Modified plane strain analysis for wall deflection in deep excavations by considering corner effect

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ABSTRACT

Plane strain approach is commonly adopted in engineering practices today for analysis of wall deflections during underground excavations owing to its convenience and lower cost. For small-to-medium sized excavations, however, a three-dimensional approach would be more appropriate for the wall deflection because of the influence of corner effect by the excavation geometry. This study is aimed at modifying currently adopted plane strain analysis, so that the influence of excavation geometry can be considered. Two options (buttress-wall & cross-wall) are proposed for the modification. A three-dimensional analysis is also conducted in comparison with the proposed options. Results indicate the influence of excavation geometry on the wall deflection can be adjusted by the proposed options for the case of small-to-medium sized excavations. For large excavation areas, however, the proposed options appear to overly correct the wall deflections, suggesting refinements are warranted in the future.

Keywords: diaphragm wall deflection; deep excavation; geometry effect; plane strain analysis; TORSA; Plaxis3D

1 INTRODUCTION

Plane strain approach is routinely adopted in engineering practices for analysis of wall deflection in deep excavation due to convenience and lower cost. The analyzed wall deflection (δ_{PS}), however, would tend to overestimate the actual value (δ_{3D}), in view of the constraints by excavation geometry, as shown in Fig. 1.

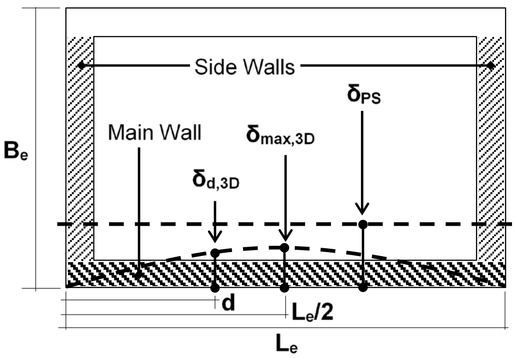

Fig. 1. Schematic illustration of wall deflections computed by plane strain and 3D analyses.

For small-to-medium sized excavations, the degree of overestimation in wall deflections would be more severe and result in the plane strain analysis too conservative and not economical. To cope with this problem, one may consider to apply a three-dimensional analysis, or to revise the plane strain approach such that it can take 3D geometry, or corner effect, into account.

This study is aimed at modifications of the plane strain approach for small-to-medium sized excavations. The common software, TORSA3 (SGRDF 2016), is employed for computation. Three-dimensional analyses by Plaxis3D (Plaxis 2011) are also conducted for comparison with the plane strain results. To interpret 3D geometry effect, the plane strain ratio (PSR) is adopted, which is defined as the ratio of the maximum 3D wall deflection ($\delta_{max,3D}$) to the plane strain deflection (δ_{PS}).

2 MODIFICATION OPTIONS

Three modification options are considered in this paper. Option 1, as previously proposed by Hsieh and Lu (1999) and Hsieh et al. (2010), assumes the side walls as the buttress walls. Option 2 is proposed in the current study and assumes the side walls as the cross walls. Option 3 adopts the existing PSR studies by Finno et al. (2007) and Ou et al. (1996) and their results are applied directly to the plane strain analysis.

2.1 Buttress-wall option

This option assumes the side walls attached to the main wall as the buttress walls. Due to the friction between buttress walls and the adjacent soils within the excavation area, the deflection of main wall is therefore reduced. To account for this effect, Hsieh et al. (1999, 2010) assume the contribution to main wall deflection by the buttress wall frictions is equivalent to the increase in strength and stiffness of the soils within the excavation area. Details of theoretical derivations are referred to the above references, and the factors for adjustment of soil stiffness and strength are summarized as follows:

$$J_c = 1 + 0.8(B_e/L_e) \quad (1)$$

$$J_s = 1 + 0.32(B_e/L_e) \quad (2)$$

$$I_c = 1 + (B_e/L_e) \quad (3)$$

$$I_s = 1 + 2(B_e/L_e)\tan\phi' \quad (4)$$

where J and I are the adjustment factors for stiffness and shear strength of soils, respectively. The subscripts c and s denote "clay" and "sand", ϕ' is the friction angle of sand, and L_e and B_e are the length and width of the excavation area, respectively.

2.2 Cross-wall option

This option assumes the side walls attached to the main wall as the cross walls. As shown in Fig. 2, the punching shear resistance (V) in the main wall would be developed as a result of the action of soil pressure from outer boundary of the excavation area, in view of the resistance and fixity at the ends of the cross walls. The punching shear resistance will reduce the deflection of the main wall, which is considered with the same effect as by increasing the stiffness and strength of soils from outside of the excavation area.

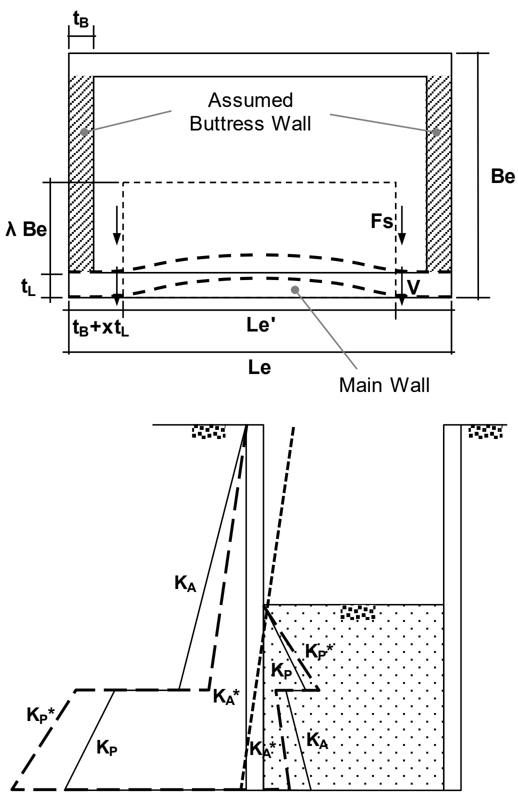

Fig. 2. Plan and cross section views showing the assumptions adopted in the cross-wall option.

Likewise, the deflection in main wall would mobilize the shear resistance (F_s) of soils within the excavation area. The shear resistance in soils would reduce the deflection of the main wall, which is considered with the same effect as to increase the stiffness and strength of soils within the excavation area.

It is noted that the reduction in main wall deflection due to the developed punching shear resistance of wall in an actual excavation case is equivalent to the effect by increasing the stiffness and strength of soils outside of the excavation area in a plane strain analysis. Since the punching shear resistance of wall will be remaining during the excavation process, the modifications in the stiffness and strength of soils on the outer boundary of the main wall would deem to be appropriate.

On the contrary, the reduction of wall deflection due to the mobilized shear resistance in soils is equivalent to the effect by increasing the stiffness and strength of soils within the excavation area in a plane strain analysis. The mobilized shear resistance in soils will be vanished along with the excavation, and hence, the modifications of stiffness and strength are assigned to the soils within the excavation area, in which the soils will be removed as the excavation proceeds.

Details of the theoretical derivations are referred to Shen (2018). The adjustment factors for the stiffness and strength of soils within the excavation area are summarized as follows:

$$J_c = 1 + 0.8(0.5 - t_L/B_e)(B_e/L_e{}') \quad (5)$$

$$J_s = 1 + 0.32(0.5 - t_L/B_e)(B_e/L_e{}') \quad (6)$$

$$I_c = 1 + (0.5 - t_L/B_e)(B_e/L_e{}') \quad (7)$$

$$I_s = 1 + (1 - 2t_L/B_e)(B_e/L_e{}')(K_0/K_p)\tan^{-1}\phi' \quad (8)$$

Similarly, the adjustment factors for the stiffness and strength of soils beyond the excavation area are summarized as follows:

$$J_c = 1 + 0.84(t_L/L_e{}')\sqrt{f_c{}'}/S_u \quad (9)$$

$$J_s = 1 + 169.6(t_L/L_e{}')\sqrt{f_c{}'}/N \quad (10)$$

$$I_c = 1 + 5.3(t_L/L_e{}')\sqrt{f_c{}'}/S_u \quad (11)$$

$$I_s = 1 - 10.6(t_L/L_e{}')\sqrt{f_c{}'}/(K_a\sigma_v{}') \quad (12)$$

The notations adopted in Eqs. (5)~(12) are the same as in Eqs. (1)~(4), except that t_L and $L_e{}'$ are the thickness and effective length of the main wall, K_0, K_a and K_p are the at-rest, active and passive pressure coefficients of soils, $f_c{}'$ is the compressive strength of wall material (i.e., concrete), S_u is the undrained strength of clay, and N is SPT blow count of sand.

3 ANALYSIS RESULTS

3.1 Parametric studies of modification options

A parametric study is performed to examine the effect of geometric and material factors on the computed 3D effect, i.e., the plane strain ratio (PSR), for various options considered in this paper, and the results are shown in Fig. 3.

The figure shows the influence of excavation length (L_e) on the computed 3D effect (PSR), while all other geometric factors are kept constant. The soil material is assumed to be a clay with $S_u/\sigma_v{}'$ varied within 0.25 and 0.40.

It is obvious that the plane strain ratio ($PSR = \delta_{max,3D}/\delta_{PS}$) increases as the increase in the excavation length (L_e), suggesting a decreasing 3D geometry effect and a more plane strain situation when the excavation length becomes large.

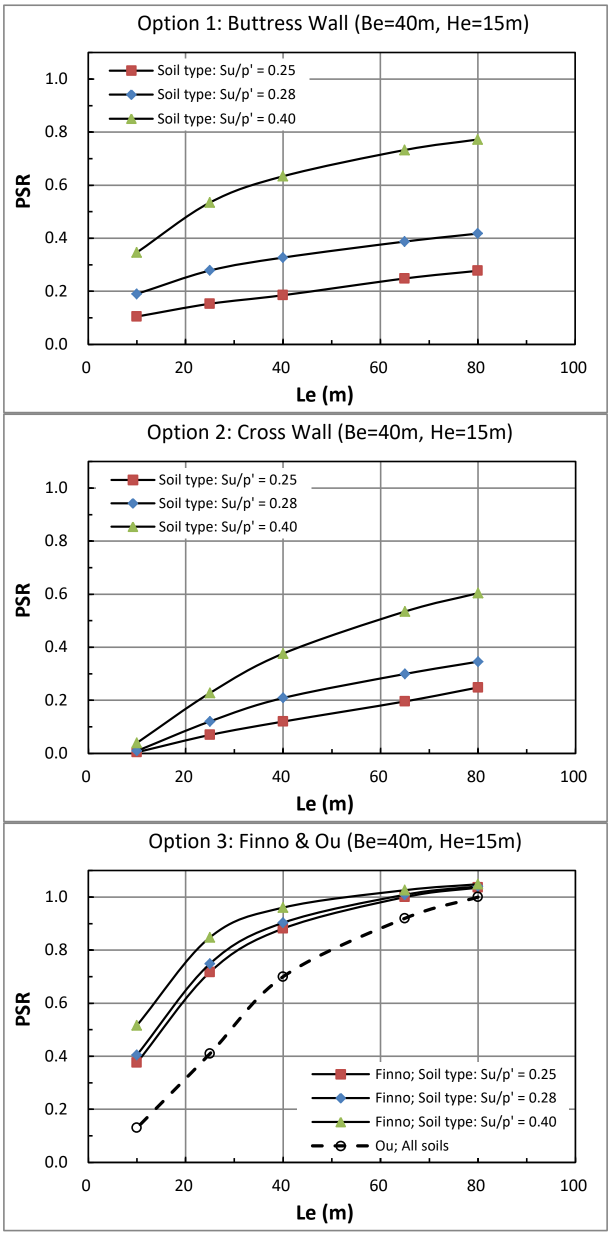

Fig. 3. Effect of excavation length (L_e) on the computed plane stain ratio (PSR) for various modification options.

In terms of material strength, we notice that the increase in the undrained strength of clay will increase the PSR, indicating the 3D (geometry or corner) effect will be influenced by the material strength and the increase in material strength will decrease the 3D effect. Hence, the soft materials will have more 3D effect (i.e., less PSR) than the hard materials do.

By comparing various modification options, we observe Option 2 (cross-wall option) would generally have the greatest 3D geometry effect (i.e., the lowest PSR), followed by those of Option 1 (buttress-wall option) and Option 3.

Option 3, based on the PSR studies by Finno et al. (2007) and Ou et al. (1996), generally shows the least 3D effect (i.e., the highest PSR). It is noticed that some PSRs are unexpectedly greater than 1.0 for larger excavation lengths in Finno's estimations. In addition, Ou's study would not be able to differentiate material type and results in the same PSR prediction for various types of material examined.

3.2 Comparisons with Plaxis3D

To compare with wall deflections of the plane strain options considered herein, three-dimensional analyses by Plaxis3D are performed.

Based on studies by Ou et al. (1996), Finno et al. (2007) and Hsieh et al. (2010), the 3D geometric effect would deem significant for excavations with an excavation length of $L_e < 40m$ and a length-to-height ratio of $L_e/H_e < 6$. Accordingly, the above condition is adopted as the definition of small-to-medium sized excavation. In the following, the comparisons of various plane strain options with Plaxis3D analyses are made for the case of $L_e = 10{\sim}80m$ and $L_e/H_e = 1.25{\sim}10$, which covers a full range of excavation size.

As shown in Figs. 4 (a) and (b) where excavation geometries approximately fall in the range of less 3D effect (i.e., $L_e = 40{\sim}80m$ & $L_e/H_e = 5{\sim}10$), the computed maximum wall deflections by the plane strain analysis (Torsa-PS) are roughly comparable to those by the three-dimensional analysis (Plaxis3D). However, the results by Options 1 and 2 (Torsa-Op1 & Torsa-Op2) are considerably smaller than those by the three dimensional analysis (Plaxis3D), implying Options 1 and 2 appear overly modify the 3D effect and thus underestimate the wall deflection for excavation geometries with less 3D effect.

In Fig. 4 (c) where excavation geometry indicates a more obvious 3D effect (i.e., $L_e = 10m$ & $L_e/H_e = 1.25$), the computed wall deflections by the plane strain analysis (Torsa-PS) are apparently overestimated, while the results by Option 2 (cross-wall option; Torsa-Op2) are comparable to those by the three-dimensional analysis (Plaxis 3D).

In fact, wall deflections by the plane strain analysis are irrelevant to the lateral dimension of the excavation (i.e., length L_e), the thus the plane strain results in Figs. 4 (a)~(c) are all the same.

Although Options 1 & 2 could reasonably consider the 3D geometry effect for the small-to-medium sized excavations, the wall deflections are significantly underestimated for the case with larger excavation areas, indicating refinements on Options 1 & 2 are warranted to correctly reflect the 3D effect for a full range of excavation geometry.

4 CONCLUSION

This paper discusses the 3D geometry or corner effect on the wall deflection during excavation. Both plane strain approach and its modifications (namely, buttress-wall and cross-wall options) are considered in view of their computed wall deflections and the capability in reflecting the 3D effect. Three-dimensional analyses are also conducted to compare the results of the modified plane strain options. Major findings of the current study are listed below:

Parametric studies show the increase in excavation length (L_e) will reduce the 3D geometry effect or an increase in the plane strain ratio (PSR).

The 3D geometry effect will be influenced by the material strength. The increase in undrained strength of clay (S_u/σ_v') will reduce the 3D geometry effect. The soft materials will have more 3D effect (i.e., less PSR) than the hard materials do.

Plane strain modification Option 2 (cross-wall option) would generally provide the greatest 3D geometry effect (i.e., the lowest PSR), followed by those of Option 1 (buttress-wall option) and Option 3 (PSR studies by Finno et al. and Ou et al.).

Although Options 1 & 2 could reasonably reflect the 3D geometry effect for the small-to-medium sized excavations, the wall deflections are significantly underestimated for the case with larger excavation areas, indicating refinements on Options 1 & 2 are warranted to correctly reflect the 3D effect for a full range of excavation geometry.

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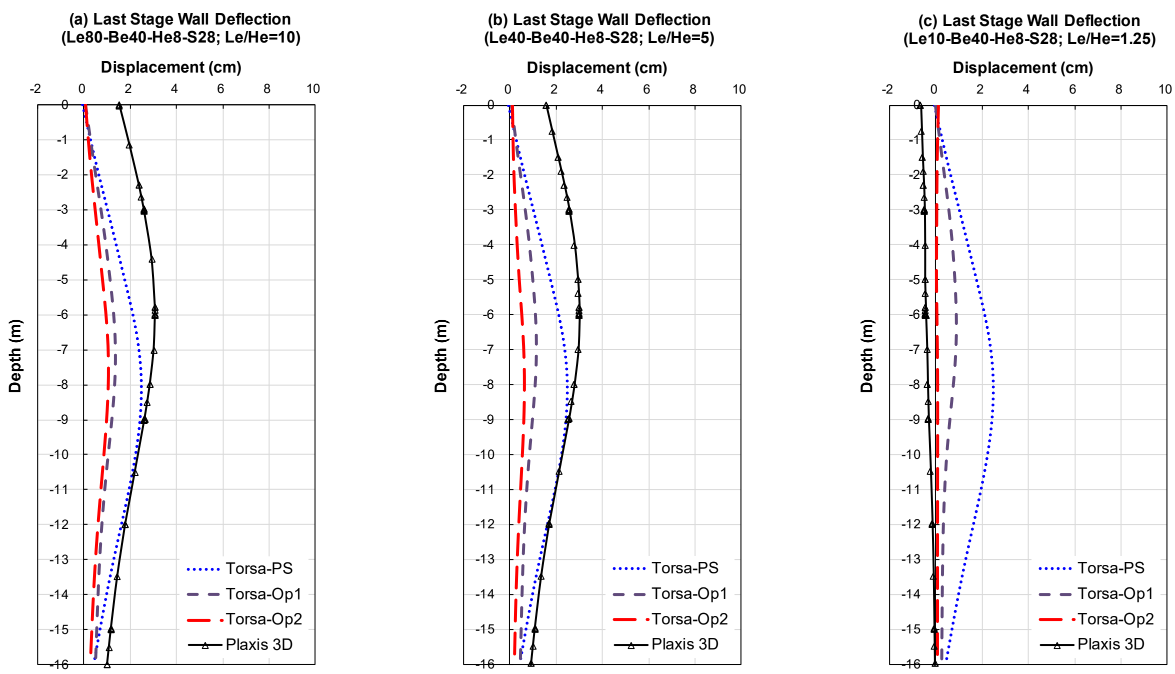

(a) $L_e = 80m$ & $L_e/H_e = 10$ (b) $L_e = 40m$ & $L_e/H_e = 5$ (c) $L_e = 10m$ & $L_e/H_e = 1.25$

Fig. 4. Comparison of wall deflections computed by plane strain modification options and a three-dimensional approach.