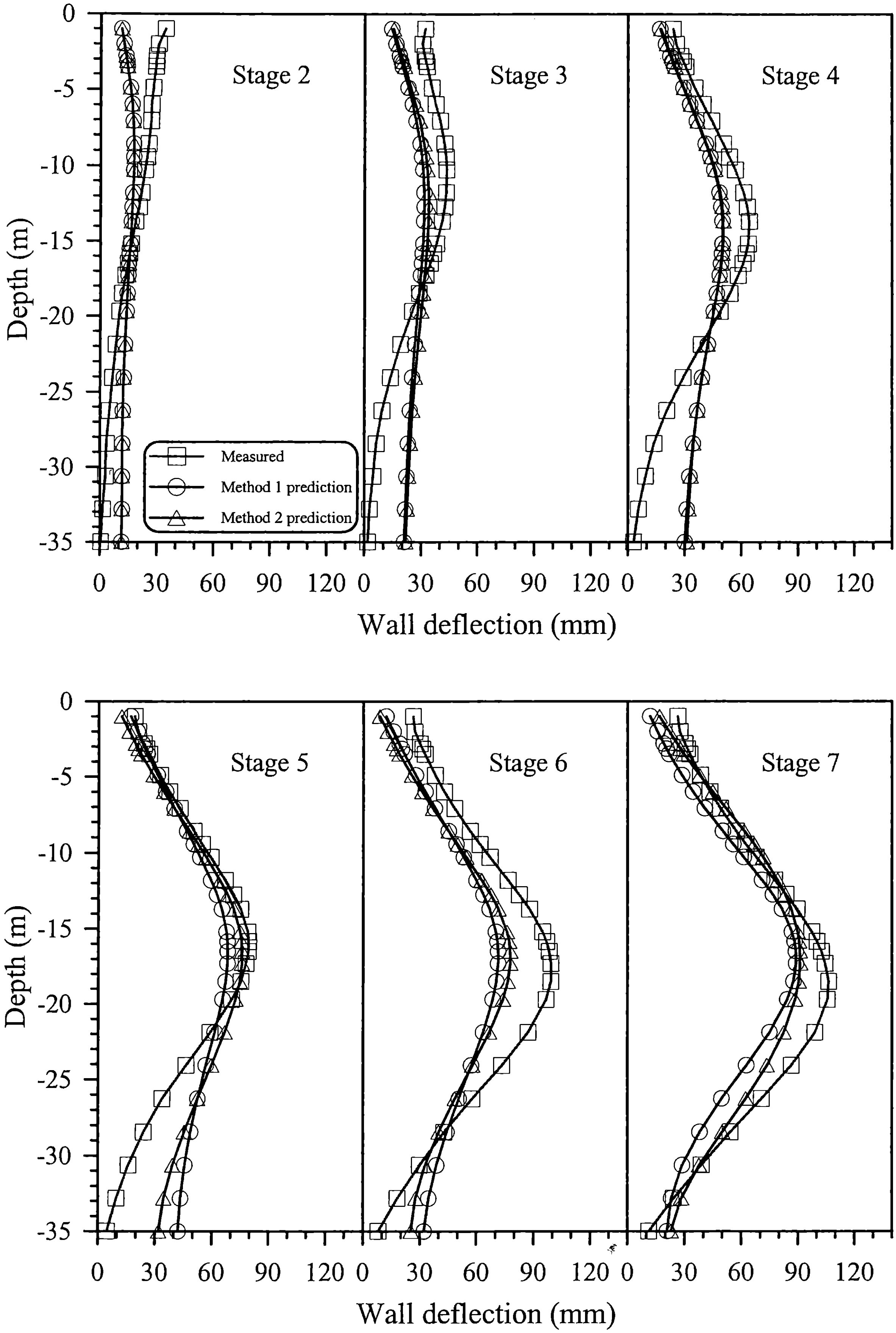

Figure 4. Wall deflection profiles in various excavation stages.

ACKNOWLEDGEMENT

This study is part of the research project No.7926 supported by Sinotech Engineering Consultants, Inc. and the financial support is gratefully acknowledged.

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