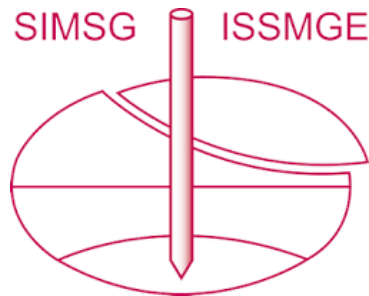


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The paper was published in the proceedings of the 7th International Young Geotechnical Engineers Conference and was edited by Brendan Scott. The conference was held from April 29th to May 1st 2022 in Sydney, Australia.

A study on the deflection behaviour of diaphragm walls supported laterally by cross walls in deep excavations

Une étude sur le comportement en déflexion des parois diaphragmes soutenues latéralement par des parois transversales dans les fouilles profondes.

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ABSTRACT: Previous studies have shown that cross walls are a highly effective lateral support system and can reduce the wall deflections considerably. A stiff system of thick diaphragm walls supported laterally by closely spaced cross walls is increasingly being adopted in Singapore for deep excavations with stringent wall deflection requirements. This paper examines the FEM analysis prediction and measured wall deflection behaviour of this system for a case study of an underground Mass Rapid Transit station excavation in Singapore. Various 2D and 3D FEM analyses using the Mohr Coulomb and Hardening Soil models are carried out to examine the effect of two of the main simplifications used in the current design practice that adopts 2D FEM analysis using Mohr Coulomb model, namely smearing the cross wall stiffness uniformly across its spacing and assuming clean contact joints at diaphragm wall-cross wall connections. The results obtained show that uniform smearing of cross wall stiffness can give reasonable wall deflection predictions for high stiffness systems. However, the clean contact joint assumption gives an overly stiff wall deflection response at the cross wall layer and consideration of soft contact joints can give better prediction of the actual deflection behaviour.

RÉSUMÉ : Des études précédentes ont montré que les murs transversaux sont un système de support latéral très efficace et peuvent réduire considérablement les déflexions des murs. Un système très rigide de murs diaphragmes, soutenues latéralement par des parois transversales rapprochées, est de plus en plus utilisé à Singapour pour les excavations profondes ayant des exigences strictes de déflexion des parois. Cet article examine la prédiction de l'analyse FEM et déflexion réelle comportement de ce système, pour une étude de cas d'une fouille souterraine d'une station de métro à Singapour. Diverses analyses méthode des éléments finis (FEM) 2D et 3D, utilisant le modèle de sol Mohr-Coulomb ainsi modèle de sol HSM sont effectuées pour examiner l'effet de deux des principales simplifications utilisées dans la pratique de conception actuelle qui adopte l'analyse FEM 2D à l'aide du modèle Mohr Coulomb, à savoir en étalant uniformément la rigidité de la paroi transversale sur son espacement et supposant des joints de contact propres au niveau des connexions paroi diaphragme-paroi transversale. Les résultats obtenus montrent qu'un étalement uniforme de la rigidité de la paroi transversale peut donner des prédictions raisonnables de la déflexion pour les systèmes à haute rigidité. Cependant, l'hypothèse d'un joint de contact propre donne une réponse de déflexion de paroi trop rigide au niveau de la couche paroi transversale et la prise en compte des joints de contact souples peut donner une meilleure prédiction du comportement de déflexion réel.

KEYWORDS: cross walls, diaphragm walls, lateral wall deflection, FEM analysis, deep excavations

1 INTRODUCTION

Deep excavations in soft clays in heavily urbanized cities like Singapore pose a design challenge as the wall deflections need to be controlled considerably to avoid damage to adjacent structures. Previous studies (Ou et al. 2006 & 2011) have shown that cross walls (CW) are a highly effective lateral support system and can reduce the wall deflections to about 0.07-0.12%H from the typical 0.2-0.5%H observed in typical braced excavations (where H is the excavation depth). Hence top-down excavations with thick diaphragm walls (DW) supported laterally by closely spaced cross walls are increasingly being adopted in Singapore for deep excavations near sensitive structures, especially in soft clays.

Cross walls are unreinforced concrete walls spanning across the excavation connecting the opposite diaphragm walls. They are constructed using trenching method similar to diaphragm wall construction. In Singapore, diaphragm wall panels are typically 0.8m to 1.5m thick and about 6m in length due to the commonly used diaphragm wall construction equipment and trench stability considerations. Each diaphragm wall panel is supported by a cross wall at the centre of the panel which leads to cross walls spacing of about 6m as well. Cross walls panels are typically 0.8 to 1m thick. Generally, a thick cross wall layer is provided under the base slab level which is usually the depth with the largest wall deflection for deep excavations in soft clay. Depending on the depth of the base slab, multiple thinner sacrificial cross wall layers which are progressively hacked during excavation may also be provided at intermediate levels.

2 CONSIDERATIONS IN ANALYSIS OF CROSS WALLS

2.1 *Methods for 2D modelling of 3D behaviour*

The deflection behaviour of diaphragm wall in this system is three dimensional (Ou et al. 2011, Erbi & Soccodato 2015) as cross walls create a corner effect similar to that observed at diaphragm wall corners (Finno et al. 2007). However, three-dimensional (3D) finite element method (FEM) analysis is time consuming and expensive. Two-dimensional (2D) FEM analysis is generally used in practice in Singapore to design this system.

Chua et al. (2009) summarized four common modelling methods for cross walls in 2D FEM analysis. These include modelling the cross walls as 1) solid elements using linear elastic model 2) solid elements using the Mohr Coulomb model 3) closely spaced fixed end anchors 4) closely spaced node-to-node anchors. In all these methods, the cross wall stiffness is smeared uniformly across the spacing between the cross walls.

2.2 *Effect of diaphragm wall deflection between cross walls*

Due to the corner effect created by the cross walls, the diaphragm wall lateral deflection is minimum at the cross walls and increases with distance from cross walls to the maximum at the mid-point between two cross walls (Ou et al. 2013). This mechanism can be likened to the deflection of an elastic continuous beam and hence depends primarily on the stiffness

of the beam (diaphragm wall) and the spacing between the supports (cross walls).

Hsieh et al. (2012) proposed an equivalent beam model to capture this behaviour in 2D FEM analysis. They confirmed with case studies that the method can give good prediction of the wall deflection. However, it is observed that the cross wall spacing in these reported case studies are about 25 to 50m, whereas in Singapore, cross walls are typically more closely spaced at about 6m. The deflection behaviour of this stiffer configuration is investigated using 3D analysis in this paper.

2.3 Effect of condition of diaphragm wall-cross wall joint

Poor contact of diaphragm wall-cross wall joints can increase wall deflections substantially (Hsiung et al. 2001). Hsieh et al. (2008) discussed different types of joints: 1) rigid T-shaped joint where the diaphragm wall is cast as a T-shaped panel and the cross wall is cast against the stem; 2) clean contact joint where a thin steel plate is cast together with diaphragm wall at the joint and stripped off before casting the cross wall; 3) soft contact joint where the joint is cleaned by scraping with hydraulic buckets and steel brushes. They concluded that the T-shaped is the most effective joint in limiting wall deflection. In soft contact joints, the slime thickness can increase with depth and can even reach 20~30cm thick which can neutralize the restraining effect of the cross walls (Ou et al. 2006).

In Singapore, steel brushes are commonly employed to clean the joints during the cross wall trenching. This might not be sufficient to ensure clean joints. Diaphragm wall surfaces are generally quite uneven which makes it difficult to clean the slime stuck at the recesses. Steel brushes have a tendency to rotate and to move away from the diaphragm wall due to buoyancy from the bentonite fluid and this can affect the cleaning. Figure 1 shows photographs of a typical steel brush used for cleaning the joints in a project in Singapore and the joints exposed during the excavation.

In analysis, the diaphragm wall-cross wall joint is typically assumed to be an “ideal” or clean contact. This assumption and the effect of a soft contact joint are studied in this paper by comparing analysis prediction of the wall deflection with measurements from in-wall inclinometers.



Figure 1 (a) & (b): Cleaning of diaphragm wall-cross wall joints using steel brush; (c) & (d): Diaphragm wall-Cross wall and Cross wall-Cross wall joints exposed during excavation

3 CASE STUDY

3.1 Project description

The project is a 28.5m deep underground Mass Rapid Transit station excavation. The layout and a cross-section of the excavation are shown respectively in Figure 2 and Figure 3 below. The width of excavation at the narrowest portion of the station is 28.2m and at the widest portion is 43.6m. The excavation is supported by 1.5m and 1.2m thick external diaphragm walls and 1.2m thick internal sacrificial diaphragm wall. The diaphragm wall panels are 6m in length and are laterally restrained by 1m thick cross-walls at 6m spacing. There are 2 layers of cross walls – a 10m thick layer below the final excavation level (lower under platform (LUP) slab) and a 2m thick layer below the upper under platform (UUP) slab. Top-down construction method was adopted, and the upper layer cross walls were removed progressively during excavation. The construction sequence is shown in Table 1.

The geology of the site comprises the Kallang Formation (KF) overlying the Old Alluvium (OA) formation. The KF is a Holocene sedimentary deposit that comprises deposits of marine, alluvial (granular – F1, cohesive – F2), littoral (B) and estuarine (E) origins. The marine clay (MC – divided into upper and lower marine clay – UMC and LMC) is its main constituent (DSTA 2009). The OA formation is known as the oldest drift deposit in Singapore, probably placed in the Plio-Pleistocene and is thought to represent a braided river system (Pitts 1984). The OA typically shows a weathered profile with depth (Chiam et al. 2003). It varies from silty or clayey sand to sandy clay or silt and is predominantly silty or clayey sand. The ground water table is 1m below the ground surface.

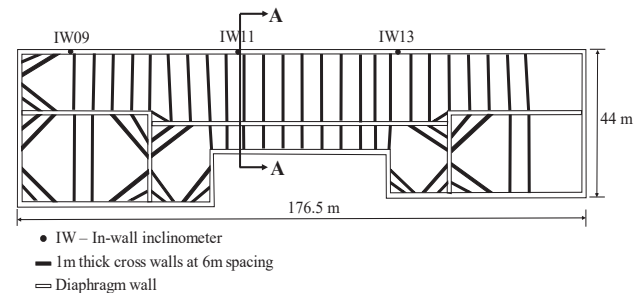


Figure 2. Layout plan of excavation and location of inclinometers

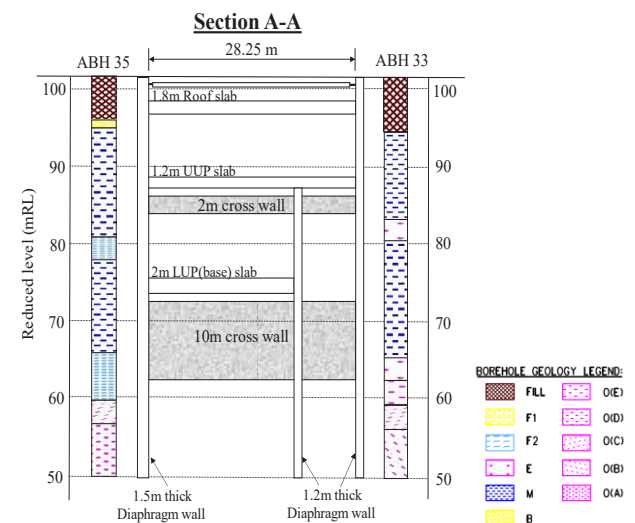


Figure 3. Excavation cross-section A-A and simplified soil profile

3.2 Measured wall deflection during construction

The actual deflection of the 1.5m thick diaphragm wall at the final excavation stage is measured at three in-wall inclinometers. The inclinometer locations are shown in Figure 2 and the deflection profiles presented in Figure 4 below. All these inclinometers show a similar overall smooth deflection profile. The maximum deflection is around 25 to 35mm, which is 0.09 to 0.12%H and occurs between the upper and lower cross walls. The deflection at the lower cross wall layer is about 5 to 25mm, which is about 25 to 80% of the maximum wall deflection and similar to the measurements reported in other papers.

Given that the walls are restrained from moving inwards by very rigid cross walls, a very marginal wall deflection equal to the elastic compression of the cross walls would be expected at lower cross wall layer. The higher deflections observed at this layer could be due to a) position of inclinometer with respect to the cross walls in plan i.e. diaphragm wall deflection like a beam between cross walls b) imperfect joints at diaphragm wall-cross wall and cross wall-cross wall contacts. These effects are studied in this paper using 2D and 3D FE analysis.

Table 1. Construction sequence

Stage	Description
Stage 1	Install diaphragm walls and cross walls
Stage 2	Excavate to base of strut at 99.5mRL
Stage 3	Install strut at 100.5mRL and preload
Stage 4	Excavate to soffit of roof slab at 96.2mRL and cast roof
Stage 5	Backfill to ground level and remove strut
Stage 7	Excavate to soffit of UUP slab at 86.65mRL
Stage 8	Cast UUP slab
Stage 9	Excavate to soffit of LUP slab at 73.15mRL (GL A-C)
Stage 10	Cast LUP slab (GL A - C)

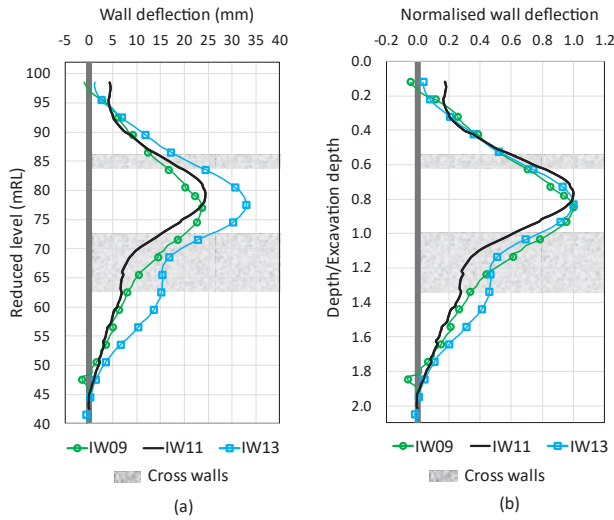


Figure 4 (a) Measured wall deflections; (b) normalized wall deflections of the 1.5m thick diaphragm wall

3.3 Finite element analysis

Cross section A-A presented in Figure 3 is used for the analyses in this study. The wall deflection measured by IW11 for the 1.5m thick diaphragm wall is used to make comparisons with analysis results.

2D and 3D FEM analyses are conducted using the FE program PLAXIS. The diaphragm walls and slabs are modelled as impermeable plates in both the 2D and 3D analyses, with the concrete stiffness reduced by 30% (0.7E) to account for

cracking. Cross walls are modelled explicitly as 1m thick linear elastic solid elements at 6m spacing in 3D analysis; and as linear elastic material clusters with the stiffness smeared uniformly across the cross wall spacing in 2D analysis. Installation of diaphragm walls, slab, struts and cross walls are modelled by “activating” the respective elements. Excavation is modelled by “deactivating” soil elements. Steady state seepage flow into the excavation is modelled at each excavation stage. Soil-structure interaction at the DW-CW interface is modelled by the standard interface elements in PLAXIS which considers the wall friction and adhesion.

The cross walls are modelled according to the actual constructed condition on site: G5 concrete is used to backfill the space between the upper and lower cross walls and Liquefied Soil Stabilizer (LSS) is backfilled above the upper cross wall layer. Parameters used in the model are summarized in Table 2 to Table 4.

Table 2. Input structural parameters for station structures

Element	2D		3D
	Axial stiffness (0.7EA) *10 ⁶ kN/m	Bending stiffness (0.7EI) *10 ⁶ kNm ² /m	Stiffness (0.7E) *10 ⁶ kPa
1.5m diaphragm wall	33.18	6.22	
1.2m diaphragm wall	26.54	3.18	
1m diaphragm wall	-	-	22.12
1.8m Roof slab	39.84	10.76	
1.2m UUP slab	26.56	3.19	
2m LUP (base) slab	44.27	14.76	

Table 3. Input structural parameters for cross walls

Material	2D		3D
	Stiffness (E) *10 ⁶ kPa	Stiffness (E) *10 ⁶ kPa	
Cross walls (G30 concrete)	4.56	27.38	
G5 concrete (between cross wall layers)	1.86	11.18	
LSS backfill (above cross walls)	0.0467	0.28	

Table 4. Hardening Soil model parameters

Soil	c' (kPa)	φ' (°)	c _u (kPa) ¹	E ₅₀ ^{ref} (MPa) ^{2,3}	m
Fill	0	30		12	
Beach sand (B)	0	30		12	
OA(D) (10<N<30)	1	32		25	
OA(C) (30<N<50)	5	35	-	66.67	0.5
OA(B) (50<N<100)	5	35		120	
OA(A) (N>100)	10	35		166.7	
UMC (>68mRL)			0.33.(161.67-z)	0.25c _u	
LMC (<68mRL)			0.67.(120-z) 4.(77-z)	0.25c _u	1
F2			1.25.(120-z)	0.25c _u	
E			0.75.(126.67-z)	0.21c _u	

¹ z: elevation in mRL

² E₅₀^{ref} = E_{oed}^{ref} and E_{ur}^{ref} = 3 E₅₀^{ref}

³ These values are also adopted for E' of Mohr Coulomb model

In the 3D analysis, two cases with different diaphragm wall thicknesses supported by cross walls at 6m spacing are analyzed to investigate the effect of diaphragm wall deflecting between cross walls. The diaphragm wall-cross wall (DW-CW) contact joints are assumed to be clean joints. Mohr Coulomb model is used.

In the 2D analysis, four cases are analyzed – DW-CW clean contact joint (base) case and three cases that adopt different methods to model soft contact joints to investigate the effect of diaphragm wall-cross wall joint condition. In all the three methods, the soft contact joints are simulated only at the lower cross wall layer in view of its thickness and past studies (Hsieh et al. 2008) that suggest that the slime thickness increases with depth. Figure 5 illustrates the FE modelling for these three methods. A summary of the FEM analyses conducted for this study and their objectives is presented in Table 5.

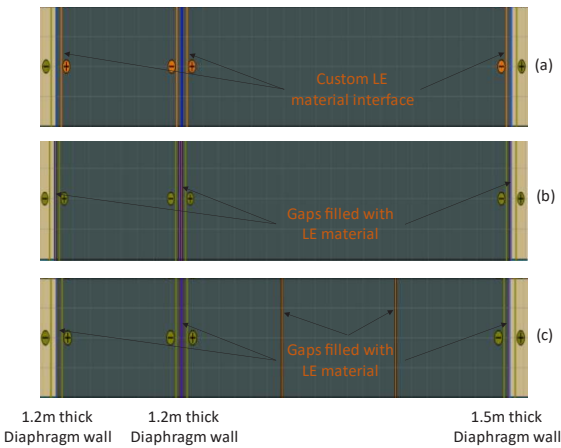


Figure 5. Illustration of FE modelling of soft contact joints at lower cross wall in (a) Method 1 (b) Method 2 and (c) Method 3

Table 5. Summary of FEM analysis cases

Type	Objective of study	Contact Joint condition	Case
3D	Deflection between cross walls	Clean	Base case
		Clean	Reduced stiffness case – 1m thick diaphragm wall
		Clean	Base case
2D	Effect of soft contact joints	Soft	Method 1 – Soft contact material properties specified for DW-CW interfaces
		Soft	Method 2 – “Gaps” filled by soft contact material modelled only at DW-CW joints
		Soft	Method 3 – “Gaps” filled by soft contact material modelled at DW-CW and CW-CW joints

3.4 3D Analysis results - deflection between cross walls

Figure 6 plots the deflection of the 1.5m thick diaphragm wall (base case) at the cross wall location and mid-point between cross walls. Both profiles are almost identical and show that there is little deflection at the cross wall layer, which does not agree well with the measured deflection.

Figure 7 compares the diaphragm wall deflection between cross walls for the base case of 1.5m thick diaphragm wall and reduced stiffness case of 1m thick diaphragm wall in plan view at the elevation of the top of lower cross wall (73mRL). The diaphragm wall undeflected position is indicated as a solid line at $y=0$. Figure 7 indicates that for the very stiff 1.5m thick diaphragm wall, there is negligible difference (around 1mm) in

the deflection at the cross wall location and between the cross walls; for 1m thick diaphragm wall, this difference increases to about 3mm.

These 3D analyses confirm that the effect of diaphragm wall deflecting between cross walls depends upon the stiffness of the DW-CW support system. The close cross wall spacing contributes to high diaphragm wall stiffness between the cross walls and results in load transfer primarily along the depth of the diaphragm wall (Figure 6) instead of along the length of the diaphragm wall on plan (Figure 7). Therefore, the simplification of uniformly smearing cross wall stiffness across the cross wall spacing in 2D FEM analysis can give reasonable results for the wall deflection for the high stiffness DW-CW systems that are commonly adopted in Singapore.

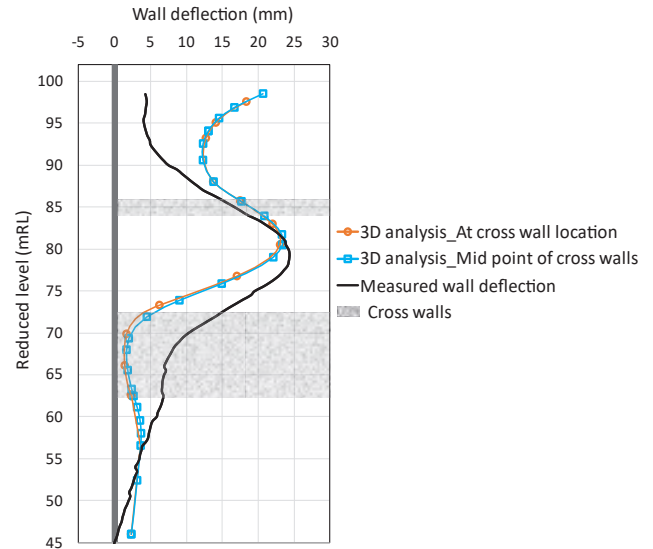


Figure 6. Diaphragm wall deflections from 3D analysis for base case

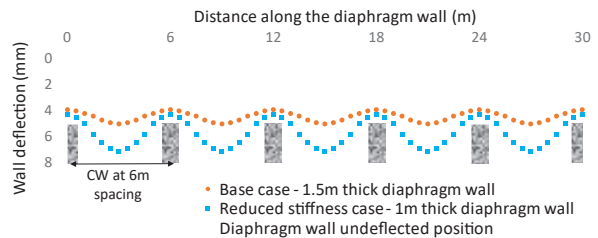


Figure 7. 3D analysis results for base case and reduced stiffness case - deflection plan view at top of lower cross wall (73mRL)

3.5 2D Analysis results

3.5.1 Base case - Diaphragm wall-Cross wall clean contact joint

The 2D analysis base case deflection profiles in Figure 8 are similar to the 3D analysis results in Figure 6. The results suggest that if the diaphragm wall-cross wall joint is assumed to be a clean contact, then there is negligible wall deflection at the depth of the lower cross wall layer and a sharp reduction in wall deflection just above it. This overly stiff behavior is different from the smooth wall deflection profiles measured which show considerable wall deflection at the cross wall layer.

Figure 8 also shows that the Hardening Soil (HS) model gives slightly better prediction of the deflection profile compared to the Mohr Coulomb (MC) model. Therefore, all 2D analyses presented in the subsequent sections use the HS model.

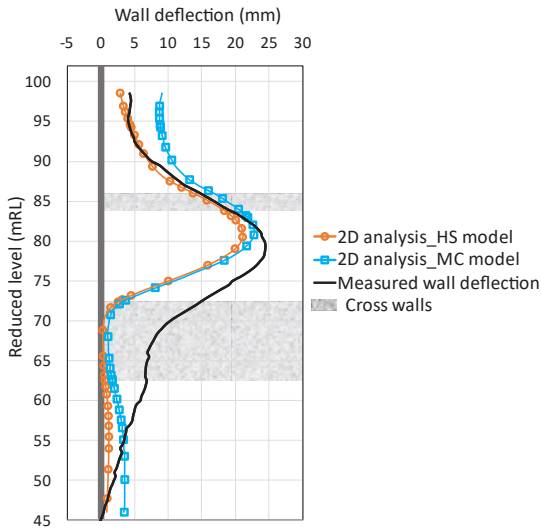


Figure 8. Measured wall deflection and predicted wall deflection from 2D analysis assuming clean contact joint condition

3.5.2 Method 1 - Soft contact joints modelled using soft contact material interface properties at DW-CW joints

Method 1 is the simplest of the three methods used in this paper to model the soft contact joints. In this method, soft contact material properties are assigned to the interfaces at the DW-CW joints. The soft contact material is modelled as a linear elastic material with the E value varied between 2MPa and 10MPa to simulate the slime struck at these joints.

Results plotted in Figure 9 show that the prediction of the deflection profile is better than the base case (clean contact joint). The maximum deflection agrees well with the measurement and is not sensitive to the E values used. Although the deflection profile at the cross wall layer is not closely captured, this method is a simple way for designers to account for soft contact joints in their analyses.

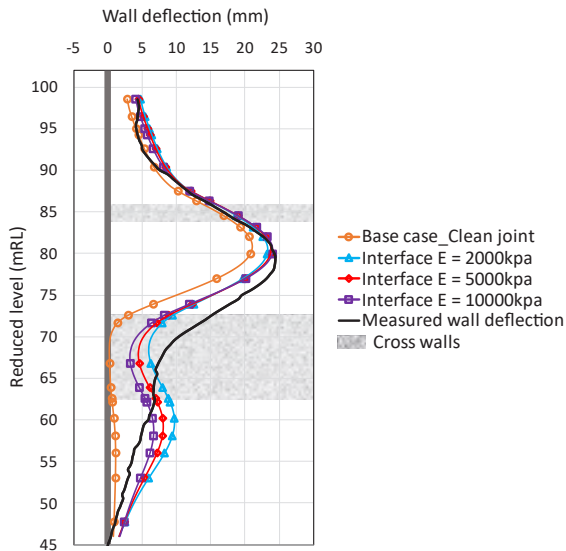


Figure 9. Measured wall deflection and deflection from 2D analysis using soft contact material for DW-CW interface

3.5.3 Method 2 - Soft contact joints modelled using “gaps” at DW-CW joints only

Method 2 uses “gaps” instead of interfaces to model the soft contact joints. “Gaps” filled with a low stiffness (E) linear elastic material are introduced at the DW-CW joints. Two gap widths are modelled – 50mm and 100mm; and the E values of the gap material are varied.

Results plotted in Figure 10 show that the predicted wall deflection is close to the results of Method 1. The maximum deflection agrees with the measurement and is not sensitive to the modulus of the “gap” material. Method 2 also does not capture closely the smooth deflection profile measured within the cross wall layer.

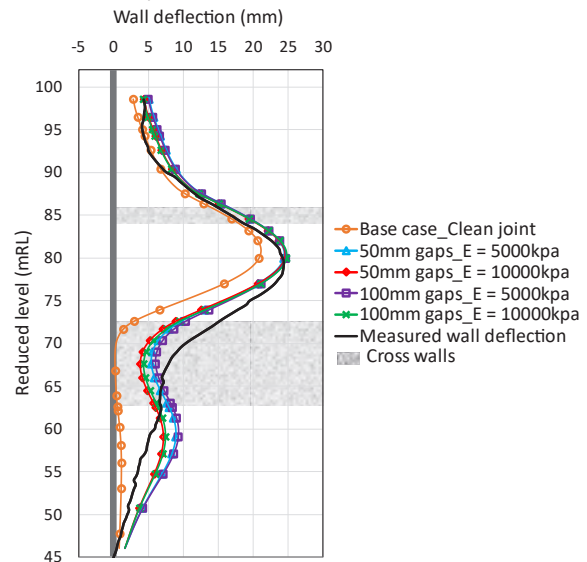


Figure 10. Measured wall deflection and deflection from 2D analysis using gaps to model soft contact joint condition at DW-CW joint only

3.5.4 Method 3 -Soft contact joints modelled using “gaps” at DW-CW and CW-CW joints

Results of Method 1 and Method 2 predict overly stiff deflection behaviour in the cross wall layer compared to the measured wall deflection. This suggests that modelling soft contact joints at DW-CW joints only partially captures the deflection response in the cross wall layer.

It is postulated that soft joints not only occur at DW-CW interfaces. “Imperfect” contacts can also occur between adjacent cross wall panels. This could arise from slime being stuck on uneven surfaces or gaps due to lack-of-fit between the ends of adjacent cross wall panels. Such effects may cause the cross walls to behave differently from the solid elements restraining diaphragm walls as assumed in 2D and 3D analysis.

Method 3 assumes that the behaviour of “imperfect” CW-CW joints can be modelled as soft contact joints. The soft contact joints are modelled similar to Method 2, by using “gaps” filled with a low stiffness (E) linear elastic material. Two gap widths are modelled – 50mm and 100mm; and the E values of the gap material are varied.

Results of the wall deflection are presented in Figure 11. Both cases give better agreement with the measured wall deflection profile than the base case, Method 1 and Method 2. The case of the 50mm gaps with 5MPa gap material and 100mm gaps with 10MPa gap material give the closest agreement with measured wall deflection. The maximum deflection is not sensitive to the E values.

These results suggest that consideration of “imperfect” CW-CW joints can give better prediction of the wall deflection profile.

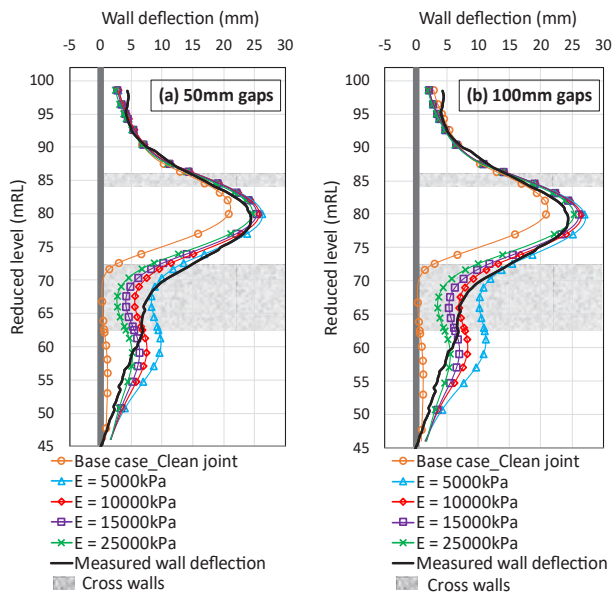


Figure 11. Measured wall deflection and deflection from 2D analysis using gaps to model soft contact joints at DW-CW joint and CW-CW joint (a) 50mm “gap” width (b) 100mm “gap” width

4 CONCLUSIONS

This paper examines the lateral wall deflection behaviour of diaphragm wall supported by cross walls. It studies the effect of two main assumptions used in the current design practice that adopts 2D FEM analysis to model this system - uniformly smearing cross wall stiffness across the spacing between the cross walls and assuming diaphragm wall-cross wall contacts to be clean contact joints. 2D and 3D analysis results show that:

- 1) Diaphragm wall deflection as a beam between cross walls is not significant for the high stiffness systems with thick diaphragm walls and closely spaced cross walls that are commonly adopted in Singapore. Hence 2D FEM analysis with uniform smearing of cross wall stiffness across its spacing can give reasonable wall deflection predictions.
- 2) The assumption of diaphragm wall-cross wall contact joints condition has a large influence in the predicted wall deflection profile.
- 3) Consideration of diaphragm wall-cross wall soft contact joints at the deeper cross walls can give wall deflection predictions that agree well with measured wall deflections.
- 4) It is postulated that “imperfect” contacts can occur between adjacent cross wall panels as well. By assuming soft contact joints between adjacent cross wall panels in addition to the diaphragm wall-cross wall soft contact joints, close agreement between the analysis deflection and the measured wall deflections can be obtained.

5 LIMITATIONS AND FURTHER STUDIES

It is recognized that other factors can affect the back analysis conducted, such as the constitutive models, soil parameters and groundwater flow assumptions.

Sensitivity analyses were carried out to investigate some of these factors but couldn't be presented here due to space constraint. MC model predicted more heave and the HS model gave better prediction of the wall deflection profile (Figure 8). The predicted deflection is not sensitive to variation of soil stiffness values within the range of values used in local practice.

Idealization of the 3D behavior of the diaphragm wall-cross wall system in a 2D analysis has limitations. In this case study, soils between the cross walls are clay and are modelled as undrained materials. Where soils of higher permeability (sands) are present between cross walls, the actual ground water flow behavior might not be realistically modelled in a 2D analysis.

Apart from the presented methods of modelling imperfect contact joints, other approaches may be investigated, such as reducing the overall stiffness of the cross wall to a percentage of its original stiffness. Further case studies of excavations supported by diaphragm walls with cross walls in different soil conditions using 3D and 2D numerical analysis could be considered to investigate the effect of above discussed factors.

6 ACKNOWLEDGEMENTS

The authors sincerely thank Land Transport Authority Singapore for allowing the use of project data and monitoring results for this paper.

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