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Mechanism of soft ground tunnel defect generation and functional degradation

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ABSTRACT

This paper deals with the mechanism of soft ground tunnel defect generation and functional degradation. The subway mileage has increased dramatically worldwide, especially in China, in the past decades and will be continuously increasing in the next decades driven by the demands on underground space usage and the advancement of tunneling technique. Subway tunnels are vulnerable to a variety of defects which, individually or interactively, deteriorate the tunnel function for providing passengers with a safe and comfortable transportation means. Understanding the mechanism of tunnel defect generation and functional degradation and providing effective maintenance measures can slowdown the tunnel defect generation and prevent the tunnel defects from developing into catastrophic structural failure. This paper summarizes typical tunnel defects and major contributing factors to the defect generation based on the findings from an inspection program of 130 km of soft ground tunnels in east China. A detailed example of the tunnel inspection and rehabilitation is presented. A framework is developed for analyzing the tunnel defects. The mechanism of tunnel functional degradation is explored associated with five critical links: environment, structure, components, joints, and materials, within a tunnel operation system. The five links individually deteriorate with time and interactively degrade the tunnel function. The research findings from this paper lay a foundation for developing practice guidance for tunnel maintenance.

1. Introduction

The subway mileage has increased dramatically worldwide, especially in China, in the past decades and will be continuously increasing in the next decades driven by the demands on underground space usage and the advancement of tunneling technique. Currently there are 96 subway lines with a total mileage of 2800 km in 19 cities in China. Qian (2011) reported that the subway lines in China were expected to reach 177 with a total mileage of 6100 km by the end of 2020 and 290 with a total mileage of 11,740 km by the end of 2050. The subway tunnels are mostly constructed in the densely populated cities located in the eastern part of China where the subsurface soils mainly consist of soft clays and silts. The soft ground tunnels are primarily constructed by shield machine and are supported by prefabricated concrete lining.

The fast construction pace and poor ground conditions leave the subway tunnels vulnerable to a variety of defects which deteriorate the tunnel function for providing passengers with a safe and comfortable transportation means. For example, Li (2014) reported that severe water and soil penetrated into the tunnel of Shanghai Metro Line No. 2 between Henan Road Station and Luojiazhui Road Station in 2006. The tunnel was forced to be closed for emergency repair. Another example is the Shanghai Metro Line No. 1 tunnel which lost over 10 cm of vertical clearance due to ovaling, suffered over 30 cm of longitudinal differential settlement, and sustained severe water leakage in 1995. With more and more subway tunnels in operation and the elongation of tunnel operation life, tunnel defects have brought urgent attention to the tunnel owners in China. It is critical to understand the mechanism of tunnel defect generation and functional degradation and to provide effective maintenance to slowdown the tunnel defect generation and to prevent the tunnel defects from developing into catastrophic structural failure.

The tunnel defects have also brought worldwide attention. The USA, UK, Germany, Japan, France, China, etc. all developed industrial manuals or national standards for tunnel inspection and maintenance (e.g., FHWA and FTA, 2003a,b). Research in tunnel inspection and maintenance has made significant advancement in recent decades. Richards (1998), Toshihiro and Yoshiyuki (2003), Ye et al. (2007), and Li (2014) discussed the lessons, practice and theories of tunnel inspection and maintenance. Haack

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et al. (1996), Davis et al. (2005), Yu et al. (2007), Yoon et al. (2009) and Victores et al. (2011) presented advanced tunnel inspection techniques, such as line-sensor camera, ground penetration radar (GPR), three-dimensional laser scanning, robot-aided tunnel inspection and maintenance system.

This paper deals with the mechanism of soft ground tunnel defect generation and functional degradation. Following the Introduction, Section 2 summarizes the typical tunnel defects identified from an inspection program of 130 km of soft ground tunnels in the eastern part of China. Section 3 discusses the major contributing factors to the tunnel defect generation. Section 4 presents a detailed example of tunnel inspection and rehabilitation. A framework for analyzing the tunnel defects is developed. Section 5 explores the mechanism of tunnel defect generation and functional degradation. At the end, in Section 6, the conclusions are made.

2. Tunnel defects

An inspection program was conducted on the soft ground tunnels located in Shanghai, Nanjing, Ningbo, and Wuxi city in east China from 2010 to 2014. Table 1 summarizes the line name, operation date, inspection date, inspection length, outside diameter, lining thickness, plate number within each liner segment, shield machine type and major defects of the inspected tunnels. In total, 12 tunnels including 9 subway and 3 roadway tunnels with a total length of about 130 km were inspected. All the 12 tunnels were excavated by earth pressure balanced (EPB) shield machine, except the Shanghai under Yangtze River tunnel which was excavated by slurry pressure balanced (SPB) shield machine. All the 12 tunnels were supported by prefabricated concrete lining consisting of 6 plates for the 9 subway tunnels, and 8–10 plates for the 3 roadway tunnels. The outside diameter of the 9 subway tunnels is 6.2 m and the outside diameter of the 3 roadway tunnels ranges from 13.0 m to 15.0 m.

The four cities where the tunnel inspection program was conducted are located close to each other in the Yangtze River Delta in east China and the subsurface conditions are very similar. The tunnels are all constructed in soft clay and silt with interlayers of fine sand. The clay and silt layers are, in general, with high water content, high plasticity, high compressibility and low undrained shear strength. The fine sand layers are typically in loose to medium dense condition. The groundwater table is close to the ground surface.

The tunnels were walked through and visually inspected. The location of defects was recorded in reference to a stationing system established throughout the tunnel. The liner rings of each inspected length were sequentially numbered so the defects could be referenced to the ring number. The defect's position within the tunnel cross-section was also recorded using a clock system with 12:00 being at the top. The tunnel deformation and the geometries of cracks and spalls were measured. The lining plates were periodically scanned by GPR to identify the defects hidden from naked eyes. Concrete samples were cored at locations of severe corrosion to identity the depth of corrosion. The major tunnel defects are discussed in the following section.

2.1. Plate faulting

The plate faulting occurs as the relative shear movement of adjacent liner plates in the longitudinal or transverse direction of the tunnel. Fig. 1 shows a photo of the plate faulting. Plate faulting generates shear stress in steel bolts at joints, reduces the tunnel clearance required for train operation safety and dislodging the waterproof materials inducing potential for leakage. Wang (2009) reported that when the faulting magnitude is smaller than 4 mm, the tunnel performs well without noticeable leakage and material overstress; when the magnitude ranges between 4 and 8 mm, the bolts start to yield and leakage initiates; when the magnitude ranges between 8 and 13 mm, the bolts are in plastic elongation state and the joint loses water tightness; when the faulting magnitude ranges from 13 to 23 mm, the tunnel structure is in critical state for failure. Factors contributing to plate faulting generation include fabrication and assembly errors of liner plates, non-uniform grouting during tunneling, alignment errors of shield driving, and differential deformation of tunnel structure.

2.2. Plate cracking and spalling

Crack is a linear fracture in the concrete caused by tensile forces exceeding the tensile strength of the concrete. Spalling is a roughly circular or oval depression in the concrete. It is caused by the separation and removal of a portion of the surface concrete revealing a fracture roughly parallel, or slightly inclined, to the surface. Fig. 2 shows a photo of the plate cracking. Cracking and spalling reduce

Table 1
Summary of information of the inspected tunnels.

Line name	Operation date yyyy.mm	Inspection date yyyy.mm	Inspected length km	OD[a] m	Liner thickness mm	Liner plate no.	TBM type	Major defects[b]
Shanghai Metro Line No. 1	1995.04	2010.01	16.1	6.2	350	6	EPB	①, ②, ⑤, ⑦, ⑧, ⑨
Shanghai Metro Line No. 6	2007.12	2013.05	0.7	6.2	350	6	EPB	①, ⑦, ⑧, ⑨
Shanghai Metro Line No. 7	2009.12	2010.12	35.0	6.2	350	6	EPB	①, ⑦
Shanghai Metro Line No. 10	2010.04	2012.06	3.8	6.2	350	6	EPB	⑦
Shanghai Metro Line No. 11	2013.08	2011.11	20.9	6.2	350	6	EPB	①, ②, ⑦
Shanghai Metro Line No. 12	2013.11	2012.07	4.5	6.2	350	6	EPB	②, ⑨
Shanghai Metro Line No. 13	2012.12	2013.11	16.4	6.2	350	6	EPB	①, ⑨
Nanjing Metro Line No. 2	2010.05	2014.04	6.4	6.2	350	6	EPB	⑦, ⑧, ⑨
Wuxi Metro Line No. 2	2013.07	2012.06	6.0	6.2	350	6	EPB	①,⑦
Ningbo Metro Line No. 1	2014.05	2012.09	0.3	6.2	350	6	EPB	②, ⑦, ⑧, ⑨
Shanghai Dapu Road Tunnel	1971.06	2012.03	1.4	10.0	600	8	EPB	①, ②, ③, ④, ⑤, ⑥, ⑦, ⑧, ⑨
Shanghai Yingbin 3rd Rood Tunnel	2011.10	2011.12	1.9	14.0	600	9	EPB	①, ①
Shanghai under Yangtze River Tunnel	2010.05	2010.01	15.0 (7.5 * 2)	15.0	650	10	SPB	①, ⑨

Notes:
[a] Outside diameter.
[b] ①: Plate faulting; ②: Plate cracking and spalling; ③: Plate corrosion; ④: Waterproof material damage; ⑤: Invert damage; ⑥: Connection bolt damage; ⑦: Leakage; ⑧: Longitudinal deformation; ⑨: Transverse deformation.