Impacts from three-dimensional effect on the wall deflection induced by a deep excavation in Kaohsiung, Taiwan

Bin-Chen Benson Hsiungⁱ⁾ and Sy-Dan Daoⁱⁱ⁾

i) Associate Professor, Department of Civil Engineering, National Kaohsiung University of Applied Sciences, 415Chien-Kung Road, Kaohsiung City, 807, Taiwan.

ii) PhD Candidate, Department of Civil Engineering, National Kaohsiung University of Applied Sciences, 415Chien-Kung Road, Kaohsiung City, 807, Taiwan.

ABSTRACT

In this paper, it aims to examine impacts from three-dimensional effect on the wall deflection induced by a deep excavation in Kaohsiung city, Taiwan. The commercial software PLAXIS 3D was used as a numerical tool for 3D finite element analyses in this study. First, a benchmark analysis was performed to simulate a case history of deep excavation in thick layers of sand (Case A) to verify the performance of 3D numerical analysis model in predicting the wall displacements. It is aware that there is a little limitation in prediction of the wall movements by using a constitutive soil model having single elastic modulus. Next, a series of parametric studies that uses the same input parameters as the benchmark analysis was conducted to model the excavation of Case A with various values of excavation length (L) and width (B). From these parametric studies, plane strain ratio (PSR), which is the ratio of the maximum wall deflection of a certain section to the maximum wall deflection of the section under the plane strain condition, was determined with various values of distance from evaluated section to the excavation corner (d), length (L) and width (B) of excavation. A relationship between PSR, d and ratio of B/L was thus interpreted. It is summarized that PSR is smaller than in sand rather than in clay for B/L more than 1.0, but it is larger than in sand rather than in clay for B/L less than 0.5. Further verification may have to be delivered later in order to explore the reason for the difference.

Keywords: deep excavation, wall deflection, three-dimensional effect, plane strain ratio, PLAXIS 3D.

1 INTRODUCTION

The wall deflection induced by a deep excavation depends on many factors such as conditions of soil and groundwater, excavation geometry, surcharge load, existence of adjacent structures, construction method, stiffness and penetration of the retaining wall, type and installation method of struts, spacing and stiffness of struts, and ground improvement. In addition, in a certain excavation, the wall deflection also depends on position of evaluated section or distance from evaluated section to the excavation corner. Effect of the position of evaluated section on the wall deflection is called to be the three-dimensional effect or corner effect on the wall deflection.

The wall deflections have been studied by many researches such as Clough and O'Rourke (1990), Ou et al. (1996), Ou et al. (2000), Ou (2006), Kung et al. (2007), Lin et al. (2007), Hsiung (2009), Wang et al. (2010), Likitlersuang et al. (2013) and Khoiri and Ou (2013). However, most of these researches mainly focused excavations in clays, not in sands. In the study of Ou et al. (1996), a concept of plane strain ratio (PSR)

was first proposed, which is the ratio of the maximum wall deflection of a certain section along the wall to the maximum wall deflection of the section under the plane strain condition. The PSR values were also determined and evaluated for a typical excavation in condition of clayey soils in Taipei, Taiwan.

In this paper, the PSR values will be determined for a deep excavation in condition of sandy soils in Kaohsiung, Taiwan. The PSR values will be interpreted using a series of parametric studies with various excavation lengths and widths. It is expected that this study could be useful to predict the 3D maximum wall deflections from 2D analyses, which is commonly adopted in engineering practice. The commercial software PLAXIS 3D, version 2013, is selected as a tool for numerical analyses in this study.

2 BENCHMARK ANALYSIS

In this section, a case history of deep excavation in Kaohsiung, Taiwan, namely Case A, was used as a basic to verify the validity and performance of the benchmark analysis, which will be applied as a base of

later numerical analyses. Case A was located in the central area of Kaohsiung city, next to the O7 station, which is on the Orange line of Kaohsiung MRT system.

The shape of Case A was rectangular with 70 m in length and 20 m in width. The excavation was carried out by the bottom-up construction method and was retained by a diaphragm wall that is 0.9 m thick and 32 m deep. It was excavated by five-stage excavation with the maximum excavation depth of 16.8 m. The retaining wall was propped by steel struts at four levels, and the horizontal spacing of the struts was average about 5.5 m. Fig. 1 below shows the cross section and ground condition of Case A.

Fig. 1. Cross section and ground condition of Case A.

A three-dimensional finite element analysis will be conducted to simulate the excavation of Case A, which is called "benchmark analysis". The commercial software PLAXIS 3D, version 2013, is selected as a numerical tool for 3D analyses in this study. PLAXIS 3D is a three-dimensional finite element program, which is developed at Delft University of Technology in the Netherlands and is made commercially available by Plaxis Bv, Amsterdam, the Netherlands.

As be seen from Fig. 1, the influences of clay layers on the excavation behavior are not significant due to their very thin thicknesses. In contrast, the sand layers

dominantly affect the excavation behavior.

According to previous researches, such as Hsieh et al. (2003), Ou (2006), Kung et al. (2007) and Schweiger (2009), the constitutive soil model adopted in numerical analysis has a very little influence on predicting the wall deflection induced by deep excavations. As a result, the linear elastic-perfectly plastic Mohr-Coulomb model (MC model), a basic model of soil, was adopted to simulate soils in the model of benchmark analysis. The distance from the lateral boundaries of this model to the retaining wall was taken to be four times excavation depth. This distance is considered because the maximum length of influence zone of settlement behind the retaining wall was four times excavation depth according to previous studies of Clough and O'Rourke (1990), Kung et al. (2007), Wang et al. (2010), and Ou and Hsieh (2011).

In the benchmark analysis, the soil layers of CL type (clayey soils) were simulated with MC model in a total stress undrained analysis, and the soil layers of SM type (sandy soils) were modeled with MC model in an effective stress drained analysis. The strength parameters of soils were directly taken from laboratory tests. Poisson's ratio was assumed as 0.35 for sand layers and 0.495 (≈ 0.5) for clay layers. For stiffness parameters, as reported by Hsiung (2009), effective Young's modulus of sandy silts and silty sands could be obtained by the following equation:

$$E' = 2000N(kPa) \quad (1)$$

in which, N is blow counts in Standard Penetration Tests (SPT).

According to the studies of Bowles (1996), Lim et al. (2010), Likitlersuang et al. (2013), and Khoiri and Ou (2013), undrained Young's modulus of clayey silts and silty clays could be estimated as follows:

$$E_u = 500S_u \quad (2)$$

in which, S_u is undrained shear strength of clays.

The diaphragm wall was simulated by plate elements, and the steel struts were simulated by elements of node-to-node anchor. The linear elastic model was adopted to simulate both the diaphragm wall and steel struts. Poisson's ratio was taken to be 0.2 for both the diaphragm wall and steel struts. The Young's modulus of the diaphragm wall was calculated by the equation of AASHTO (1998) as follows:

For concrete with normal density:

$$E_c = 4800\sqrt{f'_c} (MPa) \quad (3)$$

in which, f'_c (MPa) is the standard compressive strength of the wall concrete. The Young's modulus of steel struts was taken to be 2.1×10^5 MPa. The Young's moduli of both the diaphragm wall and steel struts were reduced by 30% to consider the cracks in the diaphragm wall due to bending moments and to consider the

repeated uses and improper installation of steel struts (see Ou, 2006).

Fig. 2 below shows results obtained from the benchmark analysis. The field measurements are also shown in this figure for comparison, and only wall deflection is demonstrated in this paper.

As can be noted from Fig. 2, the walls behave as a cantilever at the first stage of excavation because the struts at the first level have not yet installed and preloaded. The walls then become prop-mode at the subsequent stages of excavation.

The predicted wall deflections at the earlier stages of excavation (Stages 1, 2 and 3) in general are all slightly larger than the field measurements, respectively, no matter in long side or short side. Once excavation goes deeper, the predicted wall deflections at the later stages (Stages 4 and 5) are slightly smaller than the field measurements at upper parts of the wall but comparatively larger than the field measurements at lower parts of the wall, respectively. However, the maximum lateral wall displacements from both prediction and measurements are close to each other.

The main reason can be possibly related to this fact that the MC model dose not consider the strain-dependent stiffness behavior or the small strain characteristics that involve high stiffness modulus at small strain levels of soil. Only a single Young's modulus of soil can be used for MC model and such model also dose not distinguish between loading and unloading/reloading stiffness. It is thus concluded that Young's modulus of sand adopted in the MC model was thus underestimated at the earlier stages of excavation due to wider range of small strain soil area at these stages, and it thus leads to over-prediction of wall displacements herein.

Furthermore, it is aware that the heave of excavation bottom is significantly over-predicted because the MC model does not consider the higher stiffness of ground below the excavation level that is unloaded during excavation process. The over-prediction of the heave of excavation bottom then causes larger displacements at the lower wall parts and smaller displacements at the upper wall parts.

Fig. 2. Comparisons of measured and computed wall deflections from the benchmark analysis of Case A.

3 THREE-DIMENSIONAL INFLUENCE

To evaluate the three-dimensional (3D) effect on the wall deflection, a series of parametric studies was conducted on the excavation of Case A with various

values of excavation length and width. First, 3D analyses were conducted to simulate Case A with various values of excavation length and width. Next, analyses in plane strain condition (2D analyses) were also carried out with various values of excavation width

to obtain 2D results for comparison with 3D results. The excavation length (L) was varied in values of 20 m, 40 m, 60 m, 80 m and 100 m. The excavation width (B) was varied in values of 10 m, 20 m, 40 m, 60 m, 80 m and 100 m.

In order to ignore influences from complex characteristics of structure and soil, input parameters of structure and ground of said parametric studies were the same as those used in the benchmark analysis. Thus, only geometries of excavation (width and length) were varied in the parametric studies.

As indicated previously, the Plane Strain Ratio (PSR)

is defined to further evaluate three-dimensional effect on wall deflection as follows:

$$PSR = \frac{\delta_A}{\delta_{plane}} \quad (4)$$

in which, δ_A is the maximum wall deflection at a certain section along the wall, and δ_{plane} is the maximum wall deflection of the section under plane strain condition. Fig. 3 below presents results obtained from the parametric studies.

Fig. 3. Variation of the PSR with distance from the corner for constant excavation widths and various excavation lengths of Case A.

As shown in Fig. 3, PSR values corresponding to various values of distance from the corner (d), length (L) and width (B) of excavation are plotted. Once PSR value is greater, it means displacement at such location is closer to plane strain condition. For the case of B of 10 m, wall deformations all reach plane strain condition once it is approximately 20 m from the corner, except

for the case having L of 20 m. For case having B of 20 m, wall displacements are under plane strain condition for the place at 25 m from the corner, except cases of L of 20 m and 40 m. However, the maximum PSR value cannot reach 1.0 for B larger than 20 m. It can only be 0.78 for case of B of 100 m. It is because the arching effect on the wall displacements is inversely

proportional to B/L . For case of B of 100 m, the wall deflections cannot reach the plane strain condition because the minimum ratio of B/L is equal to 1.0.

Considering results shown from Fig. 3 above, a relationship between B/L and distance from the corner (d) for various PSR values is established by the linear regression method as presented in Fig. 4. Results made by Ou et al. (1996) based on excavations in clay are shown in Fig. 5 for comparison purpose.

The PSR values interpreted from the same d and B/L in Fig. 4 and Fig. 5 are compared. It is clearly seen that for B/L more than 1.0, PSR is smaller than in sand rather than in clay with the same value of d . For example, for B/L of 2.0 and d of 10 m, PSR is equal to 0.28 for sand and 0.33 for clay. In contract, for B/L less than 0.5, PSR is larger than in sand rather than in clay with the same value of d . For example, for B/L of 0.25 and d of 10 m, PSR is equal to 0.77 for sand and 0.53 for clay. Further verification may have to be delivered later in order to explore the reason for the difference.

Fig. 4. Relationship between B/L and distance from the corner (d) for various PSR values.

Fig. 5. Relationship between B/L and distance from the corner (d) for various PSR values of excavations in clays (Ou et al., 1996).

4 APPLICATION OF PSR

The relationship of Fig. 4 can be used to estimate 3D maximum wall deflections by using 2D finite element analyses for the excavation of Case A and other similar cases. Fig. 6 below shows comparison of the maximum wall deflections at the section on the long side of Case A that is 10 m away from the corner.

It is clear that the 2D finite element analysis (2D FEA) is not able to accurately predict the maximum wall deflections at the section on the long side of Case A that is 10 m away from the corner, which are heavily influenced from the three-dimensional effect. The PSR value (Ou et al., 1996), which is based on excavations in clays, is also not able to well estimate the maximum wall deflections. The maximum wall deflections predicted from the PSR value (this study) are very close to those obtained from 3D finite element analysis (3D FEA).

Fig. 6. Comparison of the maximum wall deflections at the section on the long side of Case A that is 10 m away from the corner.

5 CONSLUTION

The following are conclusions drawn from this study:

1) A restriction of the benchmark analysis in prediction of the wall lateral displacements is seen. It is because the benchmark analysis uses a basic soil model, the MC model, which only adopts a single Young's modulus of soil, dose not distinguish between loading and unloading/reloading stiffness, and also does not consider the strain-dependent stiffness behavior of soil.

2) The PSR increases gradually with increase of distance from the corner (d). The PSR increases quickly when the d is still small and then reaches to a certainly constant value. For excavations of 10 m and 20 m widths, the PSR reaches to 1.0 (i.e. wall displacements are under plane strain condition) as the d is larger than 20 m and 25 m, respectively. However, the maximum PSR value cannot reach 1.0 for B larger than 20 m. It can only be 0.78 for case of B of 100 m.

3) The PSR at a certain d value increases gradually with decrease of B/L . This result is similar to the previous study of Ou et al. (1996) for excavations in clays. However, for B/L more than 1.0, PSR is smaller than in sand rather than in clay. In contrast, for B/L less than 0.5, PSR is larger than in sand rather than in clay. Further verification may have to be delivered later in order to explore the reason for the difference.

4) A simple relationship for predicting PSR values or 3D maximum wall deflections by using 2D finite element analyses is proposed as Fig. 4 for the excavation of Case A. It is understood that such relationship does not consider all factors that affect the excavation behavior such as excavation sequence, excavation duration, surcharge condition, existence of adjacent structures and construction method of the wall. However, the relationship developed in this study can still be applicable for other excavations with the same conditions.

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