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 tunnelling 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.

Keywords: Soft Ground Tunnel, Defects, Inspection, Maintenance, Rehabilitation

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 tunnelling 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 11740 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, et al. all developed industrial manuals or national standards for tunnel inspection and maintenance (e.g., FHWA&FTA, 2003a & 2003b). 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, 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 to 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 identify 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. Figure 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 tunnelling, 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. Figure 2 shows a photo of the plate cracking. Cracking and spalling reduce the tunnel durability and serviceability by: 1) reducing the stiffness of tunnel liner and increasing the tunnel deformation; 2) damaging tunnel interior finishes; and 3)

accelerating corrosion to tunnel liner. The liner plates very often have small manufacturing defects and dimensional errors which generate stress concentration, inducing cracking and spalling during transportation, assembly and operation. Cracking and spalling can also be generated by either deformation, such as differential longitudinal and transverse deformation and concrete shrinkage due to temperature and humidity variation, or operational loads.

2.3 Plate Corrosion

The corrosive chemicals in soil, water and air corrode the concrete and reinforcement in liner plates. Figure 3 shows an example of the plate corrosion. The corrosion-induced deterioration is manifested as discoloration, cracking and spalling of the concrete cover, and loss of steel cross-sectional area with the associated corrosion products resulting in bond deterioration at the steel-concrete interface. As a consequence, the serviceability, durability and safety of the tunnel can diminish increasingly as corrosion proceeds. Concrete cracking and corrosion interact with each other to accelerate the degradation of the tunnel structure. Cracks create path for corrosive chemicals to contact with the concrete body and reduce the thickness of reinforcement protection layer to accelerate reinforcement corrosion. The corrosion products of the concrete and reinforcement occupy a much larger volume which generates cracks in concrete. Since the corrosion of the reinforced concrete is a slow process, the degree of plate corrosion is typically closely related to tunnel age.

2.4 Waterproof Material Damage

The water tightness of the tunnels is achieved by the water tightness of plates and joints. The grouting outside the tunnel provides additional resistance for water infiltration. The concrete plates are generally watertight except at locations of cracks. The joints are locations vulnerable to water leakage. The water tightness of the joints is achieved by compressing rubber gaskets

and/or sealing with water swelling strips around connection seams. The gaskets and strips can become dislodged from joints due to infiltrating water or loosening of the connection bolts. They can fail due to chemical or biological deterioration of the material caused by infiltrated water. Structural movements of the liner can also tear or otherwise distort the gaskets and strips to cause leakage.

2.5 Connection Bolt Damage

The liner plates are connected with steel bolts to form a load carrying structure. The steel bolts are vulnerable to corrosion, manifested by bolt discoloration or loss of the cross-sectional area. The bolts can be loosened by sustained dynamic traffic loads. The relative shear or lateral movement of adjacent liner plates will generate shear or tensile stress, which, under extreme conditions, will cause bolt yield or break. For example, bolt yield was observed at the Shanghai Dapu Road Tunnel under the combination of relative shear and lateral movement of adjacent liner plates. Laboratory tests during this research program showed that bolt break occurs when the lateral separation of the liner plates reaches between 11 and 23 mm. The damage to the connection bolts reduces tunnel load carrying capacity and causes leakage at joints.

2.6 Invert Damage

The invert of a tunnel is the slab on which the roadway or track bed is supported. For subway tunnels, it typically places the track bed directly on grade at the bottom of the tunnel structure. For roadway tunnels, it commonly spans the roadway between sidewalls to provide space under the roadway for ventilation and utilities. For subway tunnels, the invert damage typically occurs as the separation of track bed from the tunnel invert due to the differential longitudinal deformation. For roadway tunnels, the invert damage typically occurs as cracks on the pavement generated the differential deformation and traffic loads. Figure 4 shows the cracks identified on

the roadway pavement. The cracks are mostly orientated in perpendicular to or at 45 degrees with tunnel axial direction.

2.7 Leakage

Leakage occurs to almost every tunnel. Figure 5 shows a photo of the tunnel leakage at bolt holes. The negative consequences of leakage can vary from minor surface corrosion of tunnel appurtenances to major deterioration of the structure and thus decreased load carrying capacity of the tunnel. Leakage degrades tunnel function by corroding concrete, reinforcement, waterproof material, and connection bolts. Leakage also carries fine soil particles into tunnel creating voids behind the liner, which causes settlement of surrounding structures and generates eccentric loading on tunnel that can lead to unforeseen stresses. Leakage is caused by a variety of reasons including differential longitudinal and transverse deformation, plate faulting, waterproof material dislodging, dynamic train loading, corrosion, cracks, etc.

2.8 Longitudinal Deformation

The longitudinal deformation includes settlement and lateral deformation of tunnel structure along the tunnel axial direction. The tunnel settlement is mainly caused by soil and surcharge loads on the tunnel crown, tunnel dead load and operation load, and other environmental factors, such as regional groundwater drawdown and tunnel leakage. The lateral deformation is mainly caused by the adjacent excavation or surcharge loads.

The longitudinal differential deformation, especially the differential settlement, is the cause of many tunnel problems, such as leakage, plate faulting, connection bolt damage, and waterproof material damage. The current engineering practice typically designs the lining system with uniform thickness along the tunnel longitudinal direction. The subsurface ground condition, however, varies along the tunnel. The non-uniform subsurface condition is the most important

reason to cause the differential settlement. Other factors, such as non-uniform surcharge load, leakage, errors in excavation with the tunneling machine, stress induced by stations constructed by open-cut, etc. also contribute to the differential settlement. Although it is anticipated that the differential settlement will occur to the tunnel, it is very difficult to predict the exact location and magnitude of the differential settlement due to the uncertainties associated with the subsurface conditions and external loads during tunnel design.

2.9 Transverse Deformation

The soil pressure on tunnel consists of vertical pressure on tunnel crown and lateral pressure on both sides of the tunnel. The lateral soil pressure is typically smaller than the vertical soil pressure. The difference between the vertical and lateral soil load causes tunnel ovaling. The ground surcharge, grouting pressure, and leakage generate eccentric loads on tunnel and cause irregular tunnel transverse deformation. The tunnel transverse deformation reduces tunnel clearance and generates tensile and shear force in the connection bolts. When the tunnel lining is not properly designed with adequate stiffness, the excessive transverse deformation will impact the train operation safety and expands the joint seams to cause the connection bolt damage and leakage.

Figure 6 shows the transverse deformation of a cross section of Shanghai Metro Line No. 8 tunnel measured using three dimensional laser scanner. In Fig. 6a, the original shape of the cross section, the measured deformation, and the regressed elliptical shape are plotted in red dash lines, green dots, and blue solid lines, respectively. Figure 6b plots the deformation along the expanded tunnel circumferential length. Comparison between the measured deformation and the regressed elliptical shape shows that the deformed tunnel is not in a regular elliptical shape indicating that the earth loads are not symmetrical.

3. Factors Contributing to Tunnel Defect Generation

The major difference between tunnels and superstructures is that the tunnels are buried in soils and water. The behaviors of the tunnels are impacted by subsurface conditions, variation of regional groundwater tables, and adjacent construction activities. The corrosive chemicals in soils, water and atmosphere corrode the tunnel materials. The tunnels take sustained dynamic train loads which cause fatigue of materials. All these factors are potential causes of tunnel defects. The contributing factors to tunnel defect generation are discussed in this section.

3.1 Non-Uniform Subsurface Conditions

The subsurface strata and soil material properties vary along the tunnel longitudinal direction. The non-uniform subsurface conditions cause differential settlement along the longitudinal direction of tunnel. The differential settlement is the source of many tunnel defects such as leakage, plate faulting, connection bolt damage, and waterproof material dislodging.

3.2 Ground Settlement

The tunnels are buried in the ground and settle with the adjacent soils. The ground continues to settle in Shanghai due to regional groundwater drawdown and overbuild of high-rise buildings. Ye, et al. (2007) reported that the yearly ground settlement is about 12 mm in the downtown of Shanghai from 1990 to 2007. Li (2014) reported that there is a large ground settlement cone at the Hengshan Station of Shanghai Metro Line No. 1 due to local groundwater drawdown. The ground has settled about 100 mm from 1995 to 2005 while the total settlement of the subway tunnel has reached 110 mm.

3.3 Subway Construction Activities

The subway construction activities including shield driving, grouting, open-cut for the construction of stations and adjunct structures, and dewatering disturb the ground and cause

consolidation settlement of the tunnel. The major source of tunnelling induced settlement is the ground loss due to insufficient grouting and over excavation along curved alignment.

3.4 Adjacent Construction Activities

The adjacent construction activities, such as excavation and dewatering, during tunnel operation add additional loads on tunnel and cause eccentric tunnel deformation. Li (2014) reported that there were more than 100 construction activities occurred within the impact zone of the Shanghai Metro Line No. 1 tunnel from 1993, when the tunnel was constructed, to 2014. Although strict regulation was enforced on the adjacent construction activities, the data from field instrumentation shows that every major construction activity had impacts on the tunnel and caused tunnel settlement with magnitude ranging from 20 to 60 mm.

3.5 Ground Surcharge

The surcharge loads on ground surface cause the settlement of tunnel, especially when the loading area is relatively large and the underlying soft soil layer is thick. The surcharge loads add additional vertical stress in soils below the tunnel. The additional vertical stress not only increases primary consolidation settlement but also enlarges the tunnel impact zone and increases the secondary consolidation settlement. An investigation found that the impact zone of subway tunnels is typically larger than the impact zone analyzed in the design, resulting in higher settlement and longer consolidation time than estimated during design.

3.6 Structure Difference

A subway system typically consists of stations, tunnels, entrances, ventilation shafts, etc. Due to different structural configuration, construction methods, and operation conditions, differential settlement occurs at the connections between different structures. For example, subway stations are typically constructed by open-cut which involves in significant unloading and the stations are

designed to against floating. The unloading effect is much smaller at tunnel sections. The stress state of the soils below the station is significantly different from that below the tunnel section and causes differential settlement at the connection between the station and tunnel section.

3.7 Insufficient Grouting

The insufficient tail void grouting behind tunnel liner leaves voids between the tunnel and surrounding soil. The soil cannot mobilize reaction force and cause eccentric loading on tunnel. The insufficient grouting is the major source of tunnelling induced ground settlement. The investigation shows when the empty void is smaller than 0.5 m in diameter, the impact to tunnel structural behavior is relatively small. The impact increases with the diameter of the empty void.

3.8 Vibration Load

The sustained dynamic traffic loading generates additional vertical stress in soils beneath tunnel and changes soil structure to cause settlement during tunnel operation. The vibration traffic load also causes detachment of grouting material, which stiffens and shrinks with time, from the tunnel external surface. The detachment of grouting material creates void between tunnel and adjacent soils and generates eccentric loads on tunnel. Ye, et al. (2007) reported that the settlement of Shanghai Metro Line No. 1 tunnel was relatively small from January 1993 to April 1995 before train operation. The total settlement of the tunnel ranged from 2 to 6 mm. After the train operation, the tunnel settlement increased significantly with a yearly rate of 20 to 40 mm from April 1995 to 2000. The settlement rate reduced to 5 to 15 mm per year between 2000 and 2007 but had not been stabilized. The significant increase of tunnel settlement rate after train operation is most likely contributed to the vibration load.

3.9 Material Corrosion

The corrosion of the tunnel material includes the corrosion of the reinforced concrete, waterproof strips, and steel bolts. Revie (2000) pointed out that the corrosion to reinforced concrete includes sulfate corrosion, carbonization and chlorination. The sulfates of sodium, calcium, and magnesium present in alkali soils and water react chemically with hydrate lime and hydrated calcium aluminate in the cement paste in concrete to form calcium sulfates and calcium sulphoaluminate, respectively. These are expansive reactions and result in degradation concrete. The chlorides and carbon dioxide in atmosphere penetrate concrete without causing significant damage but promote the corrosion of steel by removing the protective oxide layer on the steel, created and sustained by the alkalinity of the concrete pore water. The mechanism of concrete carbonization and chlorination can be referred to Luca, et al. (2013).

3.10 Component Fatigue

Fatigue is a process of progressive, permanent internal structural changes in a material subject to repeated loading. These changes are mainly associated with the progressive growth of internal micro-cracks, which results in a significant increase of irrecoverable strain. At the macro-level, this will manifest itself as changes in the material's mechanical properties (Horrie, et al., 1992). Lee and Barr (2004) presented a wide range of fatigue load spectrum and pointed that the rapid mass transit belongs to super-high-cycle fatigue sustaining 10^7 to 10^8 cycles of load during its life time. Under such high-cycle loading, the strength of reinforced concrete and steel bolts are reduced due to fatigue. Based on the investigation of the Yongjia Tunnel in Ningbo, China, no fatigue cracks in liner plates were found after about 10 years of operation. The Dapu Road Tunnel in Shanghai, China, however, were revealed with significantly lower strength of concrete

and steel bolts after 37 years of operation. The reduction of the concrete and bolt strength is mostly caused by the fatigue of materials.

4. An Example for Tunnel Defect Inspection and Defect Cause Analysis

This section presents an example of tunnel inspection and rehabilitation. A framework is developed for analyzing the tunnel defects. The problems associated with the current practice of tunnel inspection and rehabilitation are discussed.

The tunnel is located in the city of Ningbo, Zhejiang Province, in the eastern part of China. Figure 7 shows the schematic view of the tunnel. The tunnel was constructed by shield driving with an outside diameter of 6.2 m and was supported by prefabricated concrete lining consisting of 6 plates connected with M30 steel bolts. The liner has a thickness of 35 cm and ring width of 1.2 m. Water swelling strips were installed around the joints for water tightness. The construction of the tunnel was completed in October 2010. Serious defects including leakage, cracking and spalling, longitudinal deformation and transverse deformation occurred to the tunnel section from ring No. 50 to 270 with a total length of about 260 m after the tunnel completion. This section of the tunnel was forced to be inspected and rehabilitated in September 2012 and the major defects from the inspection were documented and discussed in the following.

4.1 Joint Expansion

The tunnel is visually inspected and the joint expansion is measured using vernier gauge. Table 2 shows the statistics of the magnitude of the joint expansion from ring No. 50 to 270. Table 2 shows that the joint expansion magnitude ranges from 1 to 11 mm with a mean value of 4 mm in the transverse direction and 6 mm in the longitudinal direction. No obvious plate faulting was

found and the expansion of the joints in the longitudinal and circumferential direction has similar magnitude.

4.2 Concrete Cracking

The cracks in the concrete were visually identified. The width and length of the cracks were measured using vernier gauge and steel rulers, respectively. The position of the cracks within the tunnel cross-section is noted using a clock system with 12:00 being at the top. The penetration depth of the cracks is scanned using GPR. Concrete samples were cored at some locations and the conditions of the samples were analyzed in the laboratory.

Table 3 presents the statistics of the position of the cracks from ring No. 50 to 270. In total, 635 cracks were identified. The cracks are generally orientated in the longitudinal direction of the tunnel and some random cracks around bolt holes. The width of the cracks ranges from 2 mm to 20 mm. Within the 635 cracks, 232 cracks were identified near the tunnel crown at 12:00 position while the rest 423 cracks are located around the invert with 134 cracks between 5:00 to 6:00 position and 289 cracks between 6:00 to 7:00 position. Based on the GPR images and sample conditions, the cracks are mostly surface cracks and are not penetrated through the liners.

4.3 Longitudinal Deformation

The longitudinal deformation includes vertical deformation and lateral deformation along the tunnel axial direction. The vertical deformation and lateral deformation are measured at tunnel invert using level gauge and geodetic theodolite, respectively. The longitudinal deformation was measured every 10 rings. Figure 8 shows the tunnel vertical movement. In this figure, the positive values indicate upward movement and negative values indicate downward movement. Figure 8 shows that the entire section of the tunnel has settled with the magnitude ranging from 12.2 mm to 29.7 mm. The maximum settlement occurred at ring 260. Figure 9 shows the lateral

movement of the tunnel invert with positive values indicating tunnel moving north and negative values moving south. This figure shows that the tunnel is moving north. The magnitude of movement ranges from 19.9 mm to 52.7 mm with the maxima occurred at ring 210.

4.4 Transverse Deformation

The tunnel transverse deformation is measured using total station. Figure 10 shows the transverse deformation in the vertical direction ranges from -24.1 mm to -9.8 mm with the minima occurred at ring 170. The negative values indicate the tunnel vertical clearance is reduced. Figure 11 shows the transverse deformation in the lateral direction ranges from 12.1 mm to 26.0 mm with the maxima occurred at ring 240. The positive values indicate the tunnel lateral clearance is increased. The reduced vertical clearance and increased lateral clearance show that ovaling occurred at the tunnel.

4.5 A Framework for Analyzing Tunnel Defect Generation

As discussed in Section 3, the tunnel defects can be caused by a variety of reasons. To find the causes of the tunnel defects, Fig. 12 plots a framework for tunnel defect cause analysis. This framework consists of three tiers. The first tier is the tunnel structural deformation and leakage which have a direct impact on tunnel function, the second tier is the component defects, and the third tier is the factors contributing to the component damage.

Based on the tunnel inspection, the tunnel is in general moving north and severe cracks, leakage, and longitudinal and transverse deformation occurred. Using the framework developed in Fig. 12 in combination with a site visit and review of the subsurface conditions, design drawings and construction documents, it is concluded that the major factor contributing to the tunnel defects is the deep excavation on the north side of the tunnel section. The relative location of the excavation and the tunnel section is shown in Fig. 7. The excavation had a depth of about 12 m

and was supported by concrete slurry wall. The unloading effects associated with the excavation drag the tunnel to move north. The tunnel section was rehabilitated by installing steel plates inside the tunnel as shown in Fig. 13. Although the tunnel was rehabilitated and put into operation after the rehabilitation, there are several problems associated with the inspection and rehabilitation. These problems are typical in the tunnel inspection and rehabilitation practice in China. The problems are:

1. The tunnel structure is buried in soils and water and its comprehensive conditions are difficult to be evaluated. The macro-defects were visually inspected and measured while the micro-defects, such as micro-cracks in concrete and steel bolts, were not identified.
2. The structural behavior of the tunnel was not evaluated. The difficulties for tunnel behavior evaluation lie in two aspects: 1) it is lack of an effective model for tunnel structural behavior analysis. The tunnel is a complicated structure consisting of reinforced concrete plates connecting with steel bolts. Even complicated three dimensional models are difficult to catch the details of tunnel structure, especially at joints; and 2) it is lack of rational boundary conditions for tunnel structural behavior analysis. The current models mostly assume the tunnel boundary conditions are constant and ignore the variation of the boundary conditions, such as pore pressure dissipation in soils caused by adjacent excavation and surcharge.
3. The mechanism of tunnel defect generation is not clear, especially when the tunnel is in operation for a long time. The tunnel defects are generated by a variety of factors including direct factors and indirect factors which impact with each other. This brings difficulty and randomness to tunnel rehabilitation and maintenance. It is critical to

understand the defect generation mechanism which provides theoretical guidance to tunnel rehabilitation and maintenance.

5. Mechanism of Tunnel Defection Generation and Functional Degradation

The section discusses the mechanism of tunnel defect generation and functional degradation associated with five critical links: environment, materials, components, structure, and joints, within a tunnel operation system.

5.1 Environment

Figure 14 shows a flow chart for tunnel environment deterioration analysis. The tunnel environment is divided into external, internal, and operational environment. The external environment refers to the soil and groundwater surrounding the tunnel. The external environment varies with time due to the variation of local groundwater and ground disturbance during tunnelling and subsequent adjacent construction activities. The internal environment refers to the exhausts and smokes from train operation, and vapors and water from leakage. The operation environment refers to the dynamic train loads and other operational loads.

The external environment, internal environment, and operation environment interact with each other and deteriorate with time. The change of the external environment changes tunnel external loads and causes structural deformation which, in turn, impacts the train operation smoothness, increases the dynamic loading and damages the joints. The joint damage induces water leakage, deteriorating the internal environment, and causes loss of soil and groundwater, deteriorating the external environment. The deterioration of the internal environment increases the material corrosion. The deterioration of operation environment increases the fatigue of structural components.

5.2 Materials

Figure 15 shows a flow chart for tunnel material degradation analysis. The tunnel structure is mainly made of concrete and steel which are vulnerable to corrosion in a corrosive environment. The corrosion generates cracks and spalls at concrete surface, debonding between concrete and steel reinforcement, and rusty and reduction of steel bolt cross-sectional area for load carrying. The concrete and steel sustain repeated train loading which generates material fatigue. The corrosion in combination with fatigue degrades the concrete and steel quality manifested as concrete cracking and spalling as well as steel bolt cracks and cross-sectional area loss.

The material degradation reduces tunnel structure load carrying capacity and increases tunnel structural deformation. The structural deformation damages the joints by generating plate faulting, joint expansion, bolt overstress, and waterproof material dislodging which increase the probability of leakage. The leakage carries corrosive chemicals, which, in turn, accelerate the material degradation.

5.3 Components

Figure 16 shows a flow chart for tunnel component defect analysis. The tunnel structural components mainly include liner plates and steel bolts. The main causes of the tunnel component damage include 1) initial defects and damage during manufacturing, shipping and installing; 2) overstress due to eccentric loads; 3) fatigue due to sustained cyclic loading; and 4) material corrosion. The component damage is manifested as plate cracking and spalling as well as steel bolt distortion and break.

The component damage reduces tunnel structure stiffness and increases tunnel deformation. The tunnel deformation increases the leakage probability, which, in turn, deteriorates the tunnel external and internal environment and accelerates the component damage.

5.4 Structure

Figure 17 shows a flow chart for tunnel structure defect analysis. The main function of the tunnel is to provide a safe and comfortable transportation means for passengers. The structure deformation has a direction impact on tunnel function by reducing tunnel clearance to cause safety issue and reducing the train moving smoothness and passenger riding comfortableness. As such, the structural deformation is one of the most important indices for tunnel healthy evaluation. The tunnel structure deformation includes longitudinal and transverse deformation. The main contributing factors to the structural deformation include non-uniform subsurface conditions, eccentric loads, alignment error during driving, small alignment curvature, et al.

The tunnel structure deformation increase train vibration loads which accelerate the joint and component damage and increase the leakage probability. The leakage carries soils and groundwater into tunnel and deteriorates the internal and external environments. The deterioration of the environment, especially the intrusion of corrosive chemicals, facilitates the material corrosion. The joint and component damage, local soil and groundwater penetration, and material corrosion accelerate the structural deformation.

5.5 Joints

Figure 18 shows a flow chart for tunnel joint defect analysis. The prefabricated tunnel liner consists of a lot of circumferential and longitudinal joints. The joints are not only required for liner assembly during construction but also increase the tunnel structure flexibility to adjust deformation and avoid material overstress during tunnel operation. Damage to joints includes 1) concrete damage at joints, such as cracks and breakage at corners; 2) joint expansion and faulting; and 3) leakage. The contributing factors to joint damage include manufacturing errors, poor

workmanship during shipment and installation, eccentric loading, tunnel longitudinal and transverse deformation, and corrosion.

The joint damage reduces the tunnel structural load carrying capacity and increases tunnel deformation. The joint damage also increases the probability of leakage and accelerates tunnel corrosion. The tunnel structural deformation and corrosion, in turn, accelerate the joint damage.

5.6 Evolving Process of Tunnel Defect Generation and Functional Degradation

Figure 19 shows the evolving process of tunnel defect generation and functional degradation. The five links: environment, materials, components, structure and joints are connected with each other to create a malicious cycle to promote tunnel defect generation and functional degradation. As discussed above, defects at any link will trigger a cycle for tunnel defect development and functional degradation. To slowdown the tunnel defect generation and prevent tunnel defect from developing into catastrophic structural failure, tunnel maintenance practice shall actively acquire information related to the conditions of five links using advanced instrumentation and inspection techniques, select appropriate indices for evaluating the conditions of each link, and develop maintenance strategies. The theory and practice guidance of the tunnel maintenance will be discussed in a separate paper.

6 Conclusions

This paper deals with the mechanism of soft ground tunnel defect generation and functional degradation based on the findings from an inspection program for 130 km of subway and roadway tunnels in east China.

Soft ground tunnels are vulnerable to a variety of defects. The typical tunnel defects include plate faulting, plate cracking and spalling, plate corrosion, connection bolt damage, waterproof

material damage, invert damage, longitudinal deformation, transverse deformation, and leakage. The tunnel defects interact with each other to degrade the tunnel function with time. Among these tunnel defects, the longitudinal deformation, especially the differential settlement, is one of the major defects which directly impacts the train operation safety and passenger comfortableness, and generates many other tunnel defects, such as plate faulting, plate cracking and spalling, and leakage.

The tunnel defects are generated by a variety of factors. Some defects are related to the manufacture, excavation and installation errors during construction, some defects are related to the inadequate design of tunnel lining to resist unexpected earth or surcharge loads during tunnel operation, and some defects are related to tunnel material corrosion and component fatigue. The major contributing factors to the tunnel defect generation include non-uniform subsurface conditions, ground surcharge, ground settlement, adjacent construction activities, tunnel construction activities, insufficient grouting, structure difference, vibration load, material corrosion and component fatigue. These factors have a direct or indirect impact on all the tunnel defects and promote the tunnel functional degradation with age.

The mechanism of tunnel functional degradation is explored associated with five critical links: environment, materials, components, structure, and joints, within a tunnel operation system. The five links individually deteriorate with time and interactively degrade the tunnel function. Defects at any link will trigger a cycle for tunnel functional deterioration. To slowdown the tunnel defect generation and to prevent tunnel defect from developing into catastrophic structural failure, tunnel maintenance practice shall actively acquire information related to the conditions of five links using advanced instrumentation and inspection techniques, select appropriate indices for evaluating the conditions of each link, and develop maintenance strategies.

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Table 1 Summary of Information of the Inspected Tunnels.

Line Name	Operation Date	Inspection Date	Inspected Length	OD ¹	Liner Thickness	Liner Plate No.	TBM Type	Major Defects ²
	yyyy.mm	yyyy.mm	km	m	mm			
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 3 rd Road Tunnel	2011.10	2011.12	1.9	14.0	600	9	EPB	①, ⑨
Shanghai under Yangtze River Tunnel	2010.05	2010.01	15.0 (7.5*2)	15.0	650	10	SPB	①, ⑨

Notes: 1. Outside Diameter; 2. 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

Table 2 Statistics of the Magnitude of Joint Expansion

Ring No.	Transverse Joint Expansion (mm)			Longitudinal Joint Expansion (mm)		
	Maxima	Mean	Minima	Maxima	Mean	Minima
50 to 270	10	4.3	1	11	6	1

Table 3 Statistics of the Position of Cracks

Ring No.	Crown (12:00)		Invert (5:00 to 6:00)		Invert (6:00 to 7:00)		sum
	Bolt Hole	Longitudinal	Bolt Hole	Longitudinal	Bolt Hole	Longitudinal	
50 to 270	5	227	25	109	60	229	655
sum	232		134		289

Figure 1 Plate Faulting

Figure 2 Plate Cracking

Figure 3 Plate Corrosion

Figure 4 Pavement Crack

Figure 5 Leakage at Bolt Holes

a) Circular Plane View

b) Expanded along Circumference

Figure 6 Measured and Regressed Elliptical Tunnel Liner Deformation

Figure 7 Schematic View of the Tunnel Section, Ring Number and Excavation Boundary

Figure 8 Measured Tunnel Settlement along Longitudinal Direction

Figure 9 Measured Tunnel Lateral Displacement along Longitudinal Direction

Figure 10 Measured Tunnel Vertical Convergence along Longitudinal Direction

Figure 11 Measured Tunnel Lateral Convergence along Longitudinal Direction

Figure 12 Framework for Tunnel Defect Cause Analysis

Figure 13 Rehabilitating Tunnel by Installing Steel Plates

Figure 14 Flow Chart for Tunnel Environment Deterioration Analysis

Figure 15 Flow Chart for Tunnel Material Degradation Analysis

Figure 16 Flow Chart for Tunnel Component Defect Analysis

Figure 17 Flow Chart for Tunnel Structure Defect Analysis

Figure 18 Flow Chart for Tunnel Joint Defect Analysis

Figure 19 Evolving Process of Tunnel Defect Generation and Functional Degradation