Damages to Metro Tunnels due to Adjacent Excavations




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ABSTRACT: Metro tunnels are vulnerable to ground movements, therefore precautionary measures must be taken to prevent potential damages to existing tunnels if excavations are to be carried out in close proximity to tunnels. Presented herein are the regulations adopted to protect the Taipei Metro and three case histories on damages occurring to metro tunnels to illustrate how tunnels respond to activities associated with excavations. It has been found that localized ground treatment would not serve the purpose of reducing wall movements and neither would a single buried cross panel in excavations with considerable lengths.

1 INTRODUCTON

As more and more metro lines are constructed in major cities and basements tend to go deeper and deeper, protection of existing metro tunnels has become a serious concern. Metro tunnels are vulnerable to ground movements and precautionary measures are required for preventing potential damages to existing tunnels if excavations are to be carried out in the close proximity to tunnels, particularly for tunnels in services.

To address to the issue, presented herein are the regulations restricting the construction activities to be carried out in the vicinity of metro tunnels. Also presented are two case histories in which tunnels were damaged as a result of excavation and one case history in which the tunnel was damaged even before the commencement of excavation. In all these case histories, the convergences of the tunnel linings were closely monitored and the data obtained make it possible to study the response of tunnels to ground movements.

2 REGULATIONS GOVERNING ADJACENT EXCAVATIONS

As a fundamental law governing the operation of metro systems, Mass Rapid Transit Act (the Act, hereinafter) was legislated in 1988 and has been amended for a few time since then. It stipulates the principles for the construction, revenue services and maintenance, and protection of metro facilities. To comply with Article 45, which empowers the authorities to limit construction activities in the vicinity of metro facilities, of the Act, the Ministry of Transportation and Communication and the Ministry of the Interior jointly issued "Regulations Governing Construction of Public and Private Buildings and Advertising Structures along the Routes of Rapid Transit Systems" (the Regulations, hereinafter) in 1991. The Regulations were amended in 2003 and renamed to "Regulations for Banning and Restricting Constructions along the Routes of Rapid Transit Systems".

For shield tunnels, as shown in Fig. 1, construction activities are totally banned within 1m from the tunnel lining. To comply with the Regulations, metro authorities have to publish the limits of restricted zones along the routes of metro lines. If construction activities are to be carried out in the restricted zones, Building Control Authority (BCA) has to liaise with metro authorities to check whether they will have adverse influence on metro facilities. Agreement from the metro authorities is necessary for the construction license to be granted.

For soft ground, the width of the restricted zone is 100m or the thickness of soft deposits, whichever smaller, from the outer edges of metro facilities. For hard ground, this width is reduced to 30m, and for river crossings it is increased to 500m. In other situations, the width of restricted zone is 50m.

For shield tunnels, the changes in tunnel diameter are limited to 20mm in any direction. The lining should in no case ingress into the dynamic envelope of trains which is the outer limit of the space required for operation and safety.

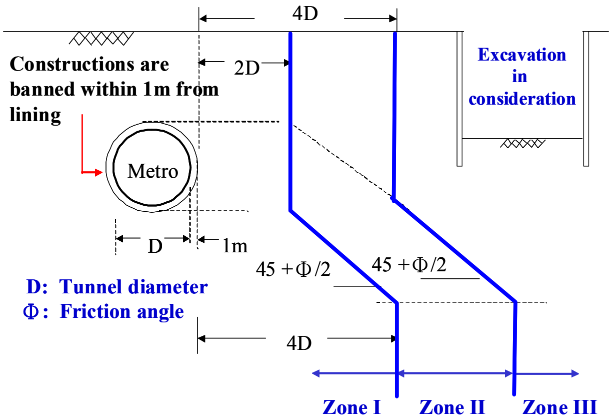

Fig. 1 Zoning for restricting excavations in the vicinity of metro tunnels

For protecting the Taipei Metro, Taipei City Government issued "Guidelines for Regulating Cases under Surveillance in Restricted Zones" (the Guidelines, hereinafter) as a supplement to the Regulations and the restricted zone is further divided into 3 zones as follows:

- Zone I: damages to metro facilities are likely to occur and measures shall be taken to protect metro facilities. Developers are required to assess ground movements to be induced and the potential influence to metro facilities as a result of ground movements. .
- Zone II: damages to metro facilities may occasionally occur and care shall be taken to avoid damage to metro facilities.
- Zone III: damages are unlikely to occur and there are no specific requirements other than instrumentation and monitoring.

In addition to requirements on limiting ground movements which are the major source of damage to metro facilities, the Guidelines also specify the quantities of various types of instruments to be installed and the frequencies of reading takings. Developers must submit their instrumentation program for approval before construction licenses are granted and have the initial readings established before the commencement of excavation. Readings must be submitted to the metro authority with 2 days after each stage of excavation is completed.

During excavation, if any reading exceeds the alert level, the metro authority must be informed and the construction plan shall be reviewed, and revised if necessary. If the risk level is exceeded, or damage is noticed on metro facilities, construction must be halted and shall not be resumed without the approval from the metro authority. In the meanwhile, licensed professional engineer(s) must be engaged to deal with the emergency.

3 DAMAGES TO METRO TUNNELS

Presented herein are 3 cases in which tunnel linings were damaged as a result of ground movements induced by activities associated with excavation. All the shield tunnels in Taipei Metro are about 6m in diameter, therefore, with a 1m thickness for the sterilized zone in which constructions are totally banned, the limit of Zone 1 at the depths of tunnels is about 13m away from the tunnel lining and the limit of Zone 2 is 12m further away. For all the practical purposes, the friction angle of soil, Φ, refer to Fig. 1, can be assumed to equal 30 degrees and the limits of the two zones can then be defined accordingly.

3.1 *Case 1 – Excavation with ground treatment*

Shown in Fig. 2 is a case in which excavation was carried out to a depth of 21.1m with a minimum distance of 12m to the nearest tunnel, i.e., the up-track (Chang, et al., 2001). The excavation was carried out in the period of 1996 to 1998 before the Regulations were amended. Specifications were not as stringent as they are nowadays, therefore, the excavation was conducted without prior approval from the metro authority and were not closely watched till cracks were observed on the linings when the excavation was about completed.

The soft deposits at surface are underlain by a thick gravelly layer at a depth of 50m. The retaining diaphragm walls were 1.2m in thickness and 36m in length. Despite the fact that, as shown in Figs. 2 and 3, jet grouting had been conducted to treat a block of soil in an attempt to reduce wall movements, lateral movements of the ground were quite large. As depicted in Fig. 4, Inclinometer SIS605 showed a maximum wall movement of 54mm at the depth coinciding with the depth of the tunnels. Figure 5 indicates that the longitudinal axis of the up-track tunnel moved by as much as 27mm laterally and settled by 33mm maximum. As a result, the invert slab became detached from the lining segments and had to be replaced.

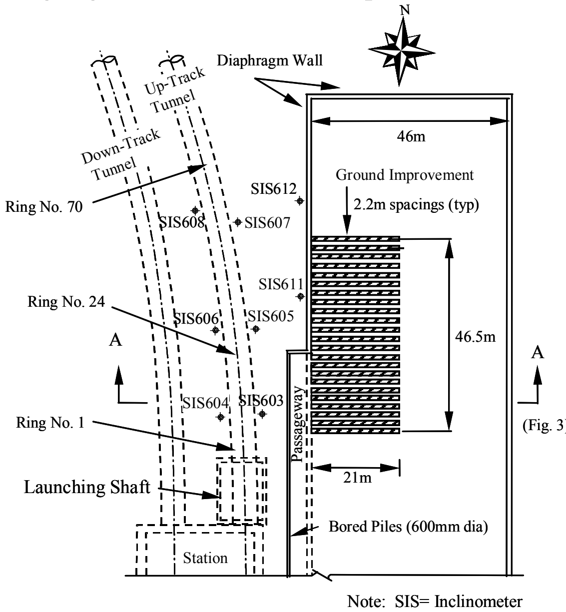

Fig. 2 Case 1 – Site plan and locations of instruments

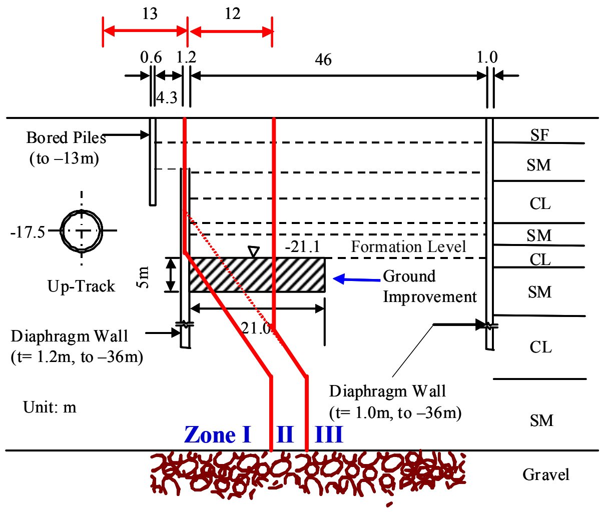

Fig. 3 Case 1 – Soil profile and excavation scheme

Shown in Fig. 6 are the convergences of linings in the tunnel obtained by configuration survey. The maximum changes in diameter were 46mm in the vertical direction and 28mm in the horizontal direction. Ring No. 24 (or, simply 24R), which appears to be the most affected, was shortened by 45mm in the vertical direction and elongated by 26mm in the horizontal direction. A total of 41 rings (10R to 50R) were severely damaged and had to be reinforced by steel segments as a secondary lining.

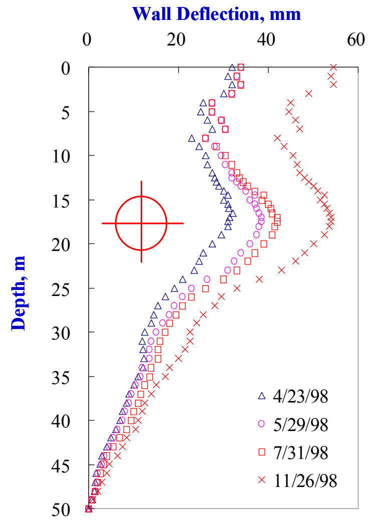

Fig. 4 Case 1 – Readings of Inclinometer SIS605

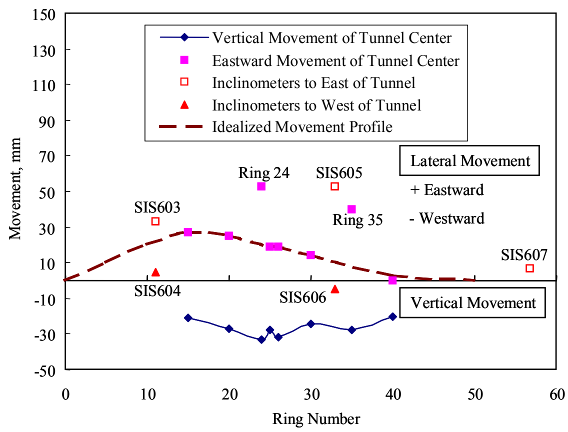

Fig. 5 Case 1 – Movements of the longitudinal axis of the up-track tunnel

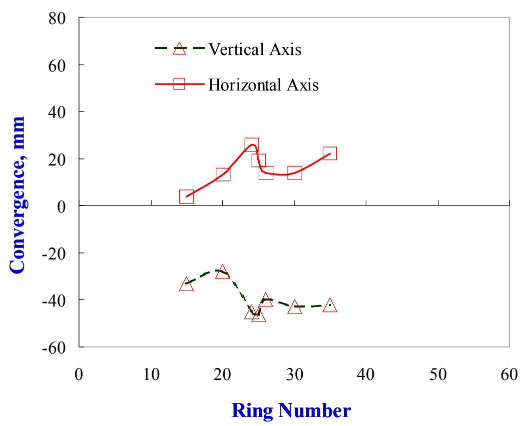

Fig. 6 Case 1 – Convergences of linings of the up-track tunnel

3.2 *Case 2 – Excavation with cross panel*

Shown in Fig. 7 is a case in which excavation was carried out to a depth of 15.9m with a minimum distance of 7.3m to the nearest tunnel, i.e., the down-track (Hwang, et al., 2010). The soft deposits at surface are underlain by a thick gravelly layer at a depth of 50m. The retaining diaphragm walls were 0.8m in thickness and 32.5m in length. As shown in Fig. 8, excavation was partly carried out in Zone 1 and measures were required for reducing ground movements. Accordingly, a cross panel, 0.6m in thickness and 10m in depth, was installed by using the diaphragm walling technique and was structurally connected to the diaphragm walls to form T-joints at its two ends.

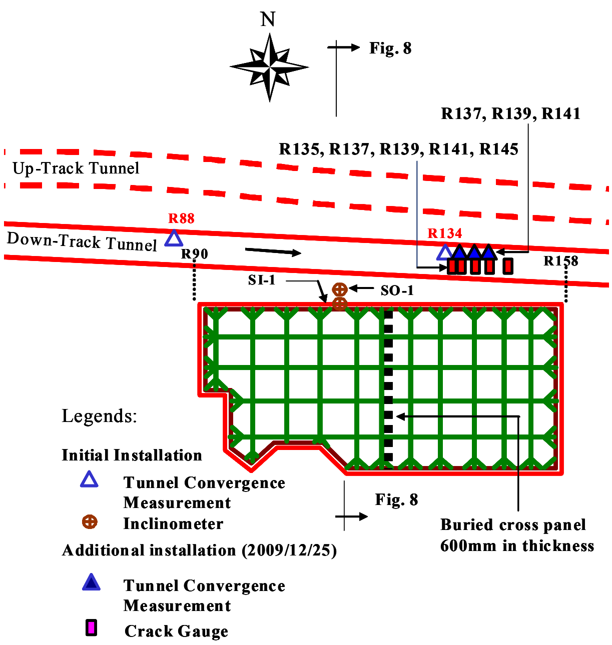

Fig. 7 Case 2 – Site plan and locations of instruments

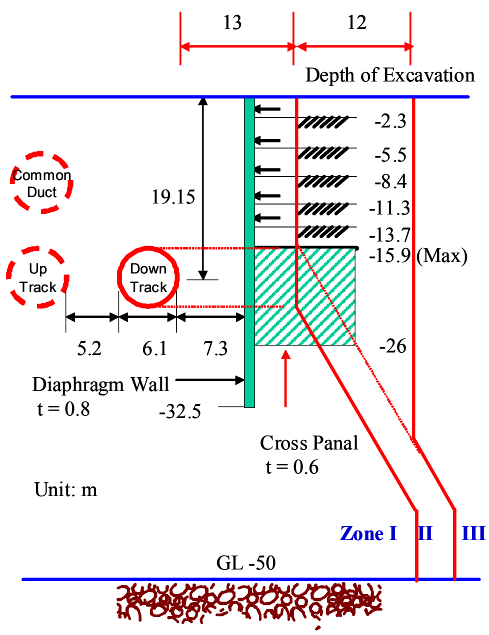

Fig. 8 Case 2- Excavation scheme

Ring No. 134 (or simply, 134R) was found to have lengthened by 19.9 mm in the horizontal direction and shortened by 13.7mm in the vertical direction on 26 October 2009 when the excavation was approaching its final depth. The former already exceeded the Alert Level of 15mm. The squashing of the ring continued; and the lengthening of the diameter in the horizontal direction reached 27.5mm and the shortening of the diameter in the vertical direction increased to 21.4mm on 18 December. Since the former exceeded the Action Level of 25mm, an injunction was issued on 25 December by the metro authority and the excavation was halted. Crack gauges were mounted on 5 rings next to 134R as depicted in Figure 7 for long-term monitoring of the changes in widths of the cracks. In addition to 134R, the convergences of 137R, 139R and 141R were also monitored daily. The readings taken for 55R to 195R on 18 January 2010 are depicted in Fig. 9.

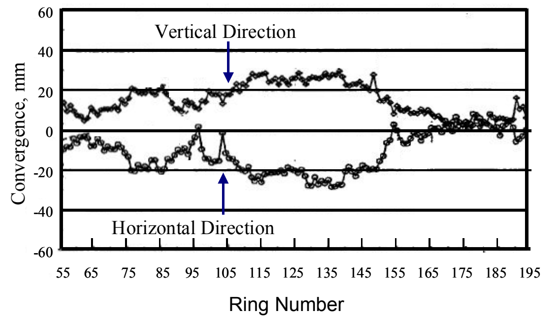

Fig. 9 Case 2- Convergence of the down-track tunnel (2010/1/18)

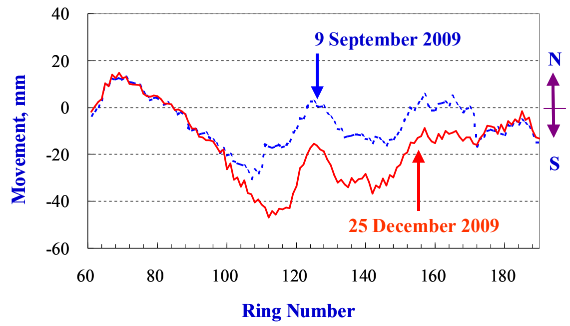

Fig. 10 Case 2- Horizontal movements of the down-track tunnel

Figure 10 shows that the longitudinal axis of the tunnel moved southward toward the excavation by, as much as, 30mm by 9 September. The section between 110R and 170R was found to have further moved by 20mm when the injunction was issued on 25 December 2009.

To avoid deterioration of the situation, temporary struts were installed at the B4 level in the excavation to limit wall movements and internal bracings were installed in the tunnel to limit the deformations of 99R to 155R. These measures were completed on 25 January 2010 and were found effective as the deformations of the tunnel did not increase further subsequently.

Figure 11 compares the readings obtained by two side-by-side inclinometers on 24 March 2010 with the results of numerical analyses using the finite element program PLAXIS. It is estimated that the toes of these inclinometers moved by 10mm or so because they did not reach the bearing stratum.

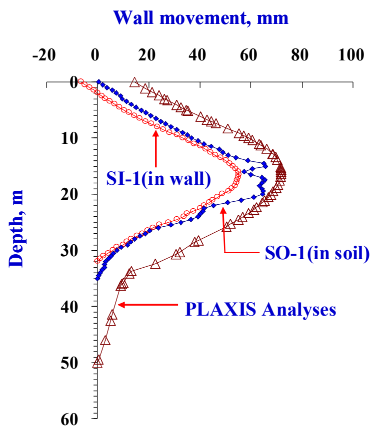

Fig. 11 Case 2- Inclinometer readings (2010//3/24)

Calculations indicated that the damage linings still have sufficient structural capacity and reinforcement is not required. However, the possibility for the down-track tunnel to further deform could not be eliminated during the construction of the up-track tunnel and the common duct, the excavation contractor made the commitment that steel linings would be installed once the changes in diameter reach 34mm in the future. With this commitment, the injunction was lifted and the excavation was resumed and completed.

3.3 *Case 3 – Diaphragm wall installation*

Shown in Figs. 12 and 13 is a case in which tunnel linings were damaged even before the commencement of excavation (Ju, et al., 2007). The diaphragm wall at a corner was only 3m to the nearest tunnel, i.e., the up-track, which was completed on 28 December 2004. The subsoil at the depth of tunnels mainly consists of silty clays (Soil Type CL). The bearing stratum was not encountered at the maximum drilling depth of 40m.

The diaphragm walls were 1m in thickness on the north side and 0.7m everywhere else. The trench collapsed during the installation of Panel #4 on 3 March 2006. As shown in Fig. 14, CCP piles, 400mm in diameter, were sunk on the both sides of the trench in the period between 5th and 8th March to ensure that this unit and two neighboring units could be successfully installed. They were installed from a depth of 2m to a depth of 12m below ground surface as depicted in Fig. 13.

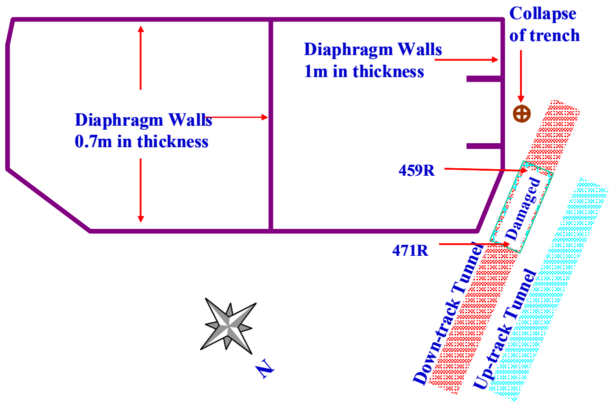

Fig. 12 Case 3- Site Plan

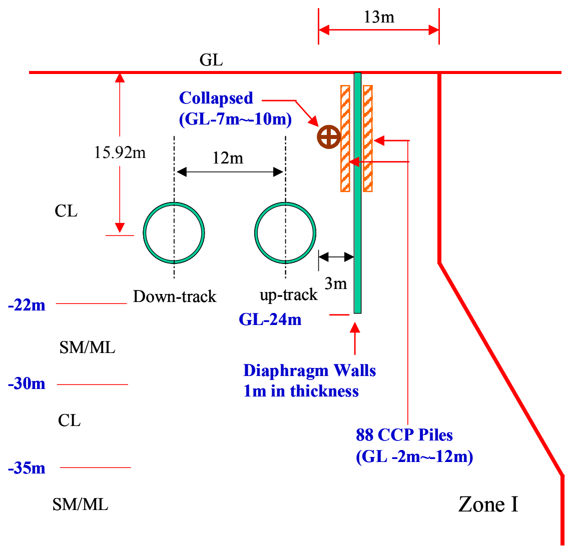

Fig. 13 Case 3 – Remedial measures

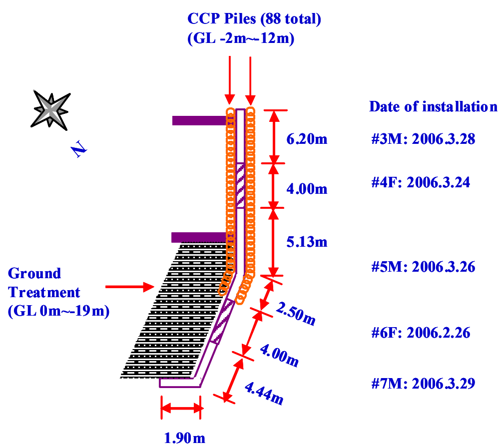

Fig. 14 Case 3- Protection measures

Cracks were observed on linings and configuration survey conducted on 18 April revealed that, as depicted in Fig. 15, the deviations from the theoretical diameters of the tunnels had increased from the initial value of 28mm to 51mm for Ring No. 467 (i.e., 467R) which appeared to be damaged most seriously. Structural analyses indicated that 463R, 465R~468R and 470R had become deficient in structural capacity and had to be reinforced. It was finally decided to install steel segments in 459R to 471R as secondary lining. Because of the squash of the tunnel, the invert slab between 450R to 473R became detached from the tunnel and had to be replaced.

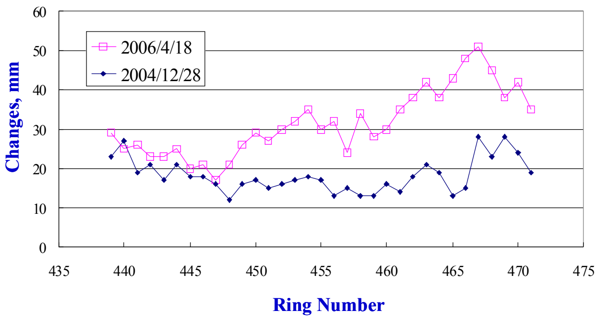

Fig. 15 Case 3- Convergences of linings

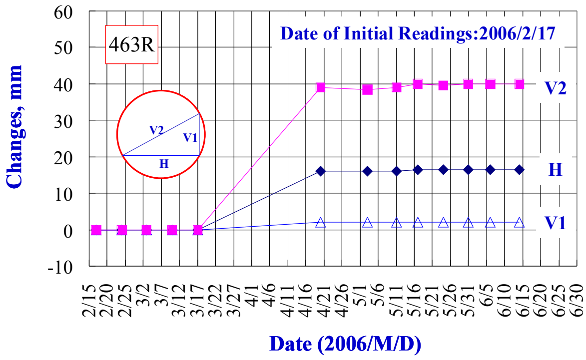

Fig. 16 Case 3- Convergences of 463R

The cause of the event is rather difficult to ascertain. It has been attributed to grouting pressure during CCP installation (Ju, et al., 2007). The accusation, however, is not supported by data. Take 463R for example, configuration survey conducted on 17 March, 9 days after the completion of CCP piles, indicated that the tunnel was stable with nil changes in diameters as shown in Fig. 16. In fact, it is inconceivable for the tunnel to be damaged by grouting carried out at positions above the crown, refer to Fig. 13, because it is very unlikely for grout to run downward except in very rare situations.

As shown in Fig. 13, although the upper portion of the trench was protected by CCP piles, the lower portion was not. Therefore, localized collapse could have happened thereat. Even without collapse, large lateral ground movement could have been induced as a result of the relief of the horizontal geo-stresses. As shown in Fig. 14, Units #3M, #4F, #5M and #7M (M stands for male and F stands for female units) were installed within a rather short 5-day period between 24 and 29 March. Ground movements could partly be attributed to the fact that trenching was carried for secondary panels before the primary panels became stable. Unfortunately, instrument readings were not taken till 20 April.

To reduce ground movements during excavation, ground treatment was carried out at the corner next to the excavation, as depicted in Fig. 14, to the same depth of the bottom of the tunnel, i.e., 19m. Two rows of cast-in-place piles were installed immediately next to the wall, followed by 6 rows of cement-soil-mixing piles giving a total of 192 piles. All these piles were of 600mm in diameter. Excavation was resumed and successfully carried out to the final depth of 11.9m.

4 CONCLUSIONS

Based on the observations made in these three cases and in many others, it can be concluded that:

(1) the trenches must be protected to prevent the side walls from collapsing if diaphragm walls are to be installed within 6m from metro tunnels and to depths below the tunnel crowns.

(2) localized ground treatment appears to be ineffective in reducing wall movements. For ground treatment to be effective, it should be all the way across the excavation to form continuous beams.

(3) even so, a single beam, or a single cross panel, will not be sufficient for the purpose in excavations with large spans.

5 REFERENCES

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