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Discussions on numerical modelling with Plaxis for ERSS design during deep excavation

Discussions sur la modélisation numérique avec Plaxis pour la conception ERSS lors de fouilles profondes

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ABSTRACT: 2D numerical modelling is usually preferred by designers. However, simplifying the problem in 2D numerical modelling is quite challenging. In this paper, cross wall modelling in 2D will be discussed. Five methods, i.e., anchor method, ratio method, method 3A, method 3B and method 3C are adopted. Diaphragm wall modelling in 3D will also be discussed and its results will be used for verifying the results predicted by 2D. Numerical analysis showed that Diaphragm wall modelled with plate in 2D usually gives larger deflection, higher shear force and bending moments. The deflection predicted by method 3A is generally closer to that by 3D than other methods while ratio method usually gives much higher deflection than other methods. Results showed that the force profiles predicted by 2D and 3D are usually similar except for the areas around base slab level. The maximum forces predicted by 3D are generally within the values predicted by 2D. At the center section of the Diaphragm wall, 2D gives shear force close to 3D with 3m panel and bending moment close to 3D with 6m panel. Results also indicated that the Diaphragm wall modelled as plate without panel cannot capture the cross wall effect on the forces.

RÉSUMÉ La modélisation numérique 2D est généralement préférée par les concepteurs. Cependant, simplifier le problème dans la modélisation numérique 2D est assez difficile. Dans cet article, la modélisation des murs croisés en 2D sera discutée. Cinq méthodes, c'est-à-dire la méthode d'ancrage, la méthode du rapport, la méthode 3A, la méthode 3B et la méthode 3C sont adoptées. La modélisation des parois moulées en 3D sera également discutée et ses résultats seront utilisés pour vérifier les résultats prédits par 2D. L'analyse numérique a montré que la paroi du diaphragme modélisée avec une plaque en 2D donne généralement une plus grande déflexion, une force de cisaillement et des moments de flexion plus élevés. La déflexion prédite par la méthode 3A est généralement plus proche de celle de la 3D que les autres méthodes, tandis que la méthode du ratio donne généralement une déflexion beaucoup plus élevée que les autres méthodes. Les résultats ont montré que les profils de force prédits par 2D et 3D sont généralement similaires, sauf pour les zones autour du niveau de la dalle de base. Les forces maximales prédites par 3D sont généralement comprises dans les valeurs prédites par 2D. Dans la section centrale de la paroi du diaphragme, la 2D donne une force de cisaillement proche de la 3D avec un panneau de 3 m et un moment de flexion proche de la 3D avec un panneau de 6 m. Les résultats ont également indiqué que la paroi du diaphragme modélisée comme une plaque sans panneau ne peut pas capturer l'effet de la paroi transversale sur les forces.

KEYWORDS: numerical modelling, ERSS design, cross wall, Diaphragm wall, deflection

1 INTRODUCTION.

Earth Retaining or Stabilizing Structure (ERSS) is required for deep excavation during the construction of MRT station, Cut and Cover tunnel as well as launch shaft. The design and performance of deep excavation was discussed and studied by many engineers and researchers (e.g. Karlsrud and Andresen 2008; Wu et al, 2015, Hsieh et al. 2017). As an alternative auxiliary measure for protection of adjacent buildings during excavation, the effectiveness of cross walls in reducing wall deflections were evaluated widely (e.g. Ou et al. 2011, Soccodato et al. 2015). Since the excavation with cross walls is essentially a 3D problem, many studies applied 3D numerical analysis to simulate the excavation with cross walls (e.g. Hsieh et al. 2013, Ou et al. 2013). Although 3D numerical modelling with Plaxis is more useful for ERSS design, 2D numerical modelling is still usually preferred by designers. However, simplifying the problem in 2D numerical modelling is quite challenging. As such, some researchers proposed simplified method to estimate the lateral wall deflection (e.g. Ou et al. 2011, Hsieh et al. 2012, Lu et al. 2016).

Studies on forces of diaphragm wall are very limited in literature as lateral displacement and ground settlement are usually more critical. In this paper, cross wall modelling in 2D will be discussed to show the effect of different modelling methods and assumptions on the forces and deflection of Diaphragm wall through 2D and 3D numerical analysis.

2 NUMERICAL MODEL

A 2D plain strain Plaxis model shown in Figure 1 was used to simulate an excavation with 35m width and 30m depth. The proposed earth retaining system comprises of 1.5m thick diaphragm wall supported by 6 layers of Reinforced Concrete (R.C.) slab and 19m thick 0.8m wide cross wall at 6m spacing. The cross wall was installed between 14.0m and 33.0m below ground level (BGL). There is an existing high-rise building founded on concrete bored piles on one side of the excavation, which is 2.4m away from the diaphragm wall. However, the pile modelling is not the main topic of this paper and would complicate the problem when compared with 3D modelling. As such, the piles are not modelled herein. For simplicity and convenience, no surcharge was applied on the ground surface. The size of the 2D model is 190m width and 75m deep.

The soil profile consists of Fill, and different weathering grades of the Old Alluvium soil OA(C), OA(B) and OA(A), which are indicated in Figure 1. The Fill was modelled with Mohr Coulomb model whereas OA was modelled with Hardening Soil model. The ground water level was set to be at the ground level. All the sandy or rock materials were modelled as drained material. There are total 7 stage of excavations, followed by casting base slab, removing slab 6, and casting concourse slab and backfilling. Slab 5, slab 4 and slab 1 were removed while slab 2 and slab 3 were kept as parts of permanent structural during backfilling.

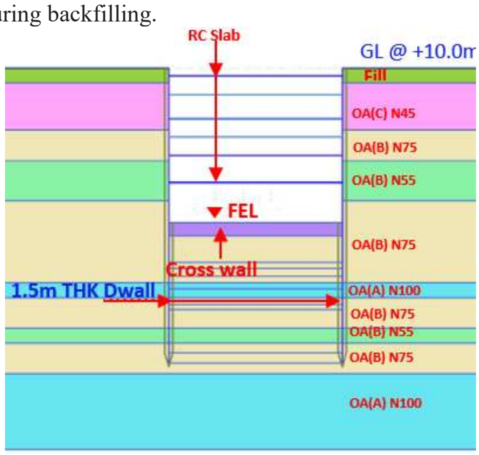


Figure 1. 2D plain strain Plaxis model with soil profiles

A 3D Plaxis model as shown in Figure 2 was used to verify the 2D cross wall modelling. The full model is 200m long by 200m wide by 75m deep. The bored piles were not modelled to simplify the problem. The slabs were modelled with plate elements in both 2D and 3D analysis. The cross wall was modelled by soil element with concrete property. For comparison, cross wall was also modelled with plate element in 3D analysis. The excavation width and depth are the same as described in 2D.

For simplicity and comparison, pore pressure was modelled by hydrostatic (phreatic) analysis in both 2D and 3D.

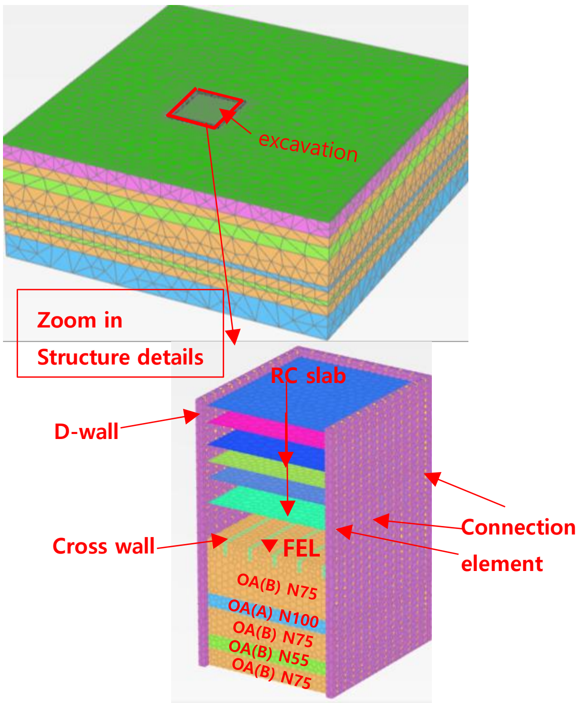


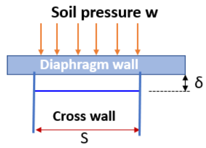
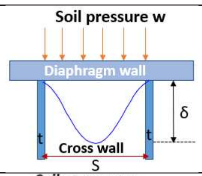
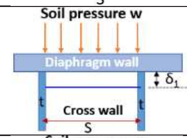
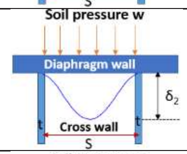
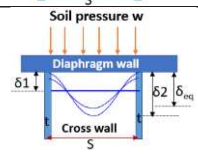
Figure 2. 3D Plaxis model

3 CROSS WALL MODELLING IN 2D ANALYSIS

3.1 *methods for cross wall modelling in 2D*

Five methods are adopted to model cross wall, which are named as anchor method, ratio method, method 3A, method 3B and method 3C. In anchor method, node to node element was used to model the cross wall with equivalent modulus EA at cross wall spacing. In other four methods, cross wall was modelled as soil element with equivalent modulus E. E of ratio method is estimated based on the area ratio between cross wall and soil. E of method 3A is the same as that of anchor method. E of method 3B is derived by assuming diaphragm wall deflects as beam fixed at both ends by cross wall (Lu et al. 2016). The five methods and equivalent modulus are summarized in Table 1.

Table 1. Summary of cross wall modelling method in 2D analysis

Method	Deflection mode	Equivalent modulus
Anchor method		$EA=SE_1$ $\delta = \frac{w}{E_1}$ $E_1 = E_{con}\frac{t}{S}$ t-cross wall spacing
Ratio method		$\delta = \frac{w}{E_1}$ $E_1 = E_{con}\frac{t}{S} + \frac{(S-t)E_{soil}}{S}$ E_{con}-modulus of concrete
Method 3A		$\delta_1 = \frac{w}{E_1}$ $E_1 = E_{con}\frac{t}{S}$
Method 3B		$\delta_2 = \frac{w}{E_2}$ $E_2 = \frac{384E_{con}}{S^4}$
Method 3C		$\delta_{eq} = \frac{1}{2}(\delta_1+\delta_2) = \frac{w}{E_{eq}}$ $E_{eq} = \frac{2E_1E_2}{E_1+E_2}$ E_1 and E_2 refer to Method 3A and 3B

3.2 *comparison for predicted deflection of Diaphragm wall*

Diaphragm wall was modeled in two different ways, i.e., plate element and soil element with dummy plate. Figure 3 presents deflection profile of Diaphragm wall predicted by different methods for 3m, 6m and 12m cross wall spacing. As shown in Figure 3, when the Diaphragm wall was modelled as plate, the predicted deflection is usually slightly larger for the same cross wall modelling.

As shown in Figure 3a, for 3m cross wall spacing, anchor method and ratio method predicted the largest deflection while method 3B and 3C predicted the smallest deflection. Method 3A predicted the deflection in between other methods. For 6m cross wall spacing, ratio method predicted the largest deflection while method 3A to 3C predicted smaller deflection than anchor method and ratio method. For 12m cross wall spacing, method 3B, method 3C and ratio method predicted much larger deflection than method 3A and anchor method.

Figure 4 presents the maximum deflection of Diaphragm wall predicted by different methods. As shown in Figure 4, in general, maximum deflection predicted by method 3A and ratio method represents the lower and upper boundary. The maximum deflection predicted by method 3A and anchor method increases slowly with the cross wall spacing while the maximum deflection predicted by method 3B, method 3C and ratio method increase with cross wall significantly.

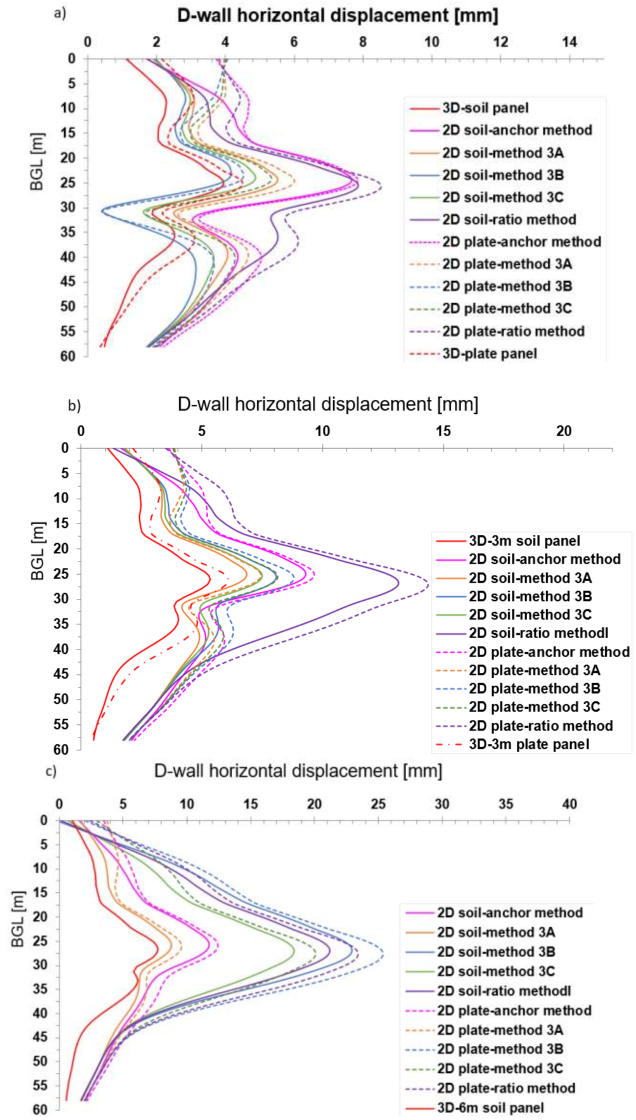


Figure 3. Deflections predicted by different cross wall methods in 2D a) 3m cross wall, b) 6m cross wall, c) 12m cross wall.

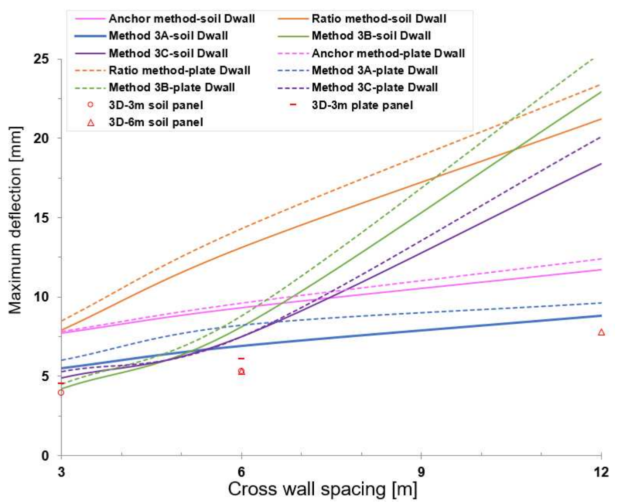


Figure 4. Maximum deflections predicted by different cross wall methods

3.3 *comparison in predicted forces of Diaphragm wall*

Figures 5 presents the force profiles of Diaphragm wall with 6m cross wall spacing predicted by different cross wall modelling methods. As shown in Figure 5, the shear force and bending moment profiles are generally consistent. However, there are some differences around base slab level, where maximum forces usually occur. Ratio method gives smaller maximum shear force and larger bending moment above base level than other method whereas ratio method gives much smaller shear force and bending moment below base level than other methods. For 3m and 12m cross wall spacing, the force profiles predicted by different methods are also quite consistent.

Figures 6 to 7 presents the maximum forces of Diaphragm wall with 3m to 12m spacing cross wall. As shown in Figures 6 to 7, for 3m spacing cross wall, method 3B gives the highest forces while ratio method gives the smallest forces. Anchor method, method 3A and method 3C are very close to each other. For 12m cross wall, forces given by anchor method and method 3A are very close. The maximum bending moments predicted by method 3B , method 3C and ratio method are significantly higher than those by anchor method and method 3A.

As shown in Figures 6 to 7, when the Diaphragm wall was modelled as plate, the predicted shear forces are 20% t0 40% higher and bending moments are 10% to 20% higher for the same cross wall modeling method. The maximum shear forces predicted by method 3B and ratio method decrease more obviously with the cross wall spacing up to 6m and then increases slowly while the maximum shear forces predicted by other methods are quite close and decrease with the spacing gradually. The maximum bending moments predicted by method 3B and 3C decrease obviously with the cross wall spacing up to 6m and then increase obviously. Unlike other methods, the maximum bending moment predicted by ratio method increases with cross wall spacing more significantly.

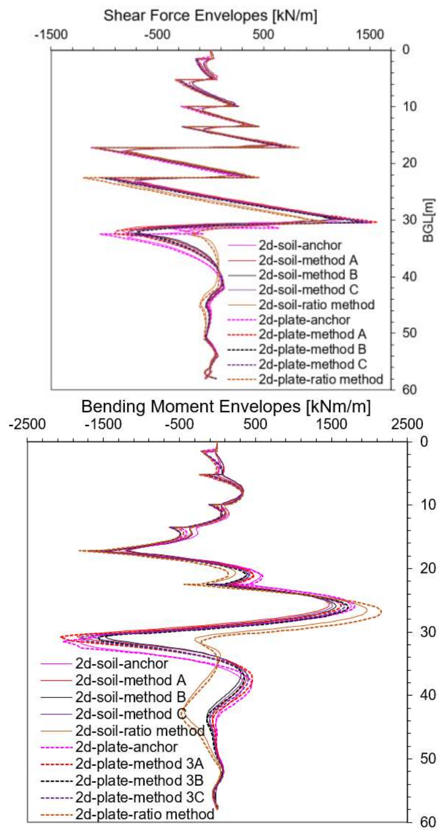


Figure 5. Forces predicted by different cross wall methods in 2D for 6m cross wall.

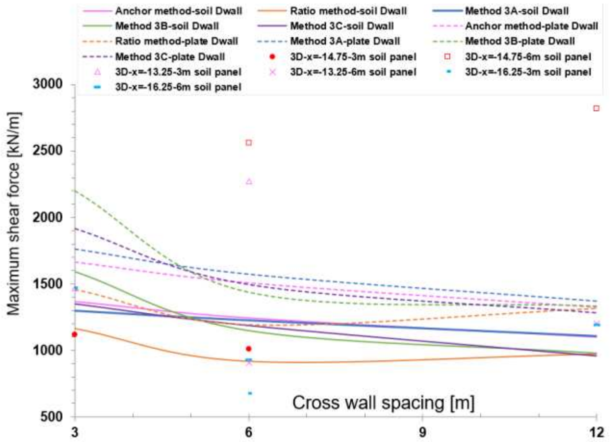


Figure 6. Maximum shear forces predicted by different cross wall methods.

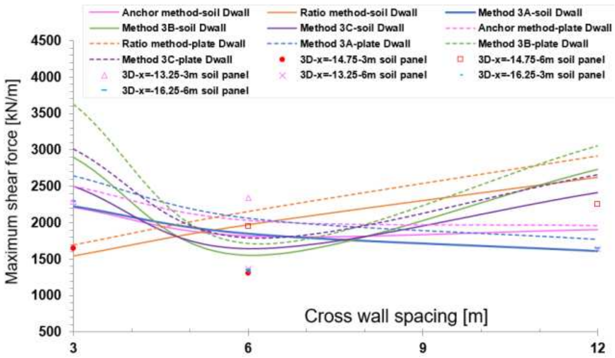


Figure 7. Maximum bending moments predicted by different cross wall methods.

4 DIAPHRAGM WALL AND CROSS WALL MODELLING IN 3D ANALYSIS

4.1 *methods for cross wall and diaphragm wall modelling in 3D*

Cross wall could be modelled as plate and soil element in 3D Plaxis. Preliminary analysis showed that force profiles of the Diaphragm wall predicted by these two methods are generally close. However, the maximum shear force occurred around base slab level predicted by plate method is about 40% higher than that by soil element. As such, the plate method is not adopted for cross wall in 3D in this study.

Diaphragm wall was modelled as plate without panel, plate with 3m to 6m panel (plate panel), and soil element with 3m to 6m panel (soil panel) with dummy plate. Connection elements are adopted and set to be free rotation to model the relationship between different panel. Figure 8 presents the sketch for layout plan of Diaphragm wall with cross wall. Figure 8a shows the Diaphragm wall with 3m panel and 3/6m spacing cross wall. Figure 8b shows the Diaphragm wall with 6m panel and 6/12m spacing cross wall. Three sections are chosen to investigate the difference among Diaphragm modelling methods and cross wall effect as well. Section 1 (x=-14.72m) is at the center of the Diaphragm wall. Section 2 (x=-13.25m) is at the left side of the section 1, 1.5m away from section 1. Section 3(x=-16.25) is at the right side of the section 1, 1.5m away from section 1. Four scenarios are simulated to obtain the deflections and forces of the Diaphragm wall for validating the 2D results. Case 1 and case 2 simulated Diaphragm wall with 3m panel, 3m and 6m spacing cross wall respectively. Case 3 and case 4 simulated Diaphragm wall with 6m panel, 6m and 12m spacing cross wall respectively. For case 1 and case 2, section 1 is always at the connection of the panel whereas section 2/3 could be at cross wall position depending on the spacing of the cross wall. For case 3 and case 4, section 1 is always at the cross wall position whereas section 2 and section 3 is 1.5m away from section 1, at the left and right side of the cross wall respectively.

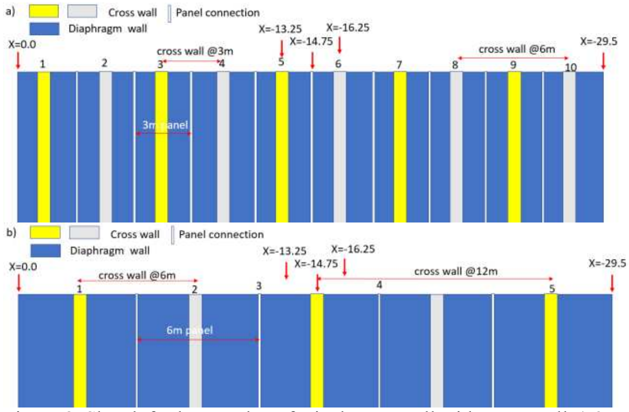


Figure 8. Sketch for layout plan of Diaphragm wall with cross wall a) 3m panel with 3/6 m cross wall spacing, b) 6m panel with 6/12m cross wall spacing.

4.2 *comparison for predicted deflection of Diaphragm wall*

Case 2, i.e., Diaphragm wall with 3m panel and 6m spacing cross wall was used for comparison for deflection and forces of Diaphragm wall predicted by different diaphragm modelling method. Figure 9 presents the predicted deflection of Diaphragm wall in 3D. As shown in Figure 9, the deflections at three sections are essentially the same. The deflections predicted by plate method are slightly larger than that by soil element method. The deflection predicted by plate without panel is basically close to that by plate with panel.

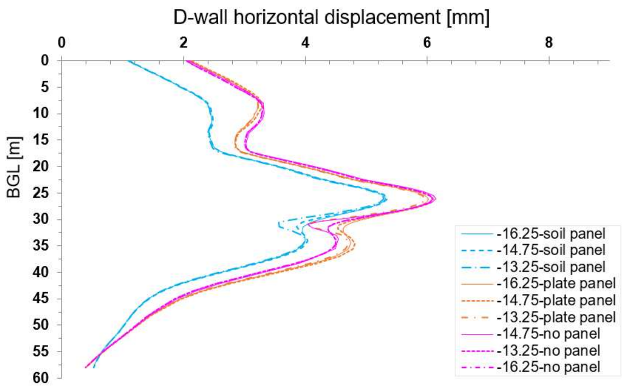


Figure 9. Deflection of diaphragm wall at three sections predicted by different Diaphragm modelling method.

4.3 *comparison for predicted forces of Diaphragm wall*

For case 2, as shown in Figure 8, section 1(x=-14.75m) is at the center of the Diaphragm wall and the connection place of 3m panel. Section 2(x=-13.25m) is at center of cross wall of 3m panel while section 3 (x=-16.25m) is at the center of 3m panel without cross wall. Figure 10 presents the force profiles at 3 sections of the Diaphragm wall predicted by three different Diaphragm modelling methods. As shown in Figure 10, the forces predicted by soil panel and plate panel method are usually very close except for maximum shear force occurred at base slab level at section 2. As shown in Figure 10 and Figure 11, at section 2, the maximum shear force predicted by plate panel method is significantly higher than that by soil panel method while the maximum bending moment of the former is slightly higher than that of the latter. The results also showed that the forces at section 2 predicted by both methods are the largest of the three sections and the forces at section 3 are the smallest, indicating obvious cross wall effect on the forces of the Diaphragm wall. On the contrary, Figure 10 and Figure 11 show that forces at section 1 predicted by plate without panel method are significantly higher than those at section 2 and section 3. Results also showed that the forces at section 2 and section 3 are essentially the same, indicating no cross wall effect on the wall forces when Diaphragm wall was modeled by plate without panel.

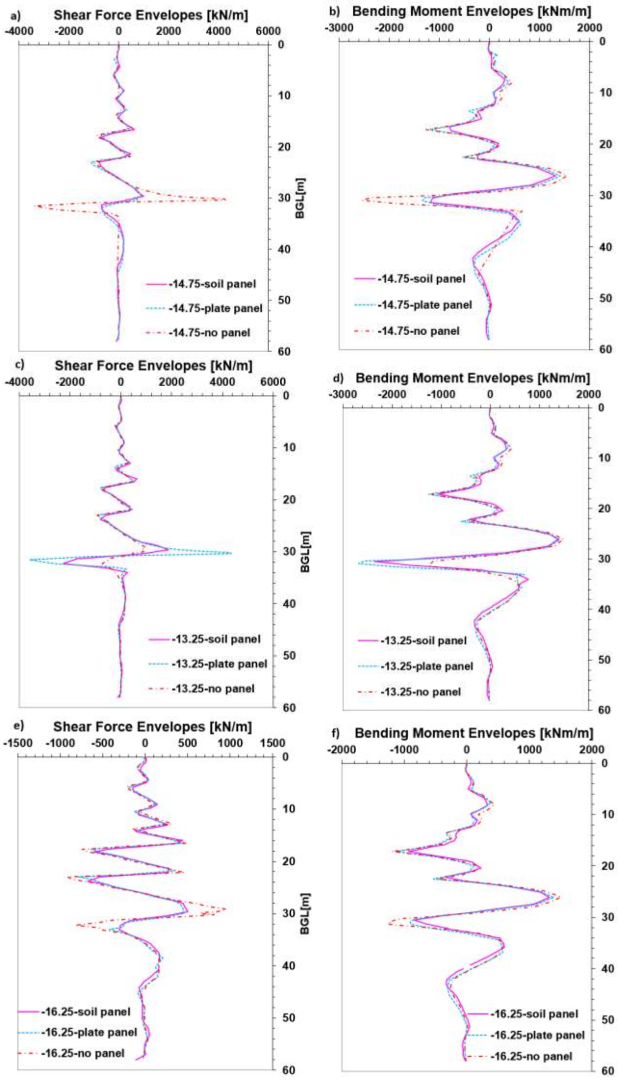


Figure 10. Forces of Diaphragm wall at three sections predicted by different Diaphragm modelling method. a) and b) at section 1(x=-14.75m), c) and d) at section 2 (x=-13.25m), e) and f) at section 3 (x=-16.25m)

4.4 *effect of cross wall spacing on Diaphragm wall*

Case 1 and case 2 were used to study the cross wall spacing effect on the Diaphragm wall deflection and forces. The only difference between these two cases is the cross wall spacing, which will affect section 3(x=-16.525) significantly. In case 1, cross wall spacing is 3m and section 3 is at the center of the cross wall while in case 2, the spacing is 6m and section 3 is at center of the panel but without cross wall. For both cases, the panel is 3m.

Figure 12 shows that the deflection of Diaphragm wall with 6m cross wall spacing is higher than that with 3m cross wall spacing. Results showed that the force profiles of Diaphragm wall with different cross wall spacing are similar. However, the maximum forces are indeed different due to the difference in cross wall spacing. The biggest difference can be seen from section 3 as shown in Figure 13. As shown in Figure 13, for section 3, the maximum forces of the Diaphragm wall with 3m cross wall spacing are significantly higher than those with 6m cross wall spacing. This difference could not be captured when Diaphragm wall was modelled as a plate without panel.

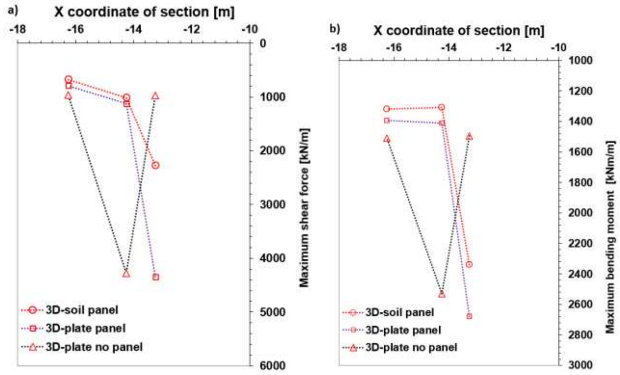


Figure 11. Maximum forces of Diaphragm wall at three sections predicted by different Diaphragm modelling method.

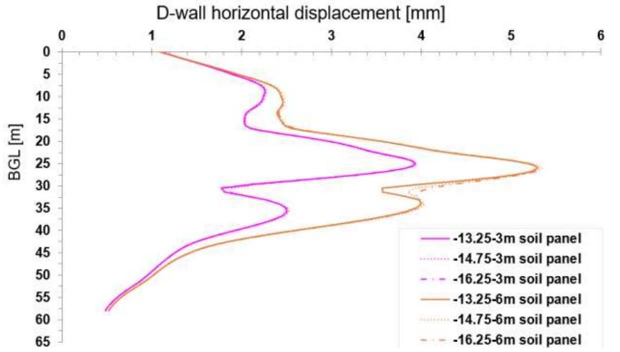


Figure 12. Deflection of diaphragm wall with 3m/6m cross wall spacing.

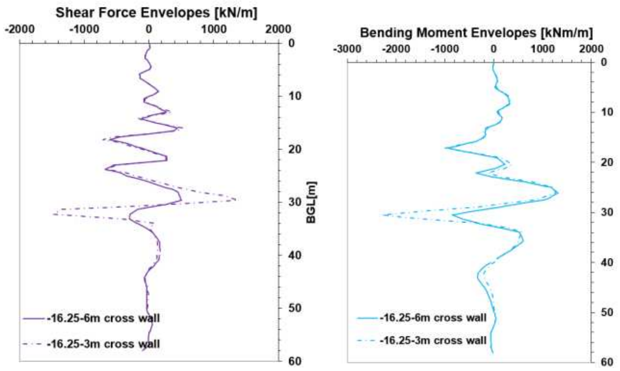


Figure 13. Forces of diaphragm wall with 3m panel and 3m/6m cross wall spacing at section 3(x=-16.25m).

5 COMPARISON BETWEEN 2D AND 3D ANALYSIS FOR CROSS WALL MODELLING

As shown in Figures 3 to 4, the deflection predicted by method 3A of 2D is generally closer to that by 3D than other methods for Diaphragm wall with cross wall spacing up to 12m. The deflection predicted by anchor method is also roughly close to that by 3D. For diaphragm wall with 3m to 6m cross wall spacing, method 3B and 3C gave deflections close to 3D. Ratio method gave much higher deflection for Diaphragm wall with 6m to 12m cross wall spacing.

Result in the previous sections showed that the forces profiles predicted by 2D and 3D are usually similar except for the areas around base slab level. Figures 14 presents the typical comparison in forces of diaphragm wall with 6m cross wall spacing between 2D and 3D analysis. As shown in Figures 6 to 7, the maximum forces at three sections predicted by 3D are generally within the values predicted by 2D. Tables 2 to 3 summarize the difference in maximum shear force and bending moment between 2D and 3D analysis. As shown in Table 2, in general, for section 1, 2D gives much closer shear force to 3D with 3m panel; for section 2 and 3, all methods give closer shear force to 3D for 3m panel with 3m cross wall and 6m panel with 12m cross wall. As shown in Table 3, in general, for section 1, 2D give much closer bending moment to 3D with 6m panel; for section 2 and 3, anchor method and method 3A give very close bending moment to 3D for 3m panel with 3m cross wall, 6m panel with 12m cross wall while method 3B and 3C give closer bending moment to 3D for 3m panel, 6m panel with 6m cross wall.

Table 2. Summary of difference in maximum shear force between 2D and 3D analysis (in percentage)

section	B*(m)	S*(m)	m1#	m2#	m3#	m4#	m5#
1	3	3	22	4	16	42	20
	3	6	23	-9	22	14	17
	6	6	-51	-64	-52	-55	-54
	6	12	-61	-66	-61	-65	-66
2	3	3	-7	-21	-12	8	-8
	3	6	-45	-60	-46	-49	-48
	6	6	37	1	35	27	31
	6	12	-8	-19	-8	-18	-20
3	3	3	-7	-21	-12	8	-8
	3	6	84	36	82	70	76
	6	6	34	-1	32	24	28
	6	12	-7	-18	-7	-18	-20

Note: *-B and S denotes panel width and cross wall spacing respectively, #-m1 to m5 denotes anchor method, ratio method, method 3A, 3B and 3C respectively.

Table 3. Summary of difference in maximum bending moment between 2D and 3D analysis (in percentage)

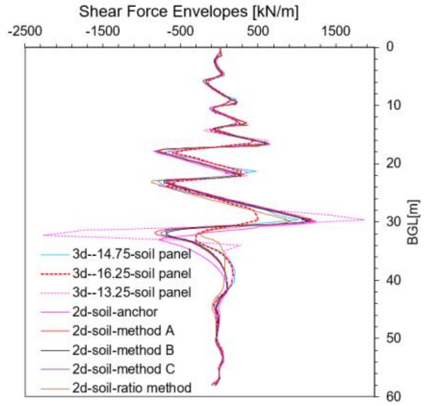
section	B*(m)	S*(m)	m1#	m2#	m3#	m4#	m5#
1	3	3	34	-7	35	76	52
	3	6	39	50	41	19	26
	6	6	-3	-33	-3	27	9
	6	12	-22	-16	-21	-33	-30
2	3	3	-3	-33	-3	27	9
	3	6	-22	-16	-21	-33	-30
	6	6	33	44	35	14	20
	6	12	16	60	-2	67	47
3	3	3	-3	-33	-3	27	9
	3	6	38	49	40	18	25
	6	6	34	45	36	15	21
	6	12	15	59	-3	66	47

Note: *-B and S denotes panel width and cross wall spacing respectively, #-m1 to m5 denotes anchor method, ratio method, method 3A, 3B and 3C respectively.

6 CONCLUSIONS

In general, compared to Diaphragm wall modelled with soil element, Diaphragm wall modelled with plate in 2D usually gives larger deflection, higher shear force and higher bending moments. Maximum deflection predicted by method 3A and ratio method in 2D represents the lower and upper boundary. The deflection predicted by method 3A is generally closer to that by 3D than other methods. The deflection predicted by anchor method is also roughly close to that by 3D. For diaphragm wall with 3m to 6m cross wall spacing, method 3B and 3C gave deflections close to 3D. Ratio method usually gives much higher deflection than other methods.

Results showed that the force profiles predicted by 2D and 3D are usually similar except for the areas around base slab level. The maximum forces at three sections predicted by 3D are generally within the values predicted by 2D. At the center section of the Diaphragm wall, 2D gives shear force close to 3D with 3m panel and bending moment close to 3D with 6m panel. Results also indicated that the Diaphragm wall modelled as plate without panel cannot capture the cross wall effect on the forces while Diaphragm wall modelled as soil element or plate with panels can reflect the cross wall effect on the forces. However, the shear forces could be extremely high at cross wall location when plate with panels are adopted for modelling Diaphragm wall.



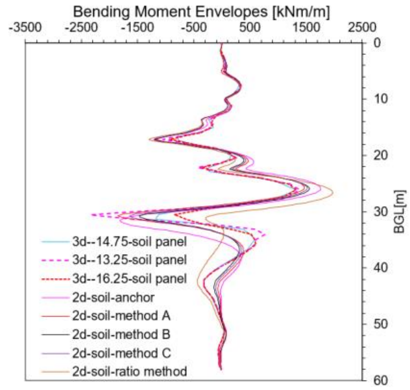


Figure 14. Comparison for forces of diaphragm wall with 6m cross wall spacing between 2D and 3D analysis for three sections.

7 REFERENCES

Kjell Karlsrud & Lars Andresen 2008. Design and performance of deep excavation in soft clays. *6th international conference on case histories in geotechnical engineering,* Arlington, VA. Paper No 12.

Hsieh H., Huang Y., Hsu W., and Ge L. 2017. On the system stiffness of deep excavation in soft clay. *Journal of GeoEngineering*, 12(1), 21-34.

Hsieh PG, Ou CY., Lin YL 2013. Three-dimensional numerical analysis of deep excavations with cross walls. *Acta Geotech* 8:33–48.

Hsieh PG, Ou CY, Shih C 2012. A simplified plane strain analysis of the lateral wall deflection for excavations with cross walls. *Can Geotech J* 49(10):1134–1146.

Lu, YT, Pittraro, G A, Tang C 2016. Cross wall supported deep excavation in Singapore-a back analysis with review of monitored performance. Proceedings of Underground Space 2016, 100-112.

Ou CY, Hsieh PG, Lin YL 2013. A parametric study of wall deflections in deep excavations with the installation of cross walls. *Computers and Geotechnics* 50, 55–65.

Ou, C. Y., Hsieh, P. G., and Lin, Y. L. 2011. Performance of excavations with cross walls. *J. Geotech. Geoenviron. Eng*., 137(1), 94–104.

Soccodato F.M., Tropeano G., Erbì E. and Pintus F. 2015. Numerical analyses of cross and buttress walls Effectiveness. *Proceedings of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development*, 4061-066.

Wu S., Ching J., and Ou C. 2015. Simplified Reliability-Based Design of Wall Displacements for Excavations in Soft Clay Considering Cross Walls. *J. Geotech. Geoenviron. Eng*., 2015, 141(3): 06014017.