Response of a Taipei Rapid Transit System (TRTS) tunnel to adjacent excavation

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ABSTRACT

During the construction of the Taipei Rapid Transit System (TRTS) tunnels, a section of tunnel in the Panchiao Line was damaged as a result of adjacent excavation. Cracks appeared in reinforced concrete segments, the concrete slab on the invert was displaced and detached from the segments. The event is a valuable case history for establishing criteria regulating excavations to be carried out adjacent to existing tunnels.

KEYWORDS: shield tunneling, monitoring, deep excavation, damage

1. INTRODUCTION

Subsequent to the completion of a section of the Panchiao Line tunnels of the Taipei Rapid Transit System (TRTS) in November 1995, excavation was carried out to the east of the tunnels for a highrise building with a 5-level deep basement. The plan and section of the excavation site adjacent to the tunnels are shown in Figs. 1 and 2. To safeguard these tunnels, ground response was closely monitored by using inclinometers. Furthermore, instruments were installed on tunnel segments to measure the stresses and strains induced. Readings of these instruments indicated significant movements of the up-track tunnel and failure of structural members due to the excavation. Cracks were observed in the segments. The concrete slab on the invert was dislocated and became detached from the segments due to distortion of the tunnel linings. The down-track tunnel, however, was not affected.

2. GROUND CONDITIONS

As shown in Fig. 2, the subsoils at the site consist of a sequence of alternating silty clay (CL) and silty sand (SM). Underlying these clay and sand layers is a thick layer of gravels (GM) which is extremely permeable and is very rich in water reserve. Because of excessive pumping for drawing water from this underlying gravelly layer in the past, the hydraulic pressures in the overlying subsoils were once much lower than their current levels. Therefore, the silty clays were mildly over-consolidated with Su values generally increase from 15 to 40 kPa with depth. The SPT N-values in the silty sands generally vary from 10 to 40.

3. The TRTS TUNNELS

As shown in Fig. 3, the two tunnels have an internal diameter of 5.6m and are lined by reinforced concrete segments of 250mm thick and 1m wide. Segments are bolted together by curved bolts.

The tunnels were bored by using an earthpressure balancing (EPB) shield tunneling machine of 6240mm in outer diameter. The machine was launched from the shaft located at the southern end of the up-track tunnel and made a u-turn at the shaft located at the other end for boring the down-track tunnel. The shell of the machine was abandoned in the down-track tunnel upon the completion of the tunneling in November 1995. Subsequently, reinforced concrete slabs were cast on the inverts of the two tunnels and rails were laid.

4. ADJACENT EXCAVATION

The excavation for constructing the highrise building to the east of the tunnels was commenced 9 months later in August 1996. The building has a 5-level basement and excavation, as shown in Fig. 2. The excavation was carried out to a depth of 21.1m. The excavation opening was supported by diaphragm walls which extended to a depth of 36m below surface. Concurrent with the main excavation, a passageway was constructed to connect this building to the TRTS station located south of the tunnels. The western wall of the passageway was retained by a row of bored piles of 600mm in diameter and 13m in length. To enable this passageway to be excavated together with the deep basement at the same time, the top 7.6m of the diaphragm wall between the two was left un-cast.

To reduce the lateral movements of the retaining wall close to the tunnels, ground improvement was carried out in an area of 46.5m in length and 21m in width. High pressure jet grouting was carried out in 23 rows with a typical spacing of 2.2m, center to center, and was carried out to a depth of 5m below the base of the excavation prior to the commencement of excavation.

Excavation started in August 1996 and reached its final depth in late May 1998. The excavation program is shown in Fig. 4. The excavation was braced by 5 levels of struts which were preloaded to reduce wall movements as shown in Fig. 2.

5. OBSERVATIONS

In the area shown in Fig.1, there were 6 inclinometers (SIS603~SIS608) alongside the up-track tunnel for monitoring the ground response near the tunnel and 2 inclinometer (SIS611~SIS612) immediately next to the diaphragm wall of the adjacent deep excavation for monitoring wall movements. Inside the up-track tunnel, there were 12 survey points (ST601~ST612) mounted at the center of the concrete slab (Fig. 3) and 12 telltales mounted across joints between segments. Furthermore, the movements of the tunnel were measured by wriggle survey and the deformations of rings were monitored by configuration survey.

In July 1998, it was observed that a portion of the concrete slab running from Ring No. 6 to Ring No. 70 in the up-track tunnel was detached from the tunnel segments leaving gaps of up to 20mm. Cracks were also observed at the tunnel crown in a 39m stretch running from Ring No. 11 to Ring No. 49. The widths of cracks varied from 0.05mm to 0.25mm. Furthermore, there was an offset of 10mm between Ring No. 24 and Ring No. 25 at the crown. The down-track tunnel, however, was unaffected.

5.1 Lateral Ground Movements

Figure 5 shows the readings of Inclinometer SIS611 at various dates. This inclinometer was very close to the diaphragm wall and the readings obtained are thus more-or-less representative of the wall movements. As can be noted from the readings that much lateral movement were induced in May 1998 in which the last stage of excavation was carried out. Subsequently, the wall appeared to be stable and very little movements were observed till the end of construction as evidenced by the small difference between the readings obtained on 2/5/99 and those obtained on 5/31/98.

A maximum wall displacement of 53mm was recorded by SIS611 at the end. It however should be noted that this inclinometer was installed in June 1997 when excavation had already reached a depth of 8m. Furthermore, the abrupt reduction in lateral movements of 20 to 30mm at depths of 12m to 19m was caused by grouting carried out in November 1997 to seal off leakage at joints between diaphragm wall panels. The profile denoted as "Adjusted Final" in the figure includes the following modifications to the readings:

a. Adding the wall displacements induced prior to the installation of the inclinometer as calculated by using the computer program RIDO
b. Removing the effects of grouting by judgment

With these modifications, the maximum wall displacement is estimated to be about 63mm.

Figure 6 shows the readings of inclinometer SIS605, which was very close to the eastern edge of the up-track tunnel. As can be noted that a maximum lateral movement of 54mm was recorded at a depth of 17.5m which incidentally corresponds to the depth of the center of the tunnel. It can also be noted from the figure, by comparing the data obtained on 7/31/98 with those obtained on 11/26/98, the lateral movements of the ground at this location were significantly large, two months after the excavation had reached its final level and the diaphragm wall had become stable.

The readings obtained at the depth corresponding to the center of the tunnel are shown in Fig. 7. It can be noted that the lateral movement of this inclinometer was about 37mm when the excavation reached its final level in late May. It then increased to 44mm in late July. At the same time, cracks in segments were observed.

5.2 Movements of Tunnel

The lateral movements of the up-track tunnel were obtained by wriggle survey and the results are compared with inclinometer readings in Fig. 8. The data points for the centers of rings, as expected, fall between those for the inclinometers on the two sides of the tunnel. The 19mm difference in movement between Ring No. 24 and Ring No. 25 is qualitatively compatible with the observation that the two rings had an offset of 10mm or so at the crown. The movements of other segments appear to be consistent with the “idealized movements profile” shown in Fig. 8.

As indicated in the lower part of Fig. 8, the vertical movements of the tunnel varied from 20mm to 33mm for the segments measured. These movements had little to do with the lowering of groundwater table because it has been found that groundwater table was stable during the period of excavation. A small fraction of these movements could be attributed to the earth filling work carried out on ground surface. This, however, is beyond the scope of this paper.

Shown in Fig. 9 are the convergences of linings in the up-track tunnel obtained by configuration survey. Ring No. 24, which appears to be the most affected, was shortened by 45mm in the vertical direction and elongated by 26mm in the horizontal direction. In theory, the squashing of the tunnel would increase the lateral movements of inclinometers on the eastern side of the tunnel and reduce the lateral movement of inclinometers on the western side. For this reason, refer to Fig. 8, the lateral movement of SIS606 was westward instead of eastward.

There were 12 telltales to measure the widening of joints between segments. All of them showed sudden changes, up to 1mm, on 20 July 1998. It definitely have something to do with the detachment of the concrete slab with the segments. The possibility that some of the structural elements failed cannot be ruled out.

5.3 Movement of Slab

Lateral movements of the concrete slab at the invert of the tunnel were measured at 12 locations, i.e., ST601~ST612, and the readings are shown in Fig. 10. The movement ranged from 13mm to 18mm for the segments measured and were fairly uniform. This range is qualitatively comparable with the lateral movements of the center of the tunnel shown in Fig. 8, except for two of the rings, Rings No. 24 and 35 of which the movements were comparatively large. It is reasonable for the slab to have smaller movements than the tunnel center because the slab is three meters below the tunnel center, where the lateral ground movements were the greatest (as shown in Fig. 6). Furthermore, the slab was detached from the segments leaving gaps of roughly 20mm between the two.

The readings of ST609 are plotted for a period of about 18 months from June 1997 to November 1998 in Fig. 11. It appears that the movements of the slab were negligible till 20 July. Then, the slab suddenly moved by 10mm or so. This phenomenon is rather inconsistent with the inclinometer readings (Figs. 6 and 7) which showed continuing movements over the several months prior to July and afterward. It is highly unlikely for the slab to become detached from the tunnel segments in the early phase of excavation. Therefore, it is unsure whether the tunnel indeed moved with the inclinometer all the time. Unfortunately, there is only one set of wriggle survey and the history of movement of the tunnel cannot be traced.

The vertical movements of the slab were also monitored and the readings are shown in Fig. 10. Contrary to the tunnel centers, the readings showed heaves of the slab at all these locations. A maximum heave of 15mm was observed at the location of Ring No. 26. The heaves at this location are plotted in Fig. 11. Judged by the fact that a sudden lateral movement occurred on 20 July 1998, it is believed that the vertical movements also occurred suddenly on that day.

6. DISCUSSIONS

Safety of tunnel as affected by adjacent excavation activities has been a primary concern and various regulatory agencies have attempted to establish criteria to restrict ground movements to be induced (Shirlaw et al 2000, Doran et al 2000). Because of the lack of case histories on damages to tunnels, most of the criteria adopted were more or less arbitrary (Richards 1998).

6.1 Performance of Tunnel

It would be of interest to investigate how much movement this tunnel can tolerate without structural damages. Although failure appears to occur on 20 July 1998, signs of distress were noticed in segments in February 1998. The idealized movement profile shown in Fig. 8 are the deviations of the center of the tunnel from the original alignment and the maximum deviation was estimated to be 27mm. Data are insufficient for determining what the movements were in February 1998. As shown by the measurements in Figs. 6 and 7, the ground continued to move after February 1998. However, it is unsure whether the tunnel followed the ground. With considerable judgment, it is assumed that the movements of the tunnel center in February 1998 were 70% of the idealized movements shown in Fig. 8. The maximum movement is then estimated to be of an order of 20mm in February 1998 and this magnitude may be considered as the allowable movement of this tunnel. It is fully understood that maximum movement is not a governing factor in evaluating the safety of tunnels. It is the curvature of the movement profile that matters. However, from a practical point of view, maximum movement is certainly an important index in evaluation of the safety of a tunnel.

It should be noted that since tunnels behave as beams, the damage potential would depend on their alignments in relation to the directions of ground movements. If a tunnel bulges toward the excavation as is the case presented here, it is more susceptible to damages because the tunnel will be lengthened as the ground moves and the joints tend to open up. If it bulges away from the excavation, it is less susceptible to damages because the joints tend to close up due to arching effects.

It is understood that vertical movements are equally important in the evaluation of safety of tunnels. Similarly, a tunnel with a sagging profile is more susceptible to damages and a tunnel with a hogging profile is less susceptible.

The performance of the up-track tunnel was affected by the adjacent excavation and repair work was subsequently carried out (Chang et al 2001).

6.2 Monitoring of Performance of Tunnel

Based on the data presented, it is clear that inclinometer readings are not representative of the movement of the tunnel. Squashing of tunnel lining should be considered if inclinometers are used to monitor the performance of a tunnel. In the case discussed here, an allowance of 10 to 20mm shall be added to or subtracted from, depending on which side of the tunnel the inclinometer is installed, the inclinometer readings to obtain the movements of the center of tunnel.

6.3 Soil-Tunnel Interaction

The excessive movements of Rings No. 24 and 35 suggest that the tunnel behaved as a beam resisting ground movements until it could no long hold. The large differences between the movements of the tunnel and the movements of the ground are rather surprising because it has been expected that long tunnels with thin segments tightened by curved bolts would offer little resistance to ground movements. In the case studied, the concrete slab at the invert must have significantly increased the rigidity of the tunnel. The rigidity of the tunnel greatly exceeds the rigidity of the surrounding soils.

When the potential risk is assessed prior to excavation, ground response is normally analyzed without considering the presence of tunnel. Since tunnels behaved as beams which will reduce ground movements in soft ground, it is necessary to take this effect into consideration to achieve a more comprehensive assessment.

7. CONCLUSIONS

Based on the data presented, the following is concluded:

1. The movement which can be tolerated by a tunnel will depend on the shape of tunnel alignment.
2. Inclinometer readings are not representative of movements of a tunnel and adjustments shall be made to account for the squashing of tunnel lining.
3. Tunnels behave as beams and will reduce ground movements induced by adjacent excavation and ground engineering activities.

Although the case presented in this paper is an isolated one, it nevertheless suggests that shield tunnels with a similar design are vulnerable to ground movements of small magnitudes.

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REFERENCES

Chang C-T, Wang M-J, Chang C-T and Sun C-W, (2001), Repair of a displaced shield tunnel of the Taipei Rapid Transit System. *Tunnelling and Underground Space Technology*, Vol.16(3)

Doran, S.R., Wood, T., Tham, S.K., Copsey, J.P., Shirlaw, J.N. and Wen, D., (2000), The assessment of limits for the movement of subway tunnels and trackwork due to adjacent construction. *Tunnels and Underground Structures*, edited by Zhao J., Shirlaw, J.N. and Krishnan, R., Balkeme, Rotterdam, pp.495-500.

Richards, J.A., (1998), Inspection, maintenance and repair of tunnels: international lessons and practice. *Tunnelling and Underground Space Technology*, Vol.13(4), pp.369-375.

Shirlaw, J.N., Tham-Lee, S.K., Wong, F.K., Ang-Wong, L.P., Chen, D.C., Osborbe, N. and Tan, C.G., (2000), Planning the monitoring required to confirm the movement and rotation of tunnels and trackwork due to excavation and tunneling. *Tunnels and Underground Structures*, edited by Zhao J., Shirlaw, J.N. and Krishnan, R., Balkeme, Rotterdam, pp.489-494.

Sinotech, (1999), Effects of Adjacent Construction to Existing TRTS Tunnel, a Report submitted to the Department of Rapid Transit Systems, October, 1999 (in Chinese).

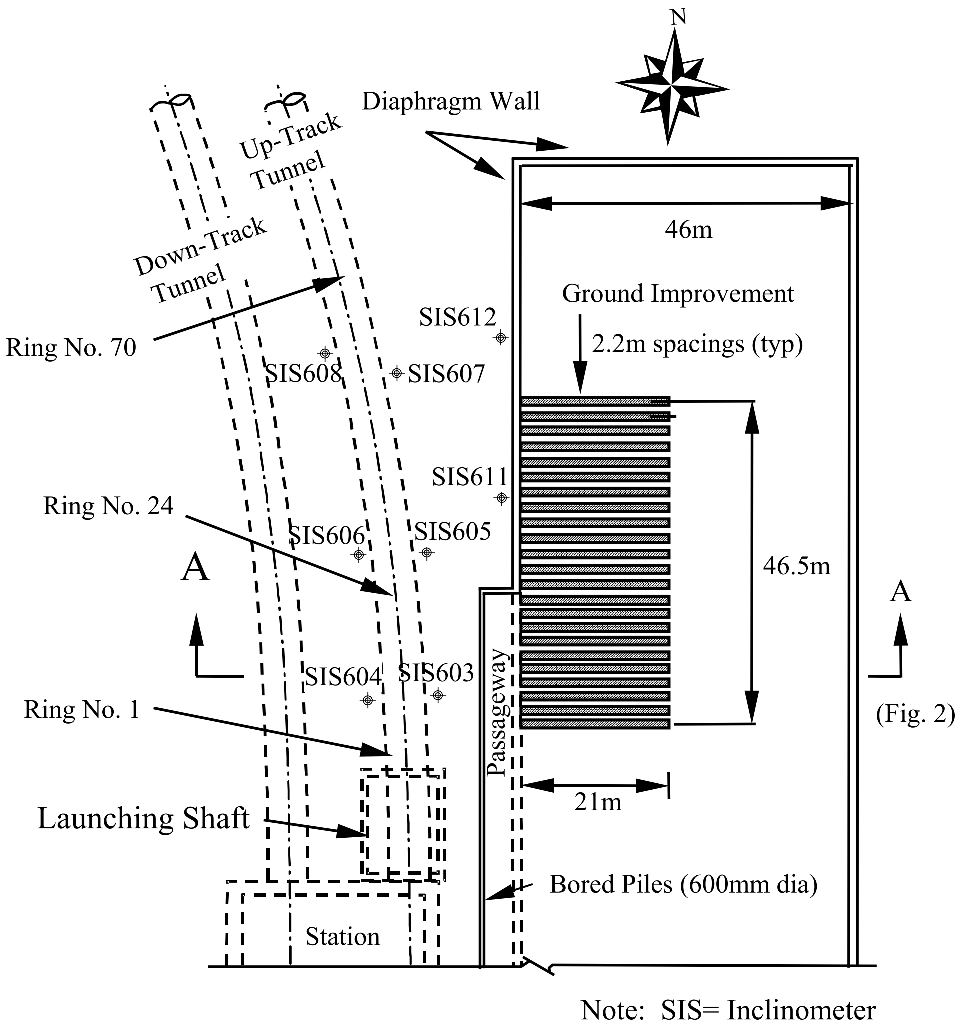

Fig. 1 Site Plan

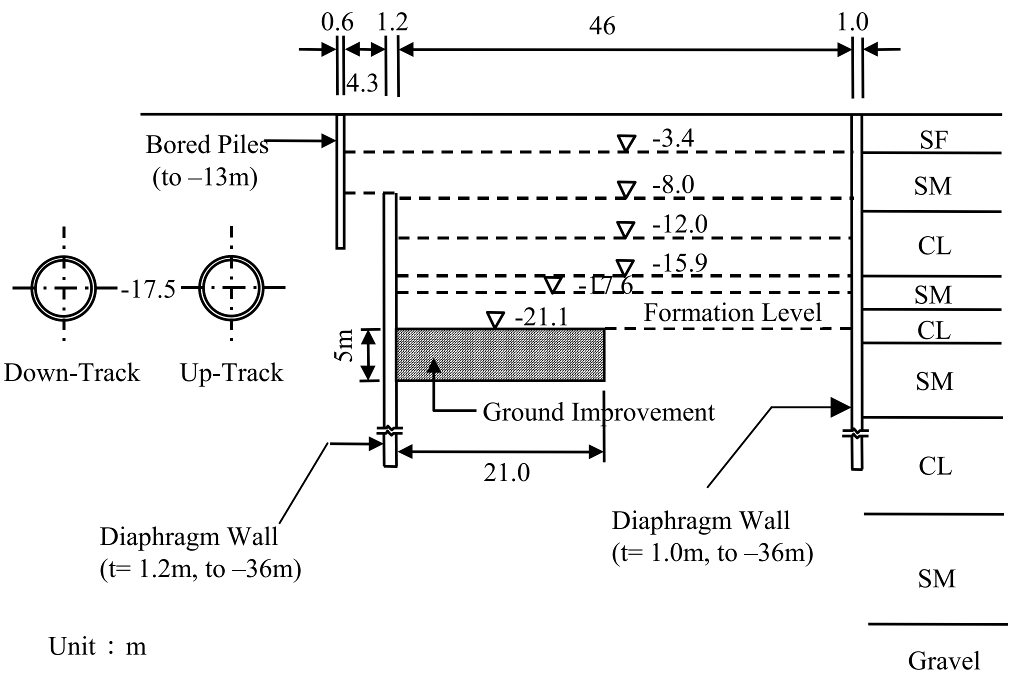

Fig. 2 Section A-A

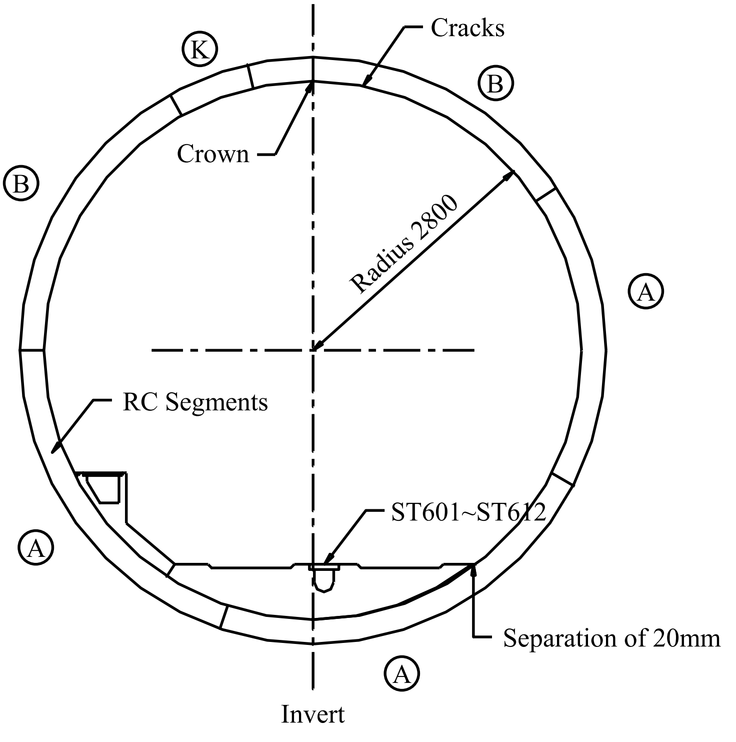

Fig. 3 Configuration of Tunnel

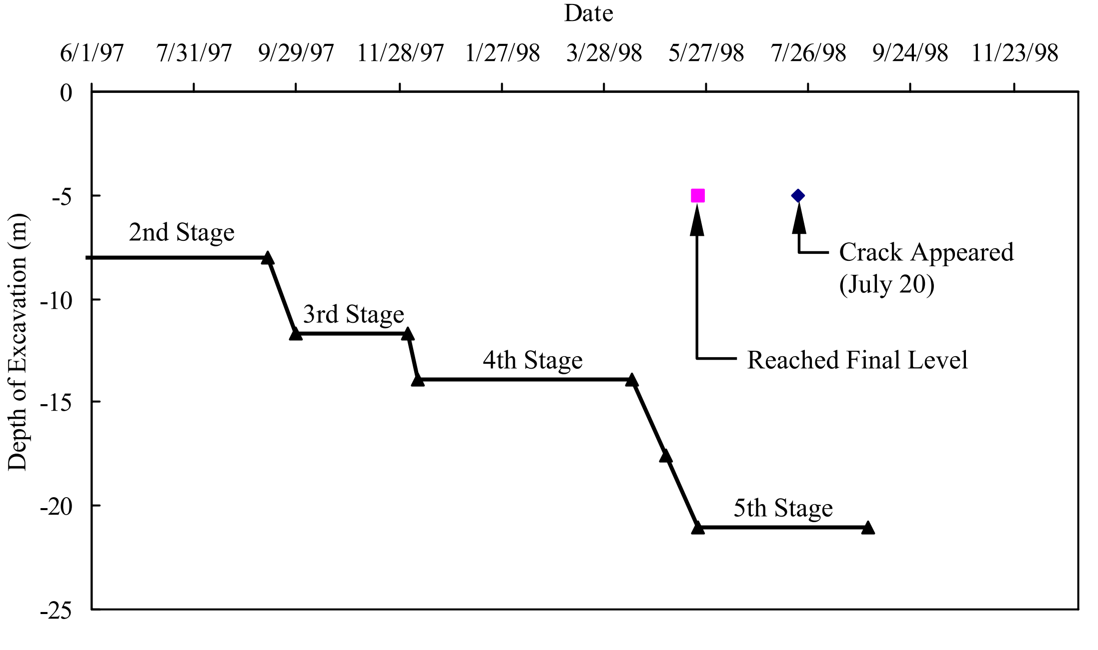

Fig. 4 Progress of Excavation

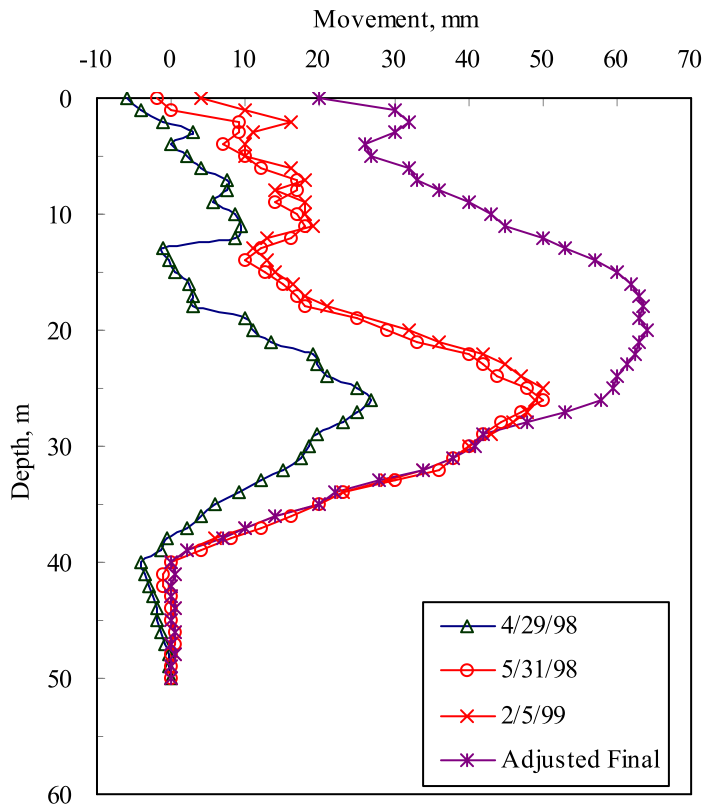

Fig. 5 Lateral Movements of Inclinometer SIS611

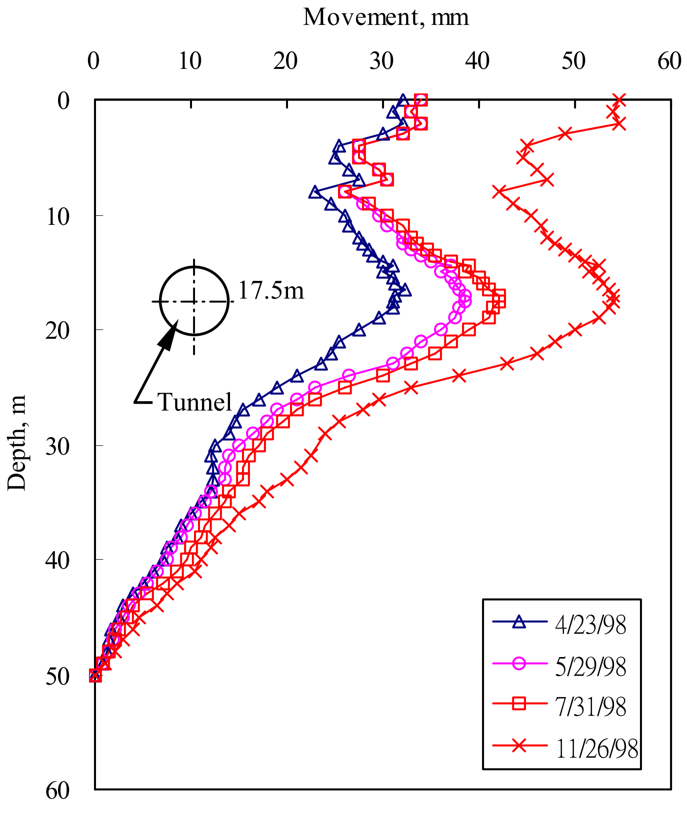

Fig. 6 Lateral Movements of Inclinometer SIS605

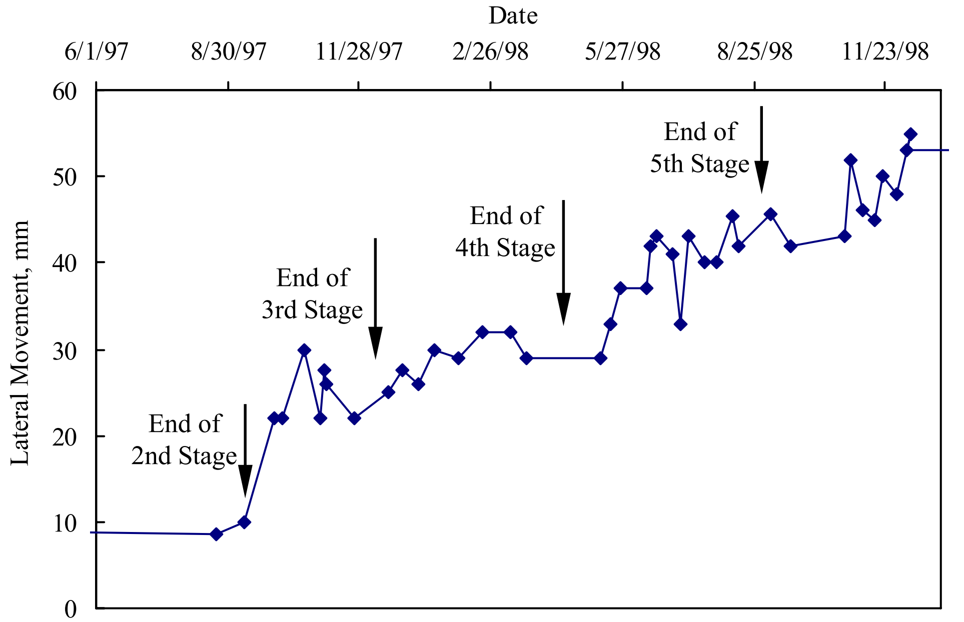

Fig. 7 Lateral Movements of Inclinometer SIS605 at Depth of Tunnel Center

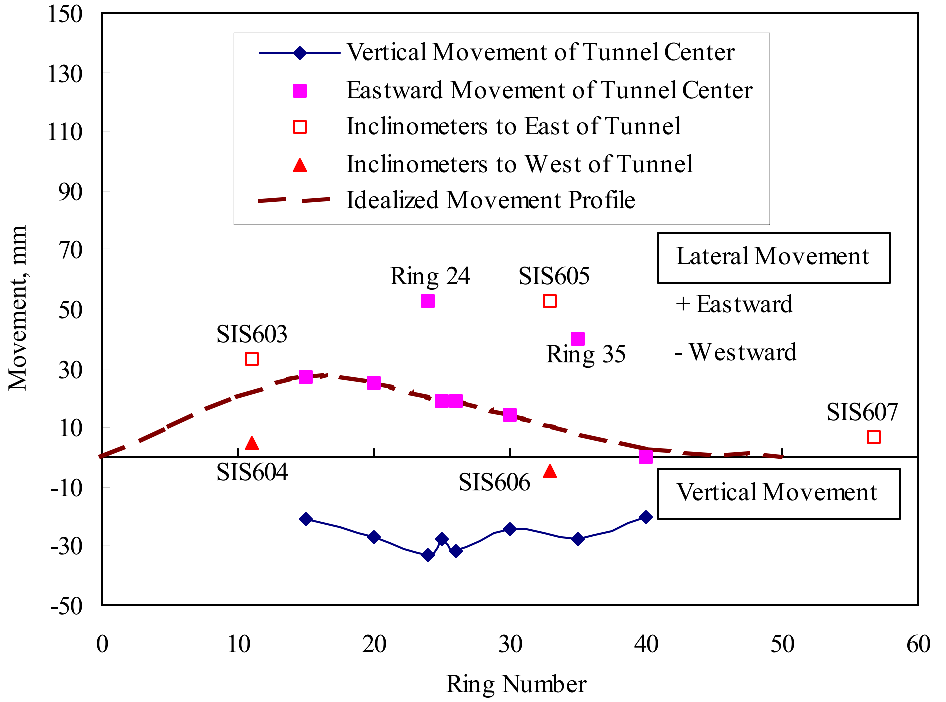

Fig. 8 Movements of the Center of the Up-Track Tunnel (Dec. 98)

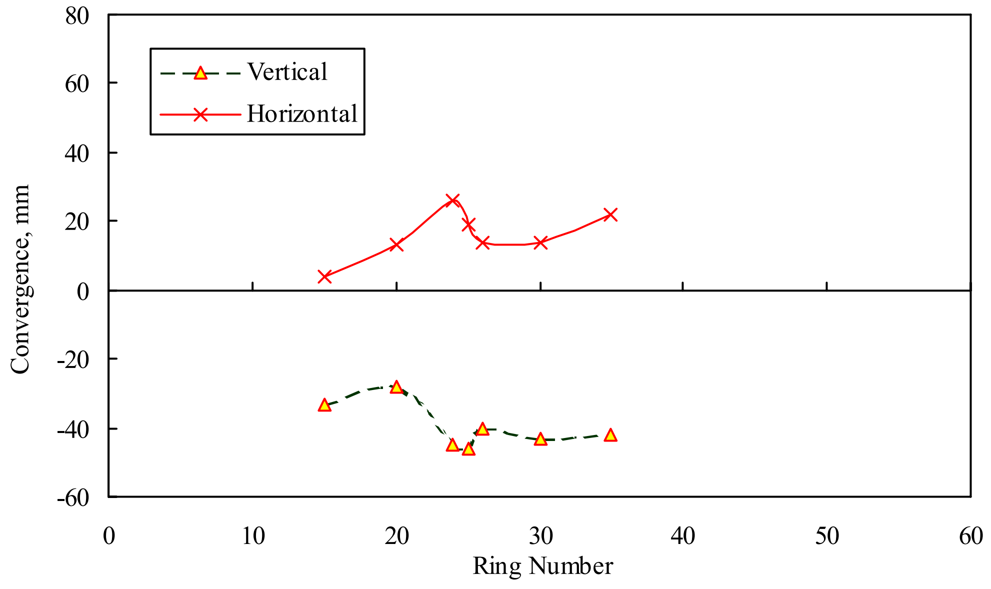

Fig. 9 Convergence of Linings of the Up-Track Tunnel (Dec. 98)

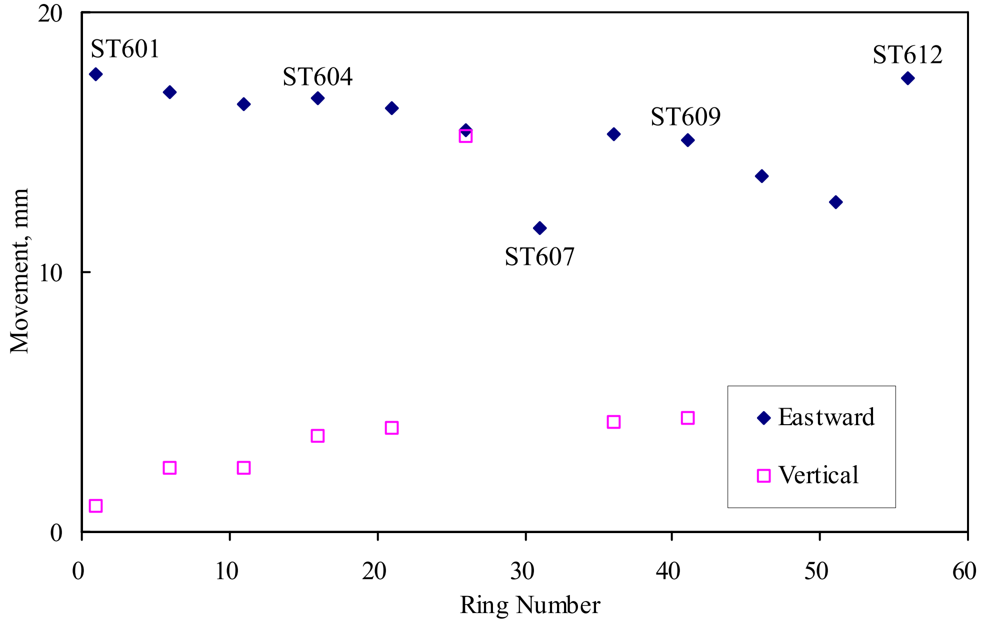

Fig. 10 Movements of the Concrete Slab (Dec. 98)

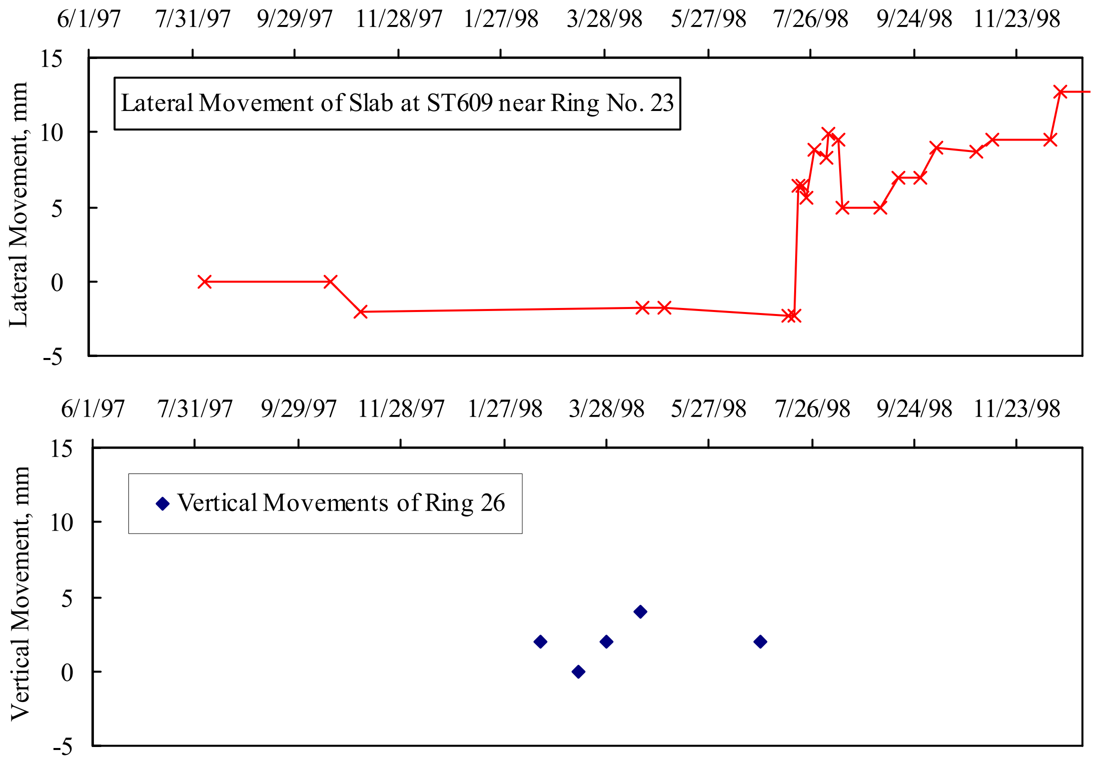

Fig. 11 Movements of Concrete Slab