EFFECTS OF JOINT DETAILS ON THE BEHAVIOR OF CROSS WALLS

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ABSTRACT

Inclinometer readings of a deep excavation project are presented in this paper to show that joint details could have significant effects on the behavior of cross/buttress walls. It is found that both T-shaped and clean contact joints are capable of limiting the lateral displacement of perimeter diaphragm wall to less than 10 mm in this case. On the other hand, a soft contact joint nullifies the restraining effect of buttress wall, resulting in a maximum wall displacement of about 30 mm for this 12 m deep excavation.

Key words: Diaphragm wall, deep excavation, wall displacement, construction joint.

1. INTRODUCTION

Cross/buttress walls are often used in deep excavation projects in Taiwan urban area to reduce diaphragm wall displacement and the associated ground movement. Cross/buttress walls provide additional lateral supports to resist the inward movement of perimeter diaphragm wall during excavation. Significant reductions in diaphragm wall displacements were reported in several deep excavation projects with the use of cross/buttress walls (Hwang, *et al.*, 2007a; Ou, *et al*., 2006). One major advantage of using cross/buttress walls in a deep excavation project is they can be constructed at the same time with the perimeter diaphragm wall. In practice, there is virtually no difference between the construction technique of cross/buttress wall and the perimeter diaphragm wall. Efforts to mobilize construction crew and equipments can therefore be kept to a minimal. This construction advantage is considered beneficially in terms of overall construction schedule and cost.

Often overlooked is one single construction detail that may eventually govern the behavior of cross/buttress wall in subsequent excavation. Perimeter diaphragm wall and cross/buttress wall are constructed panel by panel, and a structural joint between adjacent panels is required to ensure that panels are well connected (Lee, *et al.*, 1991). A well constructed joint not only provides structural rigidity between adjacent panels, but also serves as a groundwater cutoff device. However, the joint detail between perimeter diaphragm wall and cross/buttress wall is not always a major concern for contractor. Construction details are often neglected that eventually results in a weak connection between perimeter diaphragm wall and cross/buttress wall. In worst conditions, slimes or soft infill up to 30 cm in thickness may exist at the joint between perimeter diaphragm wall and cross/buttress wall, which may render the cross/buttress wall useless in providing resistance against the lateral inward movement of perimeter diaphragm wall.

This paper presents a deep excavation case with an extensive use of cross/buttress walls. Three types of joints were adopted in this case to connect the perimeter diaphragm wall and cross/buttress walls. Displacement curves of the perimeter diaphragm wall are provided in this paper to illustrate the effects of joint rigidity on the excavation behavior of cross/buttress walls.

2. PROJECT DESCRIPTION

The DTT high rise residential building is located in Da-Chi District of Taipei City, which sits geographically at the northern bank of Keelung River. The construction site occupies an area of about 2800 m^2, and the footprint of basement is about 2000 m^2. A 14-story residential building (DTT building) accompanied by a 3-level basement for underground parking is to be built. The excavation depth of the 3-level basement is about 12 m. Diaphragm wall 0.7 m in thickness and 27 m in depth is adopted as the retaining wall for basement excavation. In addition, 5 levels of internal bracings were used as excavation support. Nearby buildings are at least 10 m away from the construction site. Plan and profile of the retaining system are shown in Figs. 1 and 2, respectively. Details of the internal bracing system are outlined in Table 1. Excavation sequence is listed in Table 2.

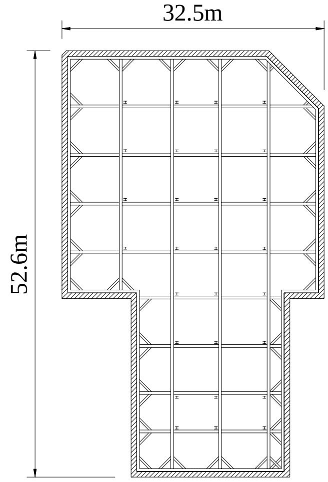

Fig. 1 Plan layout of retaining system

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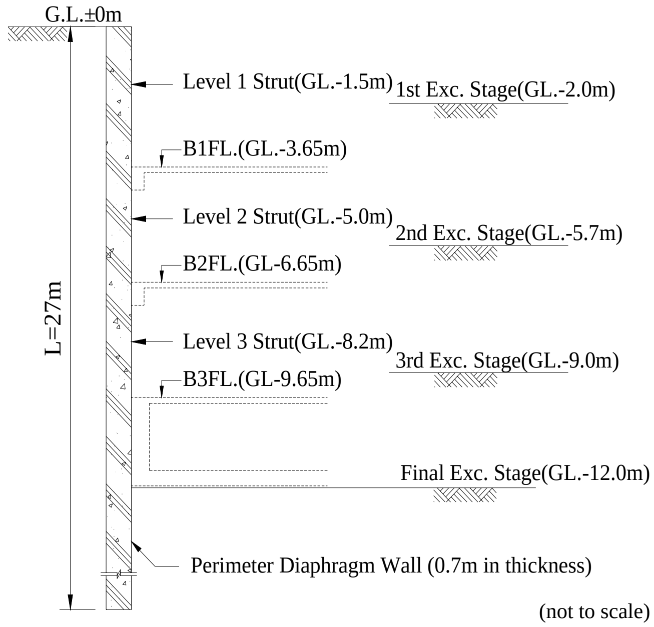

Fig. 2 Profile of retaining system

Table 1 Details of internal bracing system

Level	Strut dimension (mm)	Preload (kN)	Depth
1	H350 × 350 × 12 × 19	400	GL.–1.5 m
2	2 × H350 × 350 × 12 × 19	2 × 500	GL.–5.0 m
3	2 × H350 × 350 × 12 × 19	2 × 500	GL.–8.2 m

Table 2 Excavation sequence

Stage	Construction activities
1	Excavate to GL.–2.0 m and install level 1 strut
2	Excavate to GL.–5.7 m and install level 2 strut
3	Excavate to GL.–9.0 m and install level 3 strut
4	Excavate to GL.–12 m (final exc. stage)

A raft foundation system consisting of a base slab and ground beams with a total thickness of 2.15 m was cast together with the 0.2 m thick B3 floor slab to support the superstructure. In fear that long-term differential settlement induced by a thick clayey deposit beneath the foundation level can be detrimental to the integrity of structure, the raft foundation is strengthened by 6 rows of 0.7 m thick cross walls beneath the base slab (GL.–12 m) to a depth of 23 m (GL.–23 m). These cross walls serve as additional vertical supports to the raft foundation that increases the overall stiffness of foundation system to resist long-term differential settlement. In order to optimize the effects of cross walls, they are positioned directly under the columns as indicated in Fig. 3. The reason for cross walls running in the east-west direction rather than in the north-south direction is simply the design engineer's choice. These cross walls were cast from GL.–23 m up to GL.–2 m with reinforced concrete below the foundation level (GL.–12 m) and lean concrete above the foundation level. Cross walls were chipped away stage by stage until excavation of basement reached the final depth. Reinforcement embedded in cross walls were then exposed and cast together with the base slab to form an integral foundation system.

A beneficial side effect of the cross walls is that they provide additional lateral supports which help in reducing the displacement of diaphragm wall to a magnitude much lower than expected. It is obvious from the layout shown in Fig. 3 that cross walls also act like internal bracing in the east-west direction. Though cross walls were demolished and removed along with the soil in staged excavation, the cross walls beneath the excavation level remained intact and behaved as semi-rigid underground lateral support that refrain the inward movements of diaphragm wall in the east-west direction. Perimeter diaphragm wall on the south side is without the support of cross walls, which represents wall behavior under normal condition. A buttress wall about 7.5 m in length is also constructed. This buttress wall adjoins one of the cross wall and the perimeter diaphragm wall on the north side. It is believed that this buttress wall provides lateral support to a lesser extent than the cross walls, and perimeter diaphragm wall on the north side is expected to deform a lot more than the perimeter diaphragm walls on the east and west sides.

Four inclinometer casings, SI-1 to SI-4, were installed within the perimeter diaphragm wall to monitor the wall displacement. Locations of inclinometer casings are also shown in Fig. 3. Readings of SI-2 and SI-4 are believed to represent the excavation behavior of perimeter diaphragm wall that is markedly affected by the presence of cross walls. On the other hand, readings of SI-3 represent the effect of buttress wall on the perimeter wall. SI-1 is not affected either by cross walls or buttress wall, and its readings can be regarded as a base line for comparison.

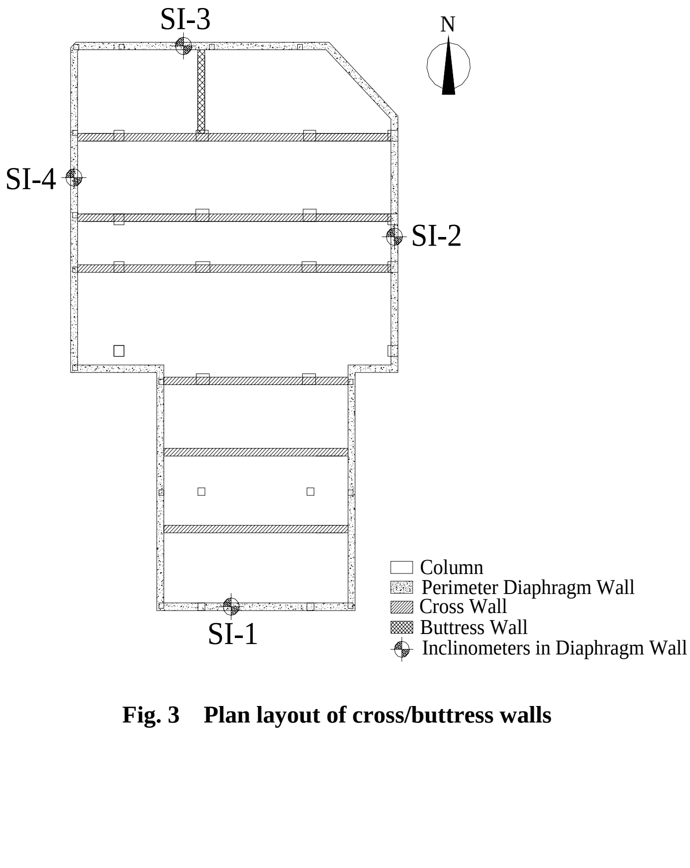

Fig. 3 Plan layout of cross/buttress walls

3. SOIL CONDITIONS

Except for a 3.5 m thick surface urban fill, top 39 m of the project site (GL.0 m ~ GL.–39 m) consists mainly of very soft to stiff silty clay with SPT N values ranging from 2 to 10. The SPT N values of this thick clayey layer increase with depth in general, and the average SPT N value is about 4. Underlying the thick silty clay deposit is a medium dense to dense silty sand layer with an average SPT N value of about 31. Thickness of this sandy layer is about 6 m (GL.–39 m ~ GL.–45 m). A very stiff silty clay layer about 9 m (GL.–45 m ~ GL.–54 m) in thickness is found beneath the sandy layer, followed by a very dense layer of silty sand to the termination depth of boreholes (GL.–54 m ~ GL.–70 m). Engineering and physical properties of individual layers are listed in Table 3 for reference, in which γ_t is the total unit weight; w_n is the natural water content; s_u is the undrained shear strength; $\bar{c}$ is the effective cohesion; $\bar{\phi}$ is the effective friction angle; C_c is the compression index; C_r is the recompression index; and E is the Young's modulus. It is noted that values listed in Table 3 are based upon either laboratory test results or empirical values in this general area. The perched ground water table is at about 2 m below surface. Piezometer installed at GL.–40 m indicated that pore water pressure at depth is about hydrostatic.

It is apparent that the thick silty clay layer found between GL.–3.5 m and GL.–39 m dominates the excavation behavior of this construction project. Figure 4 is a photo of the silty clay near the final excavation depth. Laboratory test results reveal that the average values of natural water content, liquid limit and plastic limit are 39%, 41%, and 17%, respectively. Roughly speaking, the undrained shear strength (s_u) of this thick cohesive layer increases with depth, and is empirically related to the effective overburden pressure (σ'_v) via the following equation:

$$s_u = 0.22 \sim 0.25\,\sigma'_v \qquad (1)$$

4. CONSTRUCTION DETAILS OF DIAPHRAGM WALLS

Cross walls were constructed in the same way as the perimeter diaphragm wall. The difference is that the diaphragm wall is heavily reinforced from top to bottom while cross wall is reinforced only for sections underneath the foundation level. A watertight overlapped joint (Ou, *et al.*, 1991) is adopted in the construction of perimeter diaphragm wall, which provides rigid connection between primary and secondary panels that allows the diaphragm wall to behave as an integral plate. Though in design practice, diaphragm wall is often modeled structurally as a one-dimensional beam rather than a two-way plate, and the effect of overlapped joint is routinely overlooked. Cross wall is also constructed panel by panel with overlapped joints in this case, ensuring that the cross wall is an integral element in resisting axial loadings in both vertical and horizontal directions. Panel layout of the perimeter diaphragm wall and cross walls is shown in Fig. 5. In total, there are 41 primary panels, 36 secondary panels and 2 primary-secondary panels. Layout of panels can be critical to the selection of joints between perimeter diaphragm wall and cross/buttress wall. Details regarding panel layout can be found in references (Lee, *et al.*, 1991; Xanthakos, 1994). T-shaped secondary panels were used at most of the junctions between perimeter diaphragm wall and cross walls. These T-shaped panels ensure a rigid connection between perimeter diaphragm wall and cross walls. A schematic diagram of the rigid T-shaped joint is shown in Fig. 6.

Two particular junctions on the east side, which are located near SI-2 as shown in Fig. 5, are constructed without the use of T-shaped panels. The perimeter diaphragm wall and cross walls at this junction were separately constructed with flat panels. A thin steel plate was placed at these junctions to serve as the joint between perimeter diaphragm wall and cross wall. This thin steel plate was striped off the surface of the perimeter diaphragm wall before casting the adjacent cross wall panel. Removing of the thin steel plate ensures a clean contact between the perimeter diaphragm wall and cross wall, that allows the cross wall to act as a competent support to resist the lateral displacement of perimeter diaphragm wall. This type of joint is considered as a clean contact joint (Fig. 7).

As for the buttress wall on the north side, since its main structural function is to provide vertical support to the superstructure, cares were not exercised on ensuring a rigid or clean contact at the junction between buttress wall and perimeter diaphragm wall. Though construction crew tried their best to scratch off soft clay at the junction with hydraulic bucket, it is however speculated that slime at this junction was not thoroughly cleaned. This type of joint is regarded as a soft contact joint (Fig. 8).

In summary, three types of joints were used in this project at the junctions between perimeter diaphragm wall and cross/buttress walls. Among these three types of joints, T-shaped joint provides a very rigid connection between perimeter diaphragm wall and cross wall. A clean contact joint is less rigid than a T-shaped joint, but can still be regarded as a competent lateral support to the perimeter diaphragm wall. A soft contact joint is thought to be the least effective in restraining the lateral movement of perimeter diaphragm wall.

Table 3 Engineering and physical properties of soil layers

Layer	Depth (m)	Soil type	SPT-N	γ_t (kN/m^3)	w_n (%)	s_u (kN/m^2)	$\bar{c}$ (kN/m^2)	$\bar{\phi}$ (deg.)	C_c	C_r	E (MPa)
I	0.0 ~ 3.5	Fill	11 ~ > 50	–	–	–	–	–	–	–	–
II	3.5 ~ 39	CL	2 ~ 10 (4)	18.0	39	20 ~ 80	0.0	26 ~ 30	0.35	0.04	20 ~ 40
III	39 ~ 45	SM	27 ~ 42 (31)	18.5	22	–	0.0	32	–	–	60
IV	45 ~ 54	CL	14 ~ 31 (22)	19.0	31	130	0.0	32	0.2	0.02	65
V	54 ~ 70	SM	33 ~ > 50 (43)	19.5	23	–	0.0	35	–	–	86

Note：Numbers in parentheses are average values.

Fig. 4 Silty clay of the construction site at GL.–10 m

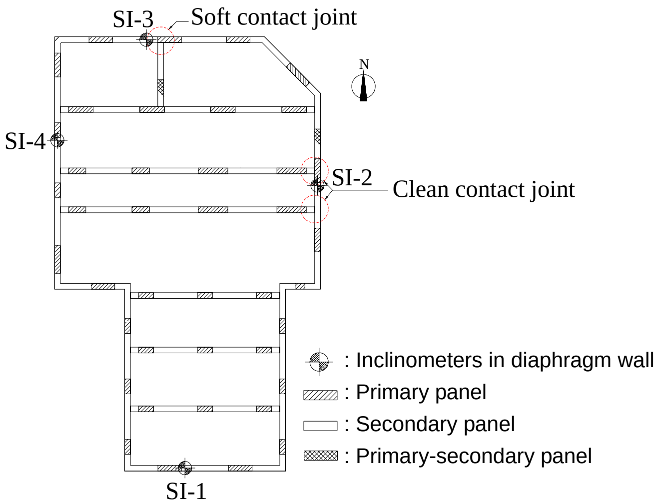

Fig. 5 Panel layout of perimeter and cross walls

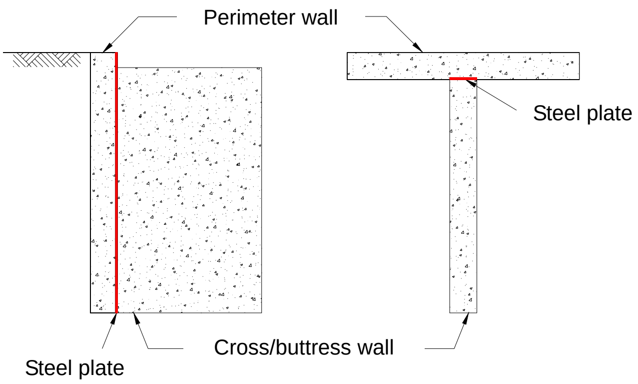

Fig. 7 Schematic diagram of a clean contact joint

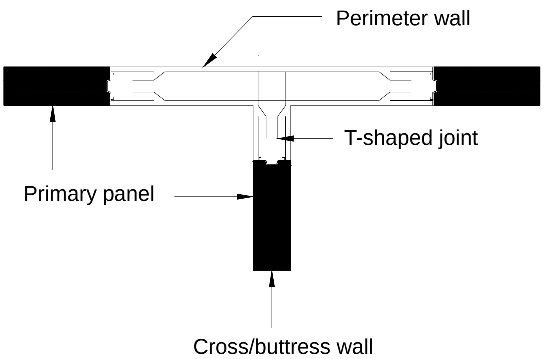

Fig. 6 Schematic diagram of a rigid T-shaped joint

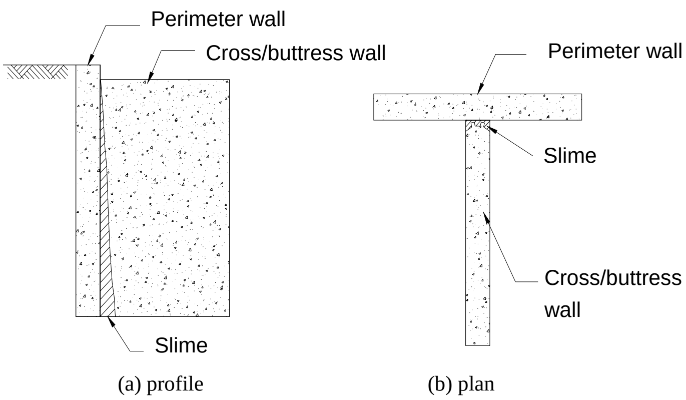

Fig. 8 Schematic diagram of a soft contact joint

5. READINGS OF INCLINOMETER CASINGS

Three of the four Inclinometer casings, SI-2 to 4, were placed at locations (Fig. 3) that could reveal the excavation behavior of these different joints. The inclinometer casing SI-1, which is not affected by either cross wall or buttress wall, serves as a basis for comparison. Monitoring results on the displacement of perimeter diaphragm wall of the final excavation stage are presented in Fig. 9 and Table 4. The maximum readings are 30.81 mm, 9.52 mm, 33.35 mm and –1.58 mm for inclinometer casings SI-1, SI-2, SI-3, and SI-4, respectively.

As shown in Fig. 9, the perimeter diaphragm wall on the east and west sides are of limited displacements, SI-2 and SI-4 both exhibit maximum lateral movements of less than 10 mm. The inclinometer casing installed near the rigid T-shaped joints (SI-4) shows a negligible movement of –1.58 mm, which is probably within the measurement tolerance of the inclinometer sensor. As for SI-1 and SI-3, the displacement curves are typical of a deep excavation in soft clay. The maximum wall displacements on the south and north sides are about 2.7% of the basement excavation depth, which are also typical for deep excavation projects in Taipei area (Woo and Moh, 1990).

It is noted that the displacement curves shown in Fig. 9 are uncorrected against toe displacement. A correction procedure outlined by Hwang, *et al.* (2007b) can be followed if desired, though it is speculated that the readings of SI-2 and SI-4 need no corrections since the perimeter diaphragm wall on the east and west sides are adequately restrained by the cross walls.

Table 4 Maximum displacements of perimeter diaphragm wall (final excavation stage)

Inclinometer	Max. displacement (mm)	Depth of max. displacement (m)	Joint type
SI-1	30.81	GL.–14.5 m	–
SI-2	9.52	GL.–6.0 m	Clean contact
SI-3	33.35	GL.–12 m	Soft contact
SI-4	–1.58	GL.–8.0 m	Rigid T-shaped

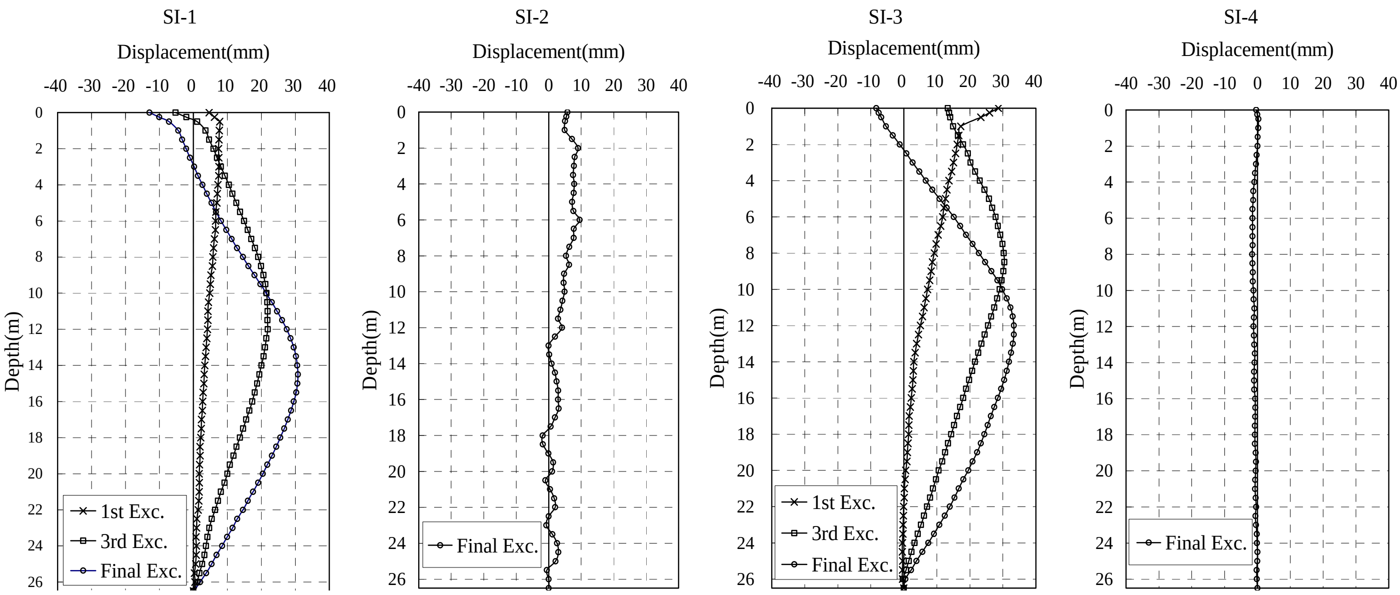

Fig. 9 Displacement curves of perimeter diaphragm wall (1st, 3rd and final excavation stages for SI-1, 3)

6. DISCUSSIONS

As shown in Fig. 9, it appears that cross walls are very effective in restraining the lateral displacement of perimeter diaphragm wall. A maximum displacement of less than 10 mm was observed for inclinometer casings installed near the junctions of cross walls and perimeter diaphragm wall. Comparatively speaking, the rigid T-shaped joint is more effective than the clean contact joint in limiting wall displacement. The inclinometer casing installed near the clean contact joint (SI-2) exhibits a maximum wall displacement of about 10 mm, compared to that of an insignificant amount of –1.58 mm near the rigid T-shaped joint (SI-4). Since the rigidity of a T-shaped joint is apparently much higher than that of a clean contact joint, it is tempting to conclude that joint rigidity governs the overall behavior of cross wall in limiting the displacement of perimeter diaphragm wall. However, considering that construction details may also have major impacts on the displacement of retaining wall (Blackburn and Finno, 2007), it is not appropriate to jump to this conclusion at this moment.

On the other hand, the displacement curves of SI-1 and SI-3 are nearly identical. SI-1 is free of the effects of cross/buttress walls while SI-3 is under the influence of a buttress wall with a soft contact joint. Judging from the displacement curves shown in Fig. 9, it appears that the buttress wall has no effect in limiting the displacement of diaphragm wall whatsoever. Soft clay or slime trapped in between the perimeter diaphragm wall and buttress wall resulted in a soft contact joint, and this soft contact joint may be the main culprit that nullifies the restraining effects of buttress wall. It is imperative that either a rigid T-shaped joint or a clean contact joint be used to ensure the effectiveness of cross/buttress walls.

7. CONCLUSIONS

1. It is found in this case history that cross walls are effective in restraining the lateral displacement of perimeter diaphragm wall, provided that either a T-shaped or clean contact joint is adopted at the junction between perimeter diaphragm wall and cross walls.
2. It is not conclusive that a T-shaped joint is better than a clean contact joint in limiting wall displacement, though there is a distinct difference in the joint rigidity. A soft contact joint is least desirable because it neutralizes the effects of cross/buttress walls.
3. The authors did not attempt to provide in-depth interpretation on the displacement characteristics of diaphragm wall in this paper, and it is advised that advanced numerical tools be adopted to further delineate the behavior of cross walls.

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