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SEGMENT CRACKS AND ALIGNMENT ISSUES FOR TUNNELING CONSTRUCTION

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This study describes the causes of shield tunnel segment cracks and alignment issues during shield tunnelling. The study was conducted in Down Town Line 3 (DTL3) contracts 926 and 927 twin tunnel projects in Singapore. It is revealed that these issues arose when Tunnel Boring Machine (TBM) shoving on curve alignment though TBM is designed with articulation, which allows the machines to handle tight curves with ease. The study focused on how construction methodology affects the quality of tunnelling in terms of alignment and segment cracks. It was found that the clearance between the tail shield and tunnel lining was not maintained during mining. As a result, the tail shield exerts stress on the segments and causes cracks. In addition, the tunnel alignment deviated from pre-designed alignment, which directly affects the safety and durability of the shield tunnel. This study concludes that a proper selection of ring type “right lead” or “left lead” and the appropriate key selection, along with the skill of the workers, significantly solve segment cracks and alignment issues.

Keywords: TBM, Alignment, Cracks, Tail-shield clearance, Ring building.

1 INTRODUCTION

In recent years, the expanding scale of construction of underground tunnels is significantly influencing infrastructure development in Singapore. In Singapore, there are several underground tunnels under construction for various purposes, including Mass Rapid Transit (MRT), cable and service tunnels. Most of the tunnel alignments were not straight. The primary reason is that physical barriers, including pile foundations, utility service lines, and geology make for curved tunnel alignments along the tunneling route. Today, most tunnel construction is based on shield-tunneling methodology, which is significantly quicker for construction, and delivers durable underground structures. Excavation of shield tunneling using earth pressure balance or slurry tunnel-boring machines (TBM) are requiring precast segments to shield the tunnel (Hemphil 2013).

This paper outlines key issues to consider during shield tunnel construction. Segment cracks, damage, and alignment issues are analyzed using a case study of Down Town Line 3 (DTL3) contracts 926 and 927 twin tunnel project in Singapore. It was observed that most segment cracks and damage occurred in the construction stage. The tunnel alignments were between urban areas and canals. The DTL3 tunnel alignment curvature radius varied from 300m - 600m, and the tunnel diameter is 6.650m, and 15m - 20m below ground level.

2 TUNNEL ALIGNMENT

Tunnel alignment is both horizontal and vertical and is a crucial aspect for TBM shoving. Tunnel alignments are developed based on analytic data from geological investigations. Geological information may dramatically change the horizontal and vertical tunnel alignment, with the most accurate geological data influencing the design of tunnel alignments. The curvature of the alignment is inevitable when tunneling through urban areas and undesirable geological areas. Additionally, curvature alignment is a significant factor for the determination of train speed.

TBM guidance systems ensure that tunnels travel through correct passageways (Shen *et al*. 2012). However, there are cases where tunnels substantially deviate from pre-designed alignments due to construction difficulties, such as soil conditions and adjacent structures, and require possible realignment. Environmental factors and geological analyses must be considered when changing the alignment.

Any error in alignment will encroach on the clearance between the segment lining and the TBM shield, which causes segment cracks and damage. To accommodate the right alignment in some cases, the segment lining may not be built in the center of the tail shield, which makes it impossible to maintain a uniform clearance. The tendency of TBM to go out of alignment is due to the high speed and curvature of the alignment corridor. Perfect ring building and TBM operations may ensure a precise tunnel alignment. Precise tunnel alignment is especially important when tunneling through public buildings and roads as public safety would be at risk.

3 PRECAST SEGMENT AND SEGMENT CRACKS AND DAMAGE

Earth Pressure Balancing (EPB) tunnel excavation requires precast segments for shields. High quality, durable, and dense concrete is used to make the precast segments to increase the lifetime of tunnels (Rivaz 2010). Proper composition of aggregate and the cement-water ratio will help to avoid the spalling effect of concrete. Precast segments represent shielding the tunnels and must be dimensioned in accordance with geology and to withstand heavy loads. Primary, secondary and special loads must be considered when designing shield segments.

3.1 Types of Segments

In the DTL3 tunnels, two different types of segments in terms of orientations “R” and “L” are used in the construction of tunnel linings. One ring of the lining comprises 6 pieces of segment, such as the two-piece trapezoidal shape, the three-piece rectangular shape, and a key segment used for ring building. “L” type and “R” type tunnel linings are usually referred as right lead and left lead, respectively. “R” type of segments are always used in the right steering of the tunnel and “L” type of segments are used in the left steering of the tunnel. Lastly, a key segment is installed to lock that particular ring. The quality of the tunnel lining depends on the installation of the regular segments and on the installation of the key segment.

The DTL3 project tunnels are 6.650m in diameter. The outer diameter of the ring is 6.350mm and the segment thickness is 275mm. The ring width average is 1400mm, gradually increasing from 1380mm-1420mm (Figure 1). The 40mm difference in width allows for uniform tunnel steering. The lining segment is designed in such a way as to maximize and minimize width right angles to the key segment.

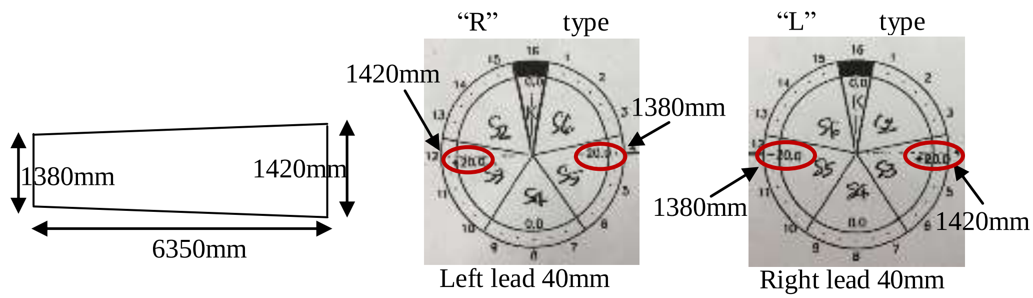

Figure 1. A ring with six segments that shows the left and right leads.

3.2 Segment Cracks and Damage

As an effect of analyzing several tunnel projects, the results of this study revealed that most segment cracks and damage occurred during the construction stage. We found that major segment cracks were in the axial direction. The following reasons were identified as main causes of cracks during the construction stage:

(1) Poor handling of segments during transportation:
Stripping, edge of segment shear off, and chipping at segment corners;

(2) Excess or eccentric or uneven thrust jack force exerted on the segments:
Apparently, the TBM system provides three hydraulic thrust jacks to uniformly apply the force to a segment;

(3) Inexperienced erector operator (impact load during the installation):
The segments are designed to be a conical shape in the middle of its inner side. The erector table is shaped to overlap with the conical inner side of the segments. Harmful movements between the erector table and segment cause spalling at the lifting point of the segment by the shearing. The segment erector operator's skill is crucial for the construction of an efficient tunnel lining.

During the ring building, the operator's awareness of pushing the thrust jack and releasing erector clamps from the segment-lifting pin is critical to avoid damaging segments. Concrete spalling at the erector guide and damages at the lifting point occur due to operator error. Segments are strong enough for axial forces, and perhaps the dynamic force of movement of an erector also creates many hairline cracks on the segments;

(4) Out-of-plane segments or gaps between the segments:
The segment-lining circumferential joints are designed to adequately resist large stresses induced from the thrust jack. In practical situations, it is impossible to build rings with perfect planes at the point of interface. Therefore, tunnel segments are not always supported sufficiently by the preceding rings. The out-of-plane segments occur due to segment erector operator errors and lack of experience (see Figure 2). In some cases, the clearance between the tail shield and the preceding ring segment is also a decisive factor in out-of-plane ring building;

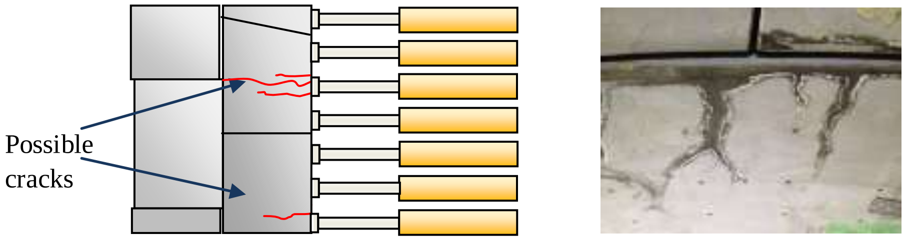

Figure 2. Out-of-plane tunnel linings.

(5) Excess lips/steps:
Segment permissible tolerances are defined in advance as circumferential and radial joints maximized to 5mm. If these tolerances are not maintained during the ring building, then the tunnel segment tightness is affected, and forces on the transferable area are reduced. This leads to increases in the stress within the segments to cause cracks, and is one of the most common reasons for radial cracks;

(6) Poor clearance between the shield and lining (Sugimoto 2006):
Although the TBM excavation carries on right alignment, the ring building may encounter difficulties due to a steep curvature of the tunnel lining. When the TBM is steering on a curve alignment, the clearance between the segment and the tail shield is diminished on the opposite side of the turn (Figure 3). The clearance between the tail shield and the segment is crucial for the cause of cracks;

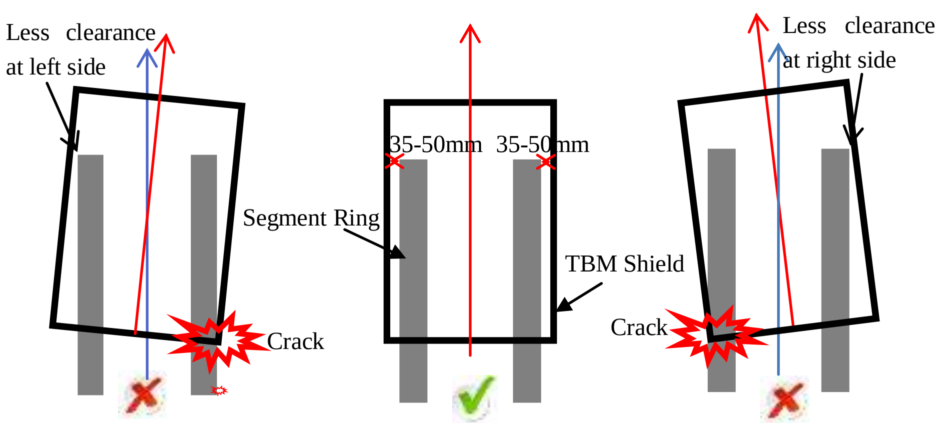

Figure 3. TBM steering and shield clearance.

The clearance between the segment lining and the shield is critical. If both make contact (Figure 4) during the excavation, an additional load on the segment, in the form of pressing, causes the cracks. This usually destroys the front portion of the segment.

Figure 4. Crack at front part of the segment due to lack of clearance.

The reason for most cracks is the lack of clearance between the shield and the lining (Sugimoto 2006). Clearance can be ensured by the correct key selection, to allow the tunnel lining to remain centered on the TBM shield and maintain an equal clearance. The curve alignment is the main reason for an insufficient clearance around the segment lining. Even in a straight alignment, the segment is not built in the center of the shield, which could lead to segment cracks.

4 RING SELECTION AND ORIENTATION

The selection of rings ensures the right passage of the TBM. For example, if the TBM is driven towards the left, then no rings possessing orientation towards the right should be installed. If this principle is not followed during ring-type selection, then this will diminish the clearance between the tail shield and segment, leading to a misalignment.

Normally, if the TBM is driven towards the left passage, then an "L"-type ring should be selected and if driven towards the right, then an "R"-type ring.

The following three factors must be considered when selecting the key position:

(1) Clearance between the tail shield and ring:
After mining is completed, the clearance between the tail shield and the preceding ring segment should be measured. While measuring, always consider the protruding part of the stiffener, grease pipe and/or grout pipe thicknesses.

(2) Tunnel alignment for left or right turns and up or down movements:
Tunnel alignment, when monitored by the guidance system to within tolerance levels under TBM operations, has a normal tolerance set to 50mm. Especially for curve alignments, the selection of ring orientation is vital, and if an imprecise ring orientation is selected, this could cause a misalignment. Proper ring orientation and ring building are always essential in support of the alignment.

(3) TBM Jack left or right lead and overhang or look up:
Upon completion of the excavation, the thrust jack extension should be measured manually or from the TBM operation Programmable Logic Controller monitor display (Figure 5):

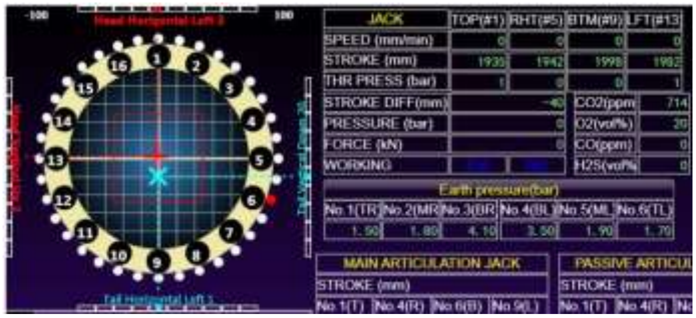

Figure 5. Thrust jack extension details after completion of mining (Enzan display).

From Figure 5, the difference in jack length data will reflect TBM orientation:

- Jack #1: 1935mm < Jack #9: 1998mm difference: 63mm as TBM look up; and,
- Jack #5: 1942mm < Jack #13: 1982mm difference: 40mm as TBM left lead

The thrust jack extension length is useful for the identification of the TBM orientation and shield clearance. However, stiffeners, grout pipe and grease pipe mounts on the shield will affect theoretical measurements of clearance between the shield and lining, which requires manual remeasurements of clearances to determine the precise key position and lining orientation.

5 CONCLUSION

This study exposed important issues related to segment cracks, damage and alignment issues in tunnel construction. The segment cracks are undesirably affecting the quality and lifetime of tunnels. In addition, cracks incur high costs for remedial measures to enhance quality and make repairs. It is important to limit cracks to ensure that segmental rings remain watertight. Crack propagation can be controlled by the use of accurate rings built at the center of the tail shield by using the precise ring type and choosing the right key position. In addition, the ring erector operator's skill also a crucial factor when ring building. In addition, the key position of the next ring in the building sequence should be selected with consideration of shield clearance, thrust jack extension, and the alignment curvature of the tunnel. Perfect TBM steering is an essential part for maintaining an accurate tunnel alignment, which is challenging when close to urban buildings and the surface must remain undisturbed. TBM steering and control of alignment greatly depends on the experience of the TBM operator.

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