CASE RECORD OF AN EXCAVATION WITH CROSS WALLS AND BUTTRESS WALLS

C. Y. Ou[1], Y. L. Lin[2], P. G. Hsieh[3]

ABSTRACT

Cross walls and buttress walls are common construction methods used in Taiwan for protection of adjacent buildings during excavation. It is generally recognized, but not verified, that both methods have good effects in reducing wall movement and ground settlement. However, the design methodologies for cross walls and buttress walls in excavations are still highly empirical because of lack of case histories with good monitoring results. In this study, a case history, with a well documented construction sequence, of good construction quality, and with good monitoring results, is presented. According to the monitoring results, the wall movement and ground settlement, at the cross wall or near it, can be reduced significantly. The effect of buttress walls in reducing wall movement or ground settlement depends on the mobilized shear strength or frictional resistance, *i.e.*, lateral movement of the retaining wall. If the excavation causes large wall movement, buttress walls should have a certain effect in reducing wall movement or ground settlement. However, buttress walls may have only a slight effect in reducing wall movement and ground settlement when the retaining wall shows only a small movement.

Key words: Deep excavation, ground settlement, wall movement, cross wall, buttress wall.

1. INTRODUCTION

The huge population in urban areas due to economic development has caused situations such as much denser buildings and deeper foundation excavations than ever before. Construction disasters and adjacent building damage often occur due to ground settlement as a consequence of deep excavation, which not only affects construction progress, but also increases public nuisance. The protection of adjacent buildings has become a major concern for designers and contractors of deep excavations. It is thus an important hazard prevention task in geotechnical engineering to conduct a study on protection of adjacent buildings when deep excavations are carried out.

Cross walls and buttress walls, as well as soil improvement, are common construction methods in Taiwan for protection of adjacent buildings during excavation. The basic configuration of a cross wall is depicted in Fig. 1, which refers to the construction of a wall, connecting two retaining walls opposite each other, prior to excavation. Although retaining walls have horizontal struts above the excavation level to resist lateral earth pressure, they are less capable to resist lateral earth pressure below the excavation level. This might cause retaining walls to deform too much during excavation. The cross wall functions as a strut-like component, which, with high compressive strength, exists before excavation. Along with excavation, cross walls should provide a powerful resistance to counteract the lateral displacement, so as to resist the lateral earth pressure on the back of the retaining walls. In theory, movement of the retaining walls near the cross wall will be restrained during excavation, and the lateral displacement of retaining walls will decrease. Ground settlement outside the excavation will be reduced too, which therefore achieves the protection of adjacent buildings.

The basic configuration of a buttress wall is depicted in Fig. 2. A buttress wall is similar to a cross wall in terms of construction. It is a concrete wall perpendicular to the retaining wall constructed before excavation, but not connected to the opposite retaining wall. The buttress walls may only contact the retaining wall without forming a whole structure with it. Thus, when the retaining wall is deformed, it will push the buttress wall to move along and a relative displacement between the buttress wall and the retaining wall may be produced. Since the stiffness of the buttress wall is usually much larger than that of the adjacent soil, when the retaining wall moves toward the excavation zone, the buttress wall will then move relative to the adjacent soil. The shear strength or frictional resistance developed on the two sides of the buttress wall will provide extra shear resistance, which will increase the overall lateral resistance, as shown in Fig. 3. That is to say, the buttress wall does not increase the moment-resistance of the retaining wall though it increases lateral resistance of the soils in front of the retaining wall. On the other hand, if a buttress wall is constructed and formed a whole structure with the diaphragm wall (retaining wall), like a T-beam in reinforced concrete structures, the buttress wall will enhance the capability of moment-resistance of the diaphragm wall. No matter whether the buttress wall is formed as a whole unit with the main diaphragm wall, the wall movement is expected to reduce to a certain extent.

According to the experiences of practicing engineers, both cross walls and buttress walls seem to have a good effect in reducing the movement of retaining walls though their effectiveness and mechanism are not verified. Both methods are becoming popular for reducing excavation-induced movement in Taiwan in recent years. Moreover, although cross walls and buttress walls have been applied in many deep excavations, research on their

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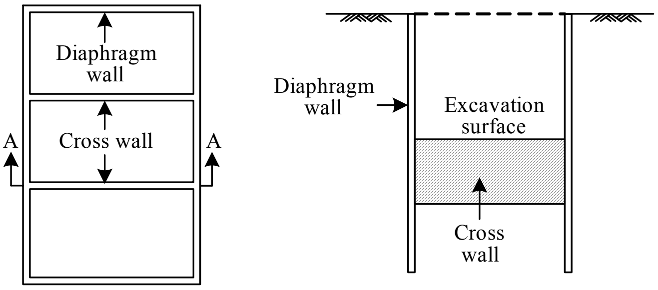
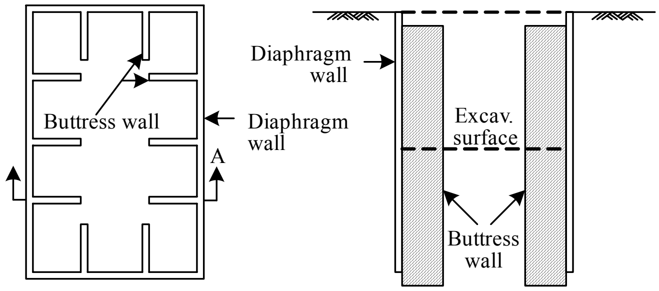


(a) Plan (b) Profile

Fig. 1 Schematic diagram of the cross wall



(a) Plan (b) Profile

Fig. 2 Schematic diagram of the buttress wall

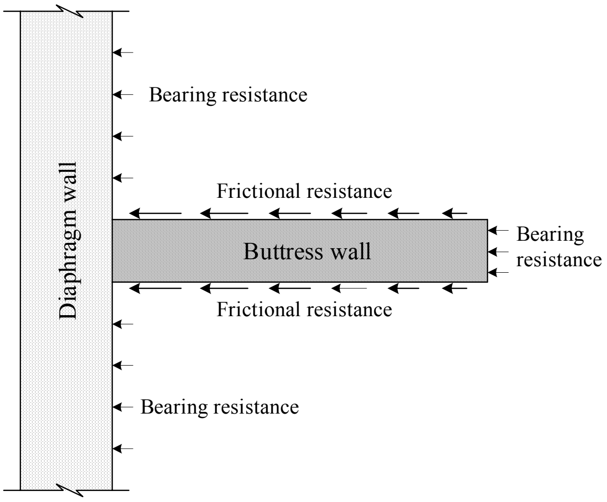


Fig. 3 Basic configuration of the buttress wall

behavior is rather deficient. Recently, Hsieh and Lu (1999) have introduced a preliminary design method for a buttress wall and Hwang, *et al.* (2003) have investigated the behavior of the buttress wall and cross wall. Current analysis and design are all resorting to the semi-empirical method. No rigorous analysis models are available, mainly due to the lack of complete case histories.

From a theoretical point of view, the effect of cross walls and buttress walls on reducing ground displacement should be related to factors, such as locations, spacing, section size, materials, and construction quality. Since each excavation case is equivalent to a large-scale field test, it is necessary to systematically consolidate these case histories, correlate factors and conduct systematic analysis of them, to further understand the behaviors of cross walls and buttress walls. By making use of the monitoring data of a real excavation case, the present paper investigates the functionality of cross walls and buttress walls to restrain ground movement, aiming to further reveal the behaviors of the cross walls and buttress walls deployed in deep excavations.

2. TYPES OF CROSS WALLS AND BUTTRESS WALLS

To ensure the cross walls with high compressive strength, they are usually constructed in the same way as diaphragm walls. Whether there is soft slime between the cross wall and the main diaphragm wall, or between panels of cross walls is an important factor that will affect the efficacy of cross walls. Caution should be taken in the construction of joints between main diaphragm walls and the cross walls.

For joints between cross walls and main diaphragm walls, there are T-type joints, separately-constructed joints, high-pressure grouting joints and partition plate joints (as shown in Fig. 4), which are described in the following:

(1) T-type joints

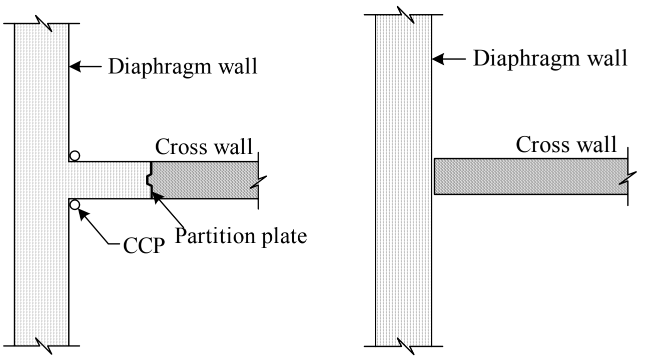
The interface between cross walls and main diaphragm walls is treated as a T-type unit, which means installing a primary unit and a partition plate at the T-type unit joint of the main diaphragm wall. A T-type steel cage is thus formed, as shown in Fig. 4(a). It usually needs two cranes to hoist a T-type steel cage into a trench, which is difficult and dangerous. The subsequent excavation of cross walls, however, can be handled by the use of steel brushes to remove slime. Since the T-type trench is of poor stability, corners are vulnerable to collapse. Hence, engineers might sometimes first perform grouting on the corners in order to avoid the collapse of the T-type trench. However, caution should be taken to avoid disturbing the soil, which might bring the reverse effect.

(2) Separately constructed joints

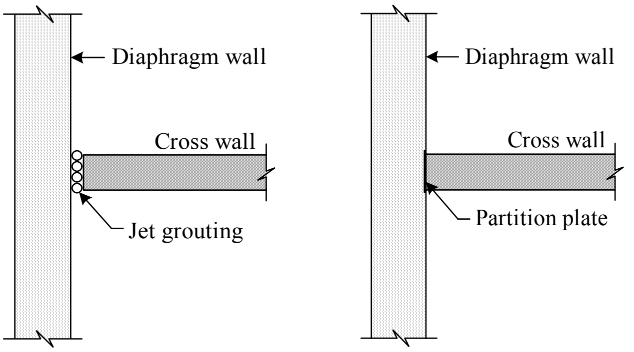
The main diaphragm wall and cross wall are constructed separately. That is, the trench excavation and concreting the cross wall commence after the construction of the main diaphragm walls is completed, as shown in Fig. 4(b). In this construction approach, though the collapse of trenches can be avoided, the soft slime between the main diaphragm wall and the cross wall may exist, which prevents the supporting functionality of the cross wall from being fully developed. The slime between the interfaces sometimes reaches 20 ~ 30 cm in thickness, which can neither be removed by grab bucket nor swept out by steel brushes, and as a consequence, affects the supporting efficacy of cross walls.

(3) High-pressure grouting joints

When separately constructing the main diaphragm wall and the cross wall, the interconnecting location is reserved to execute high-pressure grouting at a latter stage, as shown in Fig. 4(c). However, the efficacy of this method, which is supposed to replace the soil and slime in the interconnecting location, is hard to evaluate.



(a) T-type joints (b) Separately constructed joints



(c) High-pressure grouting joints (d) Partition plate joints

Fig. 4 Various types of joints connecting cross walls with diaphragm walls

(4) Partition plate joints

To avoid the problems related with the stability of T-type trenches and the removal of slime at the interface, the partition plate joint on the side of a diaphragm wall can be adopted. As shown in Fig. 4(d), one installs a partition plate on the side of the main diaphragm wall. After the construction of the main diaphragm wall is completed and the trench of the cross wall is excavated, a steel brush is used to remove the slime on the partition plate. Then, concrete is poured into the cross wall trench. This method can avoid the stability problems related to T-type trenches and the existence of slime at the interface.

If the cross wall is also a part of the building foundation, for example, if it functions like a pile foundation to bear the weight of the building or to resist uplift force, a diaphragm-type concrete wall should be reinforced. If the cross wall is only used to restrain the lateral movement of the diaphragm wall and the ground settlement, it can be filled with lean concrete.

The processing of the joints between the buttress wall and the main diaphragm wall is similar to those related to the cross wall, and there are four methods too.

3. PROJECT BACKGROUND AND CONSTRUCTION PROCEDURE

The building construction project was located in the Sinyi district, Taipei, with an excavation area of 6974 m^2. It is a building with seven floors of basements and 30 stories above the ground. A total of 115 piles, including 66 piles, 2.0 m in diameter, 45 piles, 2.5 m in diameter and 4 piles, 3.0 m in diameter, were used as the building foundation. The piles accounted for 6.6% of the total excavation area. Figure 5 displays the locations of the piles and their dimensions in the excavation.

The basement was constructed using the top-down construction method in 19 stages. The bottom of the basement or final excavation depth was 32.5 m. Table 1 lists the activities along with time periods for the construction stages, in which the 1st, 3rd, 5th, 7th, 9th, 11th, 13th, 15th, and the 17th stages are the excavation stages and the 2nd, 4th, 6th, 8th, 10th, 12th, 14th, 16th, 18th, and the 19th stages are floor slab construction or strut installation stages. The concrete floor slabs of the basements were also treated as a lateral support system during excavation. These were the girder-plates of the 1F and B1F floors (25 cm and 20 cm in thickness, respectively), the 61 cm thick flat slabs of floors B2F to B6F, and the 20 cm thick girder-plates of floor B7F. There are 10 openings, as displayed in Fig. 5, at each level of the slab for transporting the excavated soil. Besides, two types of temporary sloping struts, H400 × 400 × 13 × 21 and H428 × 407 × 20 × 35, with an 85-ton preloading were used as additional supports at the last stage of excavation. The excavation profile along with the subsurface soil profile is shown in Fig. 6.

Table 1 Construction sequence

Stage	Date	Activities
	2001/08/13-2002/02/21	Diaphragm wall construction
	2002/02/21-2002/03/30	Installation of monitoring system
	2002/03/22-2002/08/20	Construction of pile foundation
1	2002/08/17-2002/10/11	Excavated to the depth of GL. −3.5 m
2	2002/10/05-2002/10/26	Constructed the 1F floor slab
3	2002/10/20-2002/11/22	Excavated to the depth of GL. −6.35 m
4	2002/11/16-2002/12/10	Constructed the B1F floor slab at the depth of GL. −4.4 m
5	2002/12/01-2002/12/30	Excavated to the depth of GL. −10.45 m
6	2002/12/28-2003/01/26	Constructed the B2F floor slab at the depth of GL. −9.0 m
7	2003/01/14-2003/02/23	Excavated to the depth of GL. −14.8 m
8	2003/02/19-2003/03/15	Constructed the B1F floor slab at the depth of GL. −13.4 m
9	2003/03/06-2003/04/10	Excavated to the depth of GL. −18.15 m
10	2003/04/09-2003/05/04	Constructed the B4F floor slab at the depth of GL. −16.8 m
11	2003/04/26-2003/05/26	Excavated to the depth of GL. −21.5 m
12	2003/05/20-2003/06/08	Constructed the B5F floor slab at the depth of GL. −20.2 m
13	2003/06/01-2003/07/03	Excavated to the depth of GL. −26.05 m
14	2003/06/30-2003/07/15	Constructed the B6F floor slab at the depth of GL. −24.8 m
15	2003/07/18-2003/08/12	Excavated to the depth of GL. −29.4 m
16	2003/08/19-2003/08/25	Installing inclined struts
17	2003/08/21-2003/09/17	Excavated to the depth of GL. −32.5 m
18	2003/10/09-2003/10/28	Cast the foundation slab
19	2003/11/17-2003/11/19	Constructed the B7F floor slab at the depth of GL. −29.4m

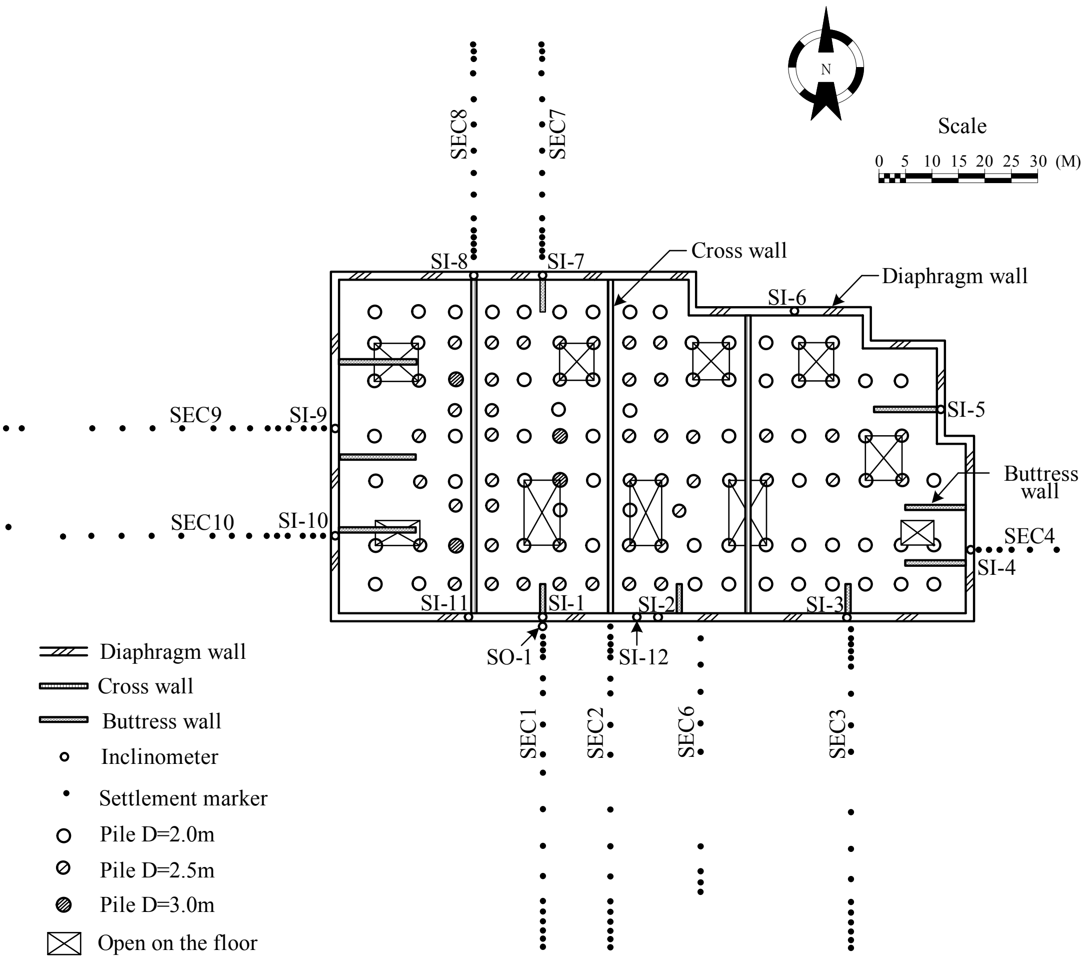


Fig. 5 Monitoring layout

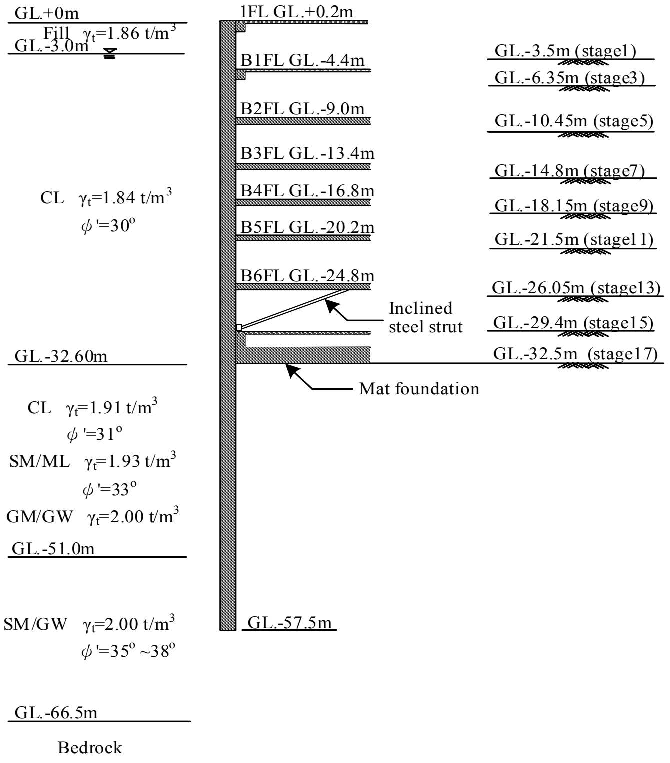


Fig. 6 Excavation and subsurface soil profiles

A 1.5 m thick diaphragm wall was used as the earth retaining structure. The depth of the diaphragm walls varied from 56.8 to 61 m, which, in general, penetrated 4 m into the cobble-gravel formation. The average depth of diaphragm walls was 57.5 m. The design compressive strength of the concrete was 280 kg/cm^2.

In this case history, the partition plate joint was adopted for cross walls and buttress walls, as shown in Fig. 4(d). The only problem was when a steel brush was used to remove the slime on the partition plate joints during the excavation of cross wall and buttress wall, the steel brush could rotate easily because there was no restriction from reinforcements connecting the units, which might slightly affect the removal of slime and in turn the construction quality of the joints. Figure 5 also shows three cross walls, 1.0 m thick and 45 m deep, which were constructed in the north-south direction. Ten more buttress walls, 1.0 m thick and 55 m deep, were also constructed. The top 1.5 m (a few are 6.0 m) of cross walls and buttress walls was backfilled with in-situ soil. The compressive strength of the concrete from 1.5 m (a few are 6.0 m) to 22 m was 140 kg/cm^2, while below 22 m in depth the strength was 245 kg/cm^2. The cross walls and buttress walls were dismantled stage by stage as excavation went deeper. The cross walls and buttress walls occupied 4.2% of the excavation area in total.

Twelve in-wall inclinometer casings, 70 m in depth, were installed in this project (numbered from SI-1 to SI-12). The casings passed through the Chingmei formation (gravel) and penetrated into the rock for 5 m, so as to keep the bottom located at a fixed position. Since the inclinometer SI-1 was only embedded to a depth of 40 m, it was complemented with an in-soil inclinometer SO-1 with the same depth. There were 168 settlement measurement points on the nearby roads and empty lots. The deployment of the inclinometers and settlement markers is shown in Fig. 5.

4. GROUND CONDITIONS

The construction site is located in the alluvium area of Keelung river, namely the K1 zone, which mainly comprises silty sand and silty clay, as described by Huang, *et al.* (1987) and Woo and Moh (1990). Compared with the Sungshan formation typical in Taipei, the silty sand layers of the fifth layer and the third layer are invisible or incomplete, which makes the division between the sixth layer and the fourth layer of the silty clay indistinct and usually forms a thick clayey soil layer, which is up to 30 m thick. As indicated by the site investigation, the soil parameters obtained via boring and laboratory testing are detailed in Fig. 7, which shows that the ground water is 3 m below the ground surface, and the water level in the gravel layer is about 11.5 m below the ground surface. The strata of the site are divided into five layers. From top to bottom, they are described as follows:

(1) From the ground surface to 3 m below, is a layer of gray silty clay, together with gravels, bricks, and sundries, with a total unit density of about 1.86 t/m^3.

(2) In the range of 3.0 m to 32.6 m below the ground surface, is a layer of gray silty clay, occasionally mixed with shells, crumbs and organics, with N values varying from 1 to 18. Its total unit density is about 1.84 t/m^3, average natural water content about 34%, void ratio between 0.8 and 1.3, liquid limit between 30 and 48, plasticity index between 10 and 23, compression index (C_c) 0.35, recompression index (C_r) 0.05, effective friction angle 30°.

(3) In the range of 32.6 to 51.0 m below the ground surface, is a layer of gray silty clay, mixed with silty sand and gravels with different thickness. The N values are between 7 and 37, but with occasional gravel layers that have N values larger than 50. As a summary of the physical property: (a) For silty clay, the N values are between 7 and 37. Its total unit density is 1.91 t/m^3, natural water content 29% on average, void ratio from 0.6 to 0.9, liquid limit from 25 to 46, plasticity index from 4 to 22, effective friction angle 31°. (b) For the silty sand interlayer, it is mainly found in the center of and on the east side of the site. Its thickness is about 2 to 7.7 m, N value 15 to more than 50, total unit density about 1.93 t/m^3, natural water content 23% on average, effective friction angle 33°. (c) For the gravel interlayer, it is roughly distributed from the east side to the center, located at depths from 39 to 45 m, with the N values larger than 50.

(4) In the range of 51.0 m to 66.7 m below the ground surface, is a layer of gray gravels mixed with silty sand. The N values are larger than 50, total unit density about 2.0 t/m^3, diameter of gravels is 2 ~ 5 cm, with the maximum gravel diameter smaller than 12 cm, effective friction angle between 35° and 38°. However, during pile construction on the east side, gravels over 30 cm in diameter are also found.

(5) Rock formation is found 66.7 m below the ground surface, which is mainly composed of weathered sand stones and has N values larger than 50.

5. MONITORING RESULTS AND DISCUSSION

The relationship between the maximum movements of the retaining wall and their excavation depths for excavations under plane strain condition and without soil improvement, cross walls, buttress walls or other remedial measures in the Taipei area has been studied by Ou, *et al.* (1993), as shown in Fig. 8. As shown in this figure, the maximum wall movement increases with the excavation depth. The wall movement in soft clay is generally greater than that in sand. The ratio of the maximum wall move-

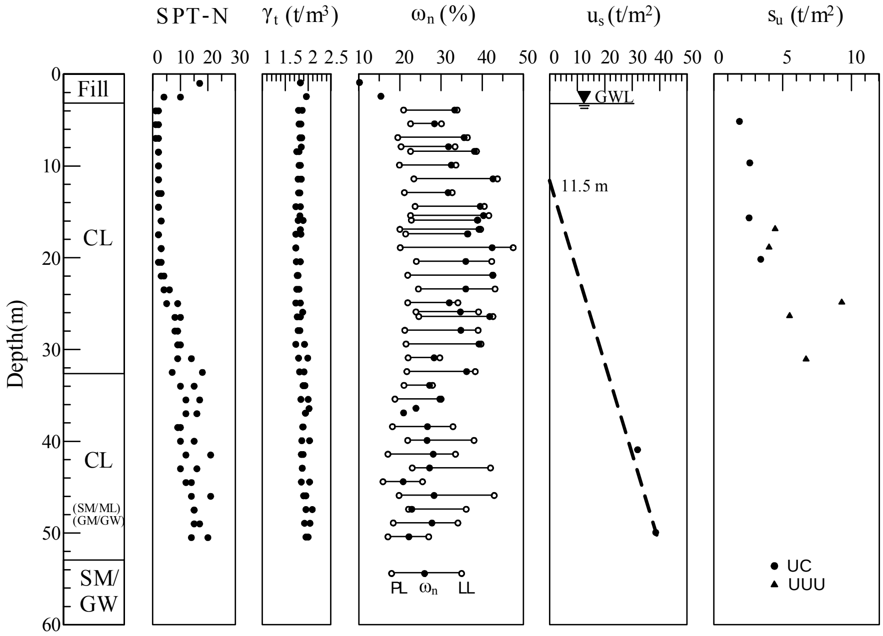


Fig. 7 **Profiles of SPT-N values, total densities, water contents, porewater pressures and undrained shear strengths for the project site**

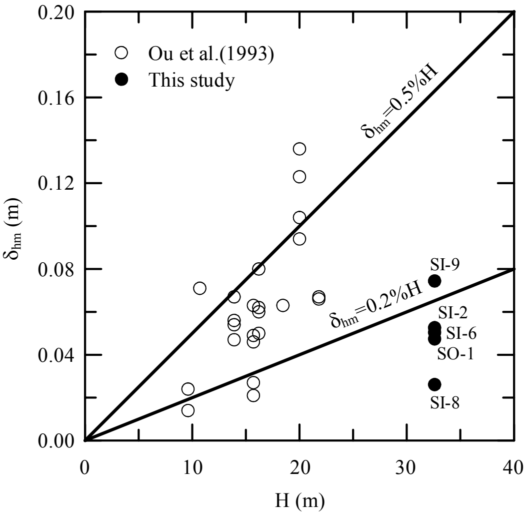


Fig. 8 **Relationship between the maximum wall movement and excavation depth for excavations without remedial measures in the Taipei area along with the monitoring results of this case history**

ment to excavation depth is around 0.2% to 0.5%, in which the upper limit is mostly for clay, the lower limit for sand and those for the alternating layers of sand and clay fall in between the two limits. This figure, representing general wall movement during excavation in the Taipei area, will be used as a basis to evaluate the effectiveness of cross walls or buttress walls in reducing movement.

Figure 9 shows the wall movements and ground settlements at some main stages for inclinometer SI-8 and its corresponding ground monitoring section SEC8, in which the inclinometer and its corresponding ground settlement monitoring section were set at the intersection between the main diaphragm wall and the cross wall. The monitoring results directly represent the restraining effect of the cross wall. As shown in this figure, the wall movement, right at the position of the cross wall, was extremely small, with the maximum movement of the wall reaching 26.1 mm. At the initial excavation stage, the lower half of the retaining wall exhibited a straight-line displacement shape. When the final excavation stage was reached, the retaining wall near the excavation surface (GL. −32.5 m) displayed a concave displacement shape with a very large curvature, while the retaining wall below the excavation bottom displayed a displacement mode like a line segment, which was perhaps caused by the restraining of the cross wall. The ground settlement for each stage was also comparatively small, with a maximum value reaching 12 mm. As shown in Fig. 8, the ratio of maximum wall movement to excavation depth was equal to 0.08%, much less the lower limit of the general trend. This implies that the cross wall has a significant effect in reducing wall movement and ground settlement.

Figure 10 shows the wall movements and ground settlements at some main stages for inclinometer SI-9 and its corresponding ground monitoring section SEC9, in which the inclinometer and its corresponding ground settlement monitoring section were set about 7 m away from the intersection between the main diaphragm wall and the buttress wall, without any cross wall nearby. The monitoring results can directly represent the partial restraining effect of the buttress wall. As shown in this figure, the displacement of the retaining wall and the ground settlement are quite significant when there are only buttress walls. When the final excavation stage was reached, the maximum movement of the retaining wall and the maximum ground settlement were 74.4 mm and 30.4 mm, respectively. As shown in Fig. 8, the ratio of maximum wall movement to excavation depth was equal to 0.23%, close to the lower limit of the general trend, which implies that the buttress wall has a certain effect in reducing wall movement and ground settlement.

Figure 11 shows the wall movements and ground settlements at some main stages for inclinometer SO-1 and its corresponding ground monitoring section SEC1, in which the inclinometer and its corresponding ground settlement monitoring section were set at the intersection between the main diaphragm wall and the buttress wall, also located about 10 m away from the cross wall. The monitoring results from them can directly represent the restraining effect of the buttress wall, and the partial restraining effect of the cross wall. As shown in this figure, the displacement of the retaining wall and the ground settlement, between two cross walls and simultaneously at the location of a buttress wall, had magnitudes between those in the previous two cases. The maximum retaining wall displacement was 47.4 mm. The ground settlement for each stage was also very small, with a maximum value being 13.4 mm. As shown in Fig. 8, the ratio of maximum wall movement to excavation depth was equal to 0.14%, which is also less than the lower limit of the general trend. Whether such a decrease of the wall movement or ground settlement at SO-1 or SEC1 is due to the existence of the buttress wall or to the location between the two cross walls remains to be resolved.

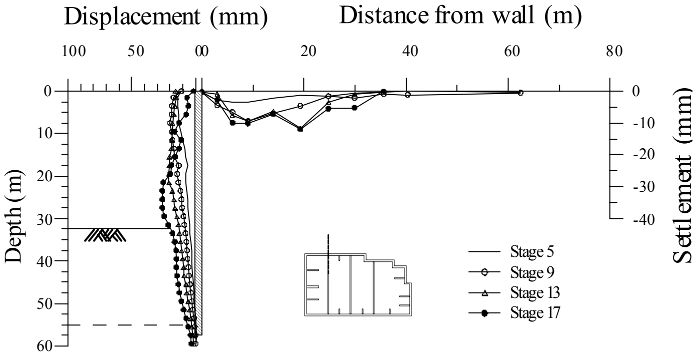


Fig. 9 **Monitoring results of the inclinometers SI-8 and its corresponding settlement monitoring section, SEC8, for some main stages**

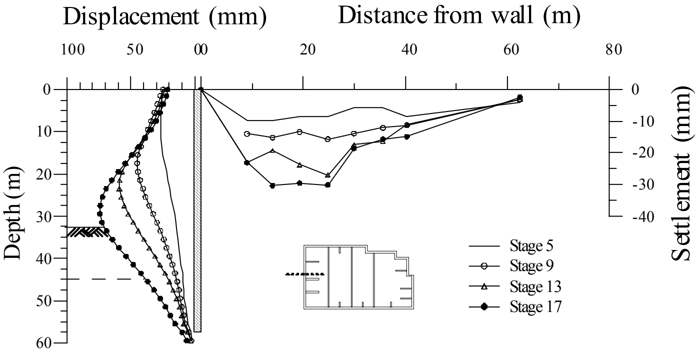


Fig. 10 **Monitoring results of the inclinometers SI-9 and its corresponding settlement monitoring section, SEC9, for some main stages**

According to Ou, *et al.* (1996), due to the arching effect at the corners of the diaphragm wall, the wall movement and ground settlement near the corners are very small. The construction of the cross wall in this case was initiated from the place near the ground surface and extended to near the bottom of the wall, which had a similar effect to the arching effect at the corners. The inclinometer SI-6 was located 9 m away from the nearest cross wall. It should show a certain effect in reducing wall movement and ground settlement. The inclinometer SI-2 was located 9 m away from the nearest cross wall and 4 m from the buttress wall. This implies that both the cross wall and the buttress wall may have a certain effect in reducing wall movement and ground settlement. By comparing the monitoring results from SI-2 and SI-6, we can conclude how effective the buttress wall can be in reducing wall movement and ground settlement. The effectiveness of the buttress wall in reducing wall movement and ground settlement at SO-1 and SEC1 can also be evaluated.

Figure 12 shows the comparison of wall movements at SI-6 and those at SI-2 at some main stages. As shown in this figure, the wall movements at SI-2 were very close to those at inclinometer SI-6. The existence of the buttress wall seems have no additional restraining effect in reducing wall movement. This may be attributed to the fact that comparatively small movement of the wall, due to proximity to the cross wall, mobilized little shear strength or frictional resistance between the buttress wall and the adjacent soils, which therefore caused the buttress to have less effect in reducing wall movement and ground settlement.

Since the magnitudes of wall movement and ground settlement at SO-1 and SEC1 at main stages were also close to those at SI-6, we can also infer that decrease of wall movement and ground settlement was mostly due to the existence of two cross walls and less affected by the buttress wall.

Other inclinometers and their corresponding settlement monitoring sections had measurement results similar to those of the SI-9, SI-8, SO-1 and their corresponding settlement monitoring sections, with the only differences in magnitude. To save space, only the maximum values of the inclinometer and settlement monitoring results at each excavation stage are summarized in Tables 2 and 3, respectively.

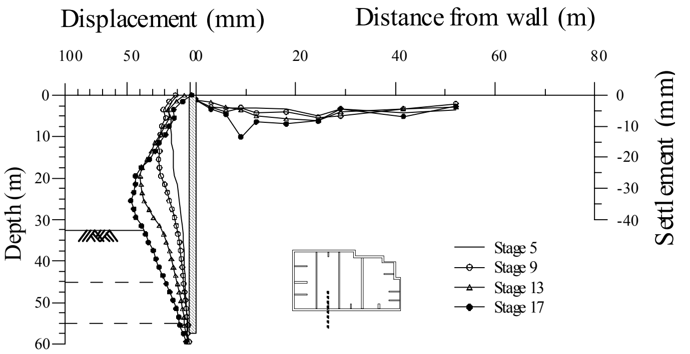
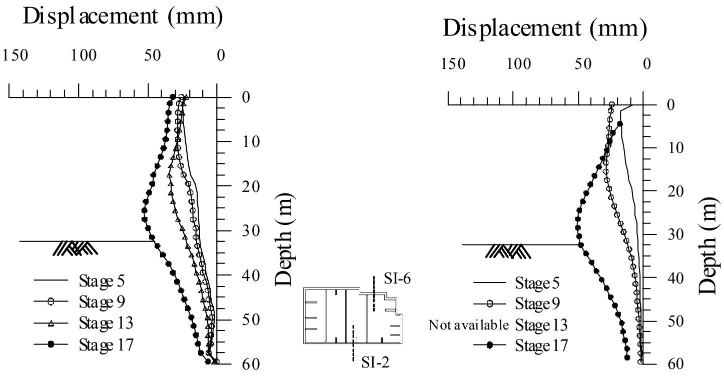


Fig. 11 **Monitoring results of the inclinometers SO-1 and its corresponding settlement monitoring section, SEC1, for some main stages**



(a) SI-2 (b) SI-6

Fig. 12 **Monitoring results of the inclinometers SI-2 and SI-6 for some main stages**

Table 2 Maximum lateral deformation of the wall at each stage (unit: mm)

Inclinometer / Stage	SI-1	SI-2	SI-3	SI-4	SI-5	SI-6	SI-7	SI-8	SI-9	SI-10	SI-11	SI-12	SO-1
Stage 1 (GL. −3.5 m)	9.6	10.0	12.1	10.3	34.1	9.9	3.9	–	11.7	9.3	8.5	4.9	3.4
Stage 3 (GL. −6.35 m)	12.6	22.1	20.4	12.8	35.4	14.1	8.5	10.1	20.9	23.2	11.3	10.2	13.8
Stage 5 (GL. −10.45 m)	20.0	25.2	23.8	22.5	36.5	18.0	14.5	14.3	26.7	20.3	12.6	12.4	17.5
Stage 7 (GL. −14.8 m)	22.7	28.6	37.5	24.5	41.7	25.4	22.4	14.8	37.5	27.3	14.7	15.6	19.0
Stage 9 (GL. −18.15 m)	28.3	28.6	50.6	31.5	52.0	29.2	35.7	19.9	45.1	32.4	12.7	19.9	25.6
Stage 11 (GL. −21.5 m)	29.2	31.8	55.0	37.5	62.5	–	39.2	19.1	49.2	36.1	19.0	21.2	34.8
Stage 13 (GL. −26.05 m)	38.7	40.1	64.2	36.7	62.7	–	40.4	23.4	59.0	47.1	19.2	25.8	40.3
Stage 15 (GL. −29.4 m)	45.1	45.9	71.0	42.2	68.7	–	40.3	29.0	73.7	51.0	34.9	27.7	46.5
Stage 17 (GL. −32.6 m)	44.0	52.6	72.6	44.7	68.4	50.4	39.6	26.1	74.4	54.8	27.2	36.4	47.4

Table 3 Maximum ground settlement of the monitoring section (unit: mm)

Section Stage	SEC1	SEC2	SEC3	SEC4	SEC6	SEC7	SEC8	SEC9	SEC10
Stage 1 (GL.−3.5 m)	–	–	−0.5	−3.4	−1.5	–	–	–	–
Stage 3 (GL. −6.35 m)	−5.2	−5.2	−6.7	−6.9	−8.9	−3.9	−4.1	−8.3	−7.2
Stage 5 (GL. −10.45 m)	−6.5	−6.3	−8.5	−11.1	−9.0	−5.6	−3.6	−9.7	−7.7
Stage 7 (GL. −14.8 m)	−7.4	−5.5	−14.1	−12.7	−9.2	−7.2	−10.6	−13.0	−10.8
Stage 9 (GL. −18.15 m)	−7.1	−8.0	−19.9	−16.5	−13.0	−7.5	−9.4	−15.7	−13.5
Stage 11 (GL. −21.5 m)	−8.4	−7.3	−22.0	−17.8	−9.7	−9.5	−8.8	−24.2	−21.3
Stage 13 (GL. −26.05 m)	−8.1	−12.1	−21.4	−17.1	−12.1	−10.7	−11.7	−27.0	−24.2
Stage 15 (GL. −29.4 m)	−14.1	−12.7	−22.3	−17.3	−20.9	−12.2	−13.4	−28.2	−27.4
Stage 17 (GL. −32.6 m)	−13.4	−13.0	−25.8	−16.0	−17.9	−14.0	−12.0	−30.4	−27.3

6. CONCLUSIONS

Cross walls and buttress walls, in addition to soil improvement, are common construction methods in Taiwan for protection of adjacent buildings during excavation. It is generally recognized, but not verified, that both the cross wall and the buttress wall have good effects in reducing wall movement and ground settlement. However, the design methodology is still highly empirical because of lack of well documented case histories for further studies. The case history presented in this study was well documented and with good monitoring results. Based on monitoring results, the following conclusions can be drawn:

The cross wall, usually constructed before excavation, connects the opposite retaining walls. The cross walls in this case history were constructed in the same way as the diaphragm wall, which should have a very high compressive strength, and the lateral movement should be an insignificant amount at the location of the cross walls. The joints connecting the cross walls with the main diaphragm walls were constructed by using partition plate joints on the sides of diaphragm walls. Steel brushes were used to remove the slime on the partition plates before concreting the cross wall trenches. However, during the removal, the steel brushes rotated slightly and might have effected the construction quality of joints and consequently affected the wall movement restrained by the cross walls. The monitoring results displayed that the movement of retaining walls and ground settlement at the position of the cross wall were reduced significantly, which amounted to a 26.1 mm maximum lateral displacement and 12 mm maximum ground settlement. Whether this movement comes from the elastic compression of the cross wall or less ideal construction quality of the joints deserves further investigation.

The lateral resistance of buttress walls basically comes from the shear strength or frictional resistance on the two sides of buttress walls. The buttress walls in the present project were 6 to 15 m long, and were constructed starting from the ground surface to the bottom of retaining walls. The two sides of the buttress walls should provide lots of extra resistance and achieved the effect of reducing wall displacement and ground settlement. However, the effect of buttress walls in reducing wall movement or ground settlement depends on the mobilized shear strength or frictional resistance, *i.e.*, lateral movement of the retaining wall. If the excavation causes large wall movement, buttress walls should have a certain effect in reducing wall movement or ground settlement. However, buttress walls may just have a slight effect in reducing wall movement or ground settlement if there is only a small movement in the diaphragm wall.

Soil test data in this case history are complete, and a comprehensive monitoring system was configured before the excavation. This case history not only can be used to study the effect of cross walls and buttress walls in reducing wall displacement and ground settlement, but can also be used for numerical verification.

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