REPAIR OF DISPLACED SHIELD TUNNEL OF THE TAIPEI RAPID TRANSIT SYSTEM

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ABSTRACT

A section of completed shield tunnel of the Panchiao Line of the Taipei Mass Rapid Transit (TRTS) was deformed and displaced due to an adjacent excavation. It was observed that the segments in the invert were separated from the concrete behind, and cracks were formed in the crown. In order to ensure the shield tunnel section meeting the structural safety requirements set out by TRTS, the tunnel underwent repair work. This paper describes the damages, discusses the selection of repair method, and outlines steel segment erection operations. It is the authors’ hope that the case presented would serve as a reference to other similar cases.

Keywords: shield tunnel, tunnel repair, concrete segment lining, steel segments.
1. INTRODUCTION

Underground constructions would unavoidably cause deformation and displacements to the ground and buildings nearby. Similarly grounding engineering adjacent to an underground structure would also cause deformation and displacements to the underground structure (Richards 1998). This paper describes a Taipei Rapid Transit System (TRTS) shield tunnel that was subjected to a nearby construction operation, and has deformed to such a degree that repair was unavoidable. Judging from the fractures and separation of the invert from the tunnel, the structural strength and integrity of the tunnel had been affected. Based on consultation and careful evaluation with the design consulting firms of both the TRTS and the nearby construction project, geotechnical experts and the contractor, strengthening the tunnel with steel inner lining was selected as the method of reinforcement. Detailed operation is presented in the following sections.

2. SITE CONDITIONS

Excavation of up-track tube of the shield tunnel began in July 1994 from the departure shaft. In March 1995, the excavation reached the U-turning shaft, and the excavation of the down-track tube commenced in June 1995. In November of the same year, all of tunnel excavations were completed. Constructions of nearby skyscrapers, began in July 1996, and the basement constructions were completed in September 1998. The Panchiao Station situated to the south of the shield tunnel began excavation in August 1998, the basement constructions were completed in July 1999. In July 1998, the contractor for the shield tunnel discovered that the invert in the up-track tube of the shield tunnel had separated from the tunnel, and hairline cracks were found in the crown (Sinotech 1999, Chang et al 2001). Fig. 1 illustrates the relative locations of the structures concerned.
3. DAMAGES OF THE SHIELD TUNNEL

On 20 July 1998 following discovery of displacement of the shield tunnel, surveying on tunnel displacement was conducted by the TRTS Surveying Team, together with the shield tunnel contractor, and the contractor of the nearby high-rise buildings. Due to differences in surveying precision, the results were drastically different. In December 1998, the shield tunnel contractor conducted yet another surveying on the crown, invert of the tunnel, the coordinates and elevations of two points on either side of the horizontal diameter of the tunnel. The surveyed results were compared with result of complete loop surveying performed in the up-track tube upon completion of the tunnel. Table 1 presents the two surveying results.

Another surveying was then performed by the shield tunnel contractor using an optical surveying instruments. The result showed the cracks were formed from segment rings 11 to 49. Opening of these cracks ranged from 0.05 to 0.25 mm. These cracks were mostly found on odd-numbered segment rings to the side that was located closer to the nearby construction site. In segment rings 21 and 25, the cracks were more concentrated and wider in opening. These phenomena agreed well with lateral load relieve of soil in the nearby construction site that would cause a greater deformation centering around segment rings 20 ~ 25. There is a 10 mm protrusion between the K-segment in the crown of segment ring 24 and the adjacent B-segment of the same ring. Observing the separation of the in-filling materials indicated that the separation was 5 mm, while the remaining 5 mm was attributed to error in the original segment installation.

The deformation of the shield tunnel was elliptical in shape, leading to a separation of the completed invert from the tunnel segment rings. The largest separation gap was about 20 mm.
4. FACTORS CONSIDERED IN REPAIRING METHOD SELECTION

Based on the damages of the shield tunnel, two possible repair methods have been proposed. The first method took into consideration of the cracks in the shield tunnel and loosening of the ground beyond the tunnel induced by the displacement, and proposed to repair the damaged tunnel with reinforcement by applying six layers of carbon fiber, and to improve the ground outside of the tunnel. The second method involved replacing the damaged segment with steel segments, and thus replacing the affected segment structure with the steel linings. In the second option, no ground improvement would be required. Steel segments would be designed to meet the original designed strength of the tunnel lining. In theory, the residual strength of the damaged concrete segment would no longer be utilized, and would be completely replaced by the steel segments. Extensive review was conducted, and the advantages and disadvantages of these two options are summarized in Table 2.

The main drawback of the carbon fiber reinforcement method lied in the fact that the bonding strength and the bonding length between the shield tunnel segment and the carbon fiber could not be ascertained, and its effect in preventing enlargement of cracks in the tunnel also could not be ascertained. Furthermore, cracks on the outer side of the damaged tunnel linings could not be repaired. Should the depths of cracks on the outer side of the damaged tunnel linings exceed the protective layer, then after a prolonged time period, corrosion of rebars in the concrete segment would reduce the strength of the segments, that might lead to eventual failure of the segments. In addition, grouting outside of the shield tunnel might subject the surrounding soil to disturbance, hence consideration should be given to possibly further displacement of the tunnel. The second option required detailed calculation on the clearance of the tunnel. Steel segment installation demanded precise, delicate adjustment. Should settlement occur again in the future, there would be insufficient clearance for rail operation.
Results of instrumental monitoring indicated that the tunnel had been gradually approaching stabilization since December 1998. The need to improve the ground surrounding the tunnel was greatly reduced. Following the above-mentioned points of consideration and careful comparison, the second method was considered a better option.

5. STEEL SEGMENT ERECTING OPERATION

Site observation indicated that hairline cracks occurred on segment rings 11 to 49. It was recommended that additional steel segment should be installed to provide additional support to segment rings 10 to 50. The erection operation of the steel segment followed the following steps:

a) Evaluating the clearance;

b) Manufacturing of segments;

c) Dismantling invert and walkway;

d) Erecting of steel segments and back-fill grouting;

e) Invert and walkway concrete placing.

5.1 Evaluating Clearance

The prerequisite for the additional steel segment inner lining is that there should be adequate clearance for safe operation of rapid transit trains. The section of the damaged shield tunnel is on an in-turning curve, the clearance is controlled by the shifting of the central point of the trains. Calculation using horizontal lineament (R=280 m), and dynamic train clearance enveloping curve revealed that installation of 100 mm steel segment was acceptable for the desired clearance for the
trains, with the width of the maintenance walkway be reduced to 550 to 450 mm. This reduction in walkway would not affect future operation of the transit system.

5.2 Manufacturing of Steel Segments

 Manufacturing of steel segments was under very strict control to ensure that the quality would meet the designed safety strength requirement. Strict quality control commences with design drawing, locating, cutting and trimming, welding and pre-erecting. Every step was close examined. High tensile strength steel and bolts were used. The quality controls are illustrated in the flow chart below:

5.3 Dismantling of Invert and Walkway

Utmost care was exercised in dismantling of the invert and walkways in order that the tunnel segments would not be accidentally damaged in the process. To achieve this goal, dismantling of the invert was conducted through drilling of boreholes in arranged rows. The entire operation is briefly described below.

a) Flexible steel measuring tape was inserted into cracks separating the invert and segment to probe the depth. It was found that the cracks were as deep as over 3 m. Hence, borehole rows arranged in 40×50 and 50×50 cm squares were drilled (Fig. 3), a number of separate blocks was thus isolated to facilitate dismantling of the invert.

b) A light portable machine was used to apply lateral pressure to the isolated blocks, thus separating the concrete blocks from their base for easy removal.
c) Small chips or debris of concrete were cleared manually, followed by water-jet blasting, and then air dried.

Dismantling of the invert and erection of the steel segments were performed every ten rings in one shift. When the invert in one shift had been removed, the steel segments were immediately installed. Following completion of steel segment erecting, the next shift of invert dismantling begun. This was performed with the purpose not to cause deformation of the newly installed steel segments due to vibration from removing of the invert.

5.4 Steel Segment Erection and Backfill Grouting

Considerations for steel segment installation involved issues on lineament and clearance. The operation procedures are briefly presented below.

a) Locating:

The center of the track was determined following surveying, locating was performed in accordance with the amount of displacement. The center of the tunnel, point a, was determined on the bottom of the original segment, then points b and g were allocated on the concrete segment (Fig. 4).

b) Assembling the segment erector:

The segments were erected using a segment erecting machine. The segment erector was first assembled at a location between concrete segment rings 9–14. It was secured by means of supporting arms on the concrete segment. Once set, segment erection would commence one by
c) Installing base steel segments A-1 and A-2:
   i) Segments A-1 and A-2 were hoisted by the segment erector crane and placed on the invert (Fig. 4).
   ii) Adjust the joints between the segments such that the joint is aligned with the central line of the tunnel. Secure temporarily with screws, and check the height of the bottom of the segments. Should the height be insufficient, raise the segments and place cushion pad to fix, adjust the screws and secure the segments.
   iii) Check the heights of points b and g, as well as net width D at the top. Use the erector to adjust the screws to secure the top of the segments.
   iv) To ensure that installing the next set of segment would not affect the finished segment sets, use fixation device on the segments to link up with concrete segments.

d) Installing upper segments:
   i) Move and install segment A-3 using the erector. Secure the bottom screws and support the segment using temporary supporting assembly (Fig. 5).
   ii) Install segment A-4 through the same procedures.
   iii) Move and install segment A-5 using the erector. Secure the bottom screws and support the segment using temporary supporting assembly (Fig. 6).
   iv) Erect segment B through the same procedures.
   v) Erect segment C by pushing it sideways, and secure temporarily with screws (Fig. 7).
   vi) Check left and right side clearance and the central line of the tunnel. If necessary, adjust the screws and then fix them.
   vii) Inspect that all securing screws are well secured, and then remove temporary support assemblies.
viii) Install a supplementary fixation lever into the screw hole in the completed segment to prevent the segment from moving.

ix) Repeat this procedure for installation and erection of all other segments. However, after segment 2, no temporary supporting is required.

x) To ensure electrical continuity, a $\phi 5$mm bare steel wire is installed each steel segment.

Steel segment erection and installation flow charts are shown in Figure 8. When erection of segments is completed, the void between the steel segment and the original concrete segment is filled through grouting. The grout is a non-shrinking mortar. Grouting follows the steps below:

a) Following an up-stage grouting sequence, open the grout hole on the steel segment.

b) Commence grouting from the grout hole in segment A-1. The upper portion of the grout hole also served as vent pipe and observation hole.

c) When grout starts to flow out of A-3 and A-4 grout holes, close A-1 grout hole, and begin grouting through A-3 and A-4 grout holes, stop grouting when grout starts to flow out of grout hole on C segment.

d) Seal off the grout holes.

5.5 Invert and Walkway Concrete Placing

The procedures for invert and walkway concrete placing are as follows:

a) Cleaning of surfaces of the segments;

b) Locating;

c) Install fixed frames and drain pipes;

d) Erecting rebars and L-steels;
e) Placing and curing of concrete.

6. CONCLUSIONS AND RECOMMENDATIONS

During the installation of the steel segment, tunnel horizontal and vertical diameter were estimated prior to removal of the invert. When segment installation was in progress, it was found that the actual final tunnel vertical diameters were smaller than the estimated values. Consequently, installation of segments was performed in a very tight and cramped space, rendering the adjustment for good clearance and true circular cross section virtually impossible. Prior to the installation of steel segments, estimations on the lineament of the concrete segment, and clearance and cross section diameters should be very precise. Manufacturing of steel segment should be of the highest quality to avoid difficulty in installation.

Invert removal would induce vibration that might cause further deformation of segments. It is recommended that during removal of the invert, monitoring should be performed.

Not only civil engineering issues should be given due considerations; overall consideration including electro-mechanical issues should also be given fully.

REFERENCES


Figure Captions

Fig. 1 Plan showing the relative locations of the structures concerned.

Fig. 2. Flow chart of steel segment manufacturing operation.

Fig. 3. Boreholes drilled for dismantling of invert.

Fig. 4. Segment erection (1).

Fig. 5. Segment erection (2).

Fig. 6. Segment erection (3).

Fig. 7. Segment erection (4).

Fig. 8. Flow chart for segment erection.
Table 1 Comparison of survey results before and after deformation of shield tunnel

<table>
<thead>
<tr>
<th>Segment number</th>
<th>Estimation basing on January 1996 survey results</th>
<th>Estimation basing on 10 December 1998 survey results</th>
</tr>
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<tr>
<td></td>
<td>Height of center (m)</td>
<td>Vertical diameter (m)</td>
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<tr>
<td>15</td>
<td>90.461</td>
<td>5.580</td>
</tr>
<tr>
<td>20</td>
<td>90.302</td>
<td>5.580</td>
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<td>24</td>
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<tr>
<td>40</td>
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<td>5.584</td>
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</table>

Notes:  
2. For vertical and horizontal diameter change: + denotes extension, - denotes shortening.  
3. Survey results of January 1996 were obtained through 8 monitoring points set on segment ring of the completed tunnel. From these 8 monitoring points, the centers and diameters of the segment were derived.  
4. In December 1998, the invert had been completed, the vertical and horizontal diameters were estimated from monitoring points on the springline, the crown, and the invert.

Table 2. Comparison of advantages and disadvantages of two repair plans

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Option 1: Carbon fiber and ground improvement</th>
<th>Option 2: Steel segments as inner linings</th>
<th>Remarks</th>
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<tbody>
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<td>Engineering cost</td>
<td>About 36,000,000</td>
<td>About 20,000,000</td>
<td>DDC estimate</td>
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<tr>
<td>Work duration</td>
<td>About 4 months</td>
<td>About 6 months</td>
<td>DDC estimate</td>
</tr>
<tr>
<td>Feasibility</td>
<td>More applicable</td>
<td>More difficult</td>
<td>Difficulty in moving steel segments</td>
</tr>
<tr>
<td>Reliability of strengthening result</td>
<td>Result of reinforcement cannot be readily ascertained</td>
<td>Result of reinforcement can be predicted and ascertained</td>
<td></td>
</tr>
</tbody>
</table>
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