Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

NON-INTRUSIVE INSPECTION AND REAL-TIME MONITORING FOR TUNNEL STRUCTURAL RESILIENCE

DONGMING ZHANG*, HONGWEI HUANG, and QINGTONG LI

Department of Geotechnical Engineering, Tongji University, 1239 Siping Rd, Shanghai 200092, China.
E-mail: zdmg123@tongji.edu.cn; huanghw@tongji.edu.cn; 1410254@tongji.edu.cn

As the number of operational tunnels is increasing incredibly fast, the maintenance pressure to ensure the structural safety of the tunnels thus becomes more and more intensive. This paper presents an integrated resiliency assessment model for tunnel deformational performance with the full utilization of field data from non-intrusive inspection and real-time monitoring system. A moving tunnel inspection vehicle (named as MTI-100) is developed for the inspection of the whole tunnel inner surface with a moving speed at 5km per hour for a minimum size of crack width at 0.3mm. Then the concerned key section of tunnels could be focused and the wireless sensing network (WSN) system is installed on the key section for real-time detailed monitoring of structural behaviors, i.e., deformation in this paper. After obtaining the huge amount of inspected and monitored data, a field-data-based resiliency model is built to analyze the resiliency behavior of tunnel structural performance. By doing so, the rational recovery strategy in terms of optimized recovery timing and recovery measures could be derived with the proposed resiliency model. Hence, an integrated assessment system for preventive maintenance, consisting of non-intrusive inspection at first, real-time monitoring at the second, and rational resiliency assessment with recovery implementation at the last, is established and well-validated by a real case for a shield tunnel in Shanghai metro line 2 at the end of this paper.

Keywords: Inspection, Monitoring, Resilience, Geotechnical, WSN

1 Introduction

Tunnels built under the ground could relief much on-ground transportation pressure. Because of such big advantages, the construction of tunnels is being increased for decades in the world. In China, by end of 2015, the mileage of operated metro tunnels has reached to 3374km, the mileage of the operated road tunnels is about 12,688km and the number for operated railway tunnels is about 13,038km. The maintenance of such large scaled underground infrastructure is becoming a big challenge in nowadays. The safety of tunnels will largely depend on its serviceability performance, where the preventive maintenance plays a great important role. It is with no doubt that the inspections and monitoring will be the daily concerns in very near future for the maintenance (Mair, 2008; Huang and Zhang, 2015).

However, the current inspection and monitoring is mainly conducted by man-power (Richards, 1998; Blom, et al., 1999). The environmental condition is the most challenging factor that prevents the inspection and monitoring from a fast and efficient manner. For instance, the time limit for current metro inspection and monitoring plan is quite critical due to the intensive daily operation requirement of metro system. Hence, the efficient non-intrusive inspection and real-time monitoring methods should be of great importance to the preventive maintenance, so that any threats to the safety of tunnels could be sensed and measured in time (Yuan, et al., 2013). In view of this circumstances, some of the vehicle-based inspection apparatus and wireless sensing network (WSN) based monitoring techniques now are paid more and more attentions (Bennett, et al., 2010; Soga, et al., 2012; Gavilán, et al., 2013; Montero, et al., 2015; Zhang, et al., 2016).

When the non-intrusive inspection based on the vehicle and real-time monitoring based on WSN techniques are applied into the real tunnels, the size of measured data will reach to the giga bit for one night inspection or monitoring. How to fully utilize the above big data to assess the safety of the tunnels now is a new challenges faced by the engineers. The authors has proposed a structural resilience analysis framework by using the measured tunnel performance (Huang and Zhang, 2016). The resilience is explained conceptually as the ability of a system to absorb the disruption caused by hazards and the ability to recover to an acceptable performance level (Ayyub, 2014). The concept of structural resiliency could derive an optimized maintenance timing and the frequency of inspection or monitoring and benefit the preventive maintenance (Zhang, et al., 2016). It is a new philosophy in maintenance design considering the structural resiliency with the help of newly developed inspection and monitoring techniques.

Thus, the main objective of this paper is to propose a generalized framework of applying non-intrusive inspection and real-time monitoring for enhancing the tunnel structural resilience with optimum repairing timing and cost. To fulfill the objective, a fast and non-intrusive inspection vehicle developed by the authors would be introduced briefly at the first. Secondly, the WSN for tunnel convergence of horizontal diameter is proposed, and the associated sensor node, network and transformation laws are present. Then, the framework of the applying the inspection and monitoring data into the resilience analysis model is described with a real application examples present at the end of this paper.

2 Fast and Non-intrusive Inspection Vehicle

A moving tunnel inspection vehicle (named as MTI-100) is developed for inspection of structural defects in metro tunnel. The current vehicle is designed based on a tunnel size with a 5.5m inner diameter of the tunnel lining. The equipment is constituted by three systems: the image acquisition system, control system and moving system, which are responsible for image capture, image record and moving control, respectively. Figure 1 shows a prototype of MTI-100 for all the three systems. The procedure of inspection can be divided into three steps: image capture; raw data transmission; image preprocessing; and defect recognition. The image capture system uses high-resolution line-scan CCD cameras and lighting to capture images of the inner surface of lining. As the quality of image could greatly affect the precision and accuracy of inspection, the image should be acquitted in a stable and clear manner. A robust lighting system and the vibration of camera have been considered in the acquisition system. The resolution of the inspection equipment can reach 0.3 mm/pixel with a moving speed at 5 km/h. The equipment can be assembled and disassembled in a short time period to leave time for the inspection. The heaviest part was optimized to be under 25kg, which is manually movable.

3 Real-time Monitoring Network System

After the inspection of structural defect for tunnels, some of the defects should be monitored closely for their time-dependent degradations. Hence, the real-time monitoring should be applied in this case for detailed measurement. Furthermore, the monitoring is often required to be real-time since the defect is sometimes severely degraded in a short period of time. Here, the tunnel convergence of horizontal diameter is specifically discussed for the detailed monitoring since the horizontal convergence is a key performance index of tunnel safety. In order to measure the deformational performance of shield tunnel, a series of micro-electronic mechanical system (MEMS) inclinometers, were developed. Some photos of the dual axis analog inclinometer are shown in Figure 2. The smallest size for the MEMS based inclinometer could be a cubic with 35mm for each edge, which is much smaller than the current size of commercial MEMS based inclinometer sensors. The MEMS based inclinometer has the functionality that the inclination of the sensor could be measured because of the change of the direction of sensors' gravity. In order to validate the MEMS sensor's adaptability to various environments, temperature drift test, power consumption test, and calibration are conducted. All the sensors are tested under the same condition. Due to the page limitation, details of the performance tests are not provided here, which could be referred to the paper by Huang et al. (2013) for more information.

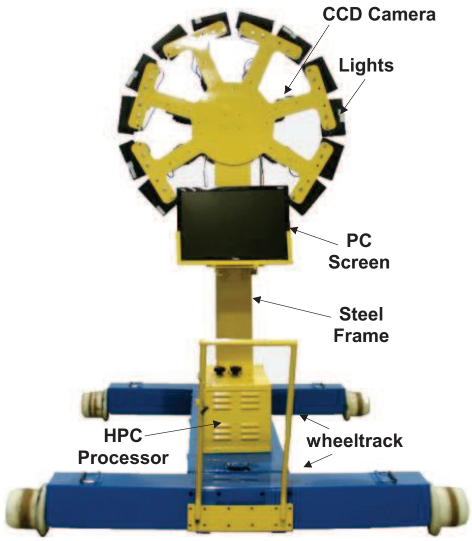
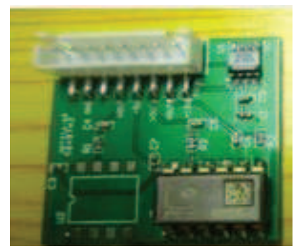
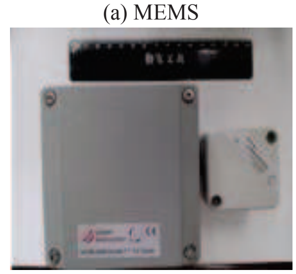


Figure 1. Layout of Moving Tunnel Inspection Vehicle (MTI-100)



(a) MEMS



(b) Packaged sensor

Figure 2. Sensor prototype

The frame of WSN consists of three basic parts: structure of network, communication protocols of network, and wireless transmission and compression methods for measured data. For the network structure, WSN adopts an expansible two-layered network topology. The network communication protocols is composed of the ZigBee and WiFi communication protocols. Figure 3 shows a layout of the network in a typical tunnel associated with the sensor nodes deployed.

A simplified transformation model is developed for calculating the horizontal convergence by using the measured tilt angle. Here, the assumption of a rigid concrete segment is made that tunnel deformation mainly depends on the joints rotation. Figure 4 is the schematic for this deformation mechanism. The horizontal convergence of tunnel can be calculated by Equation 1:

$$\Delta D = L \cdot (\Delta\theta_1 - \Delta\theta_2) \cdot \cos\alpha \tag{1}$$

where ΔD is the change of horizontal convergence, L is the distance from the base point to inner surface of segment at the tunnel center point level, $\Delta\theta_1$ is change of the tilt sensor on segment B1, $\Delta\theta_2$ is change of the tilt sensor on segment B2, α is the angle shown in the Figure 4.

4 Data-based Framework for Tunnel Structural Resilience

When the huge amount of data have been collected by the inspection and monitoring, the collected database could be utilized in the resiliency analysis. Resiliency analysis model could help the engineers understand an optimized strategy for maintenance or recovery. The index for tunnel performance should be specified prior to the discussion of structural resiliency. The tunnel horizontal convergence ΔD is adopted as tunnel structural performance in this paper (shown in Figure 4), which is probably the widely used index both in practices (MTPRC, 2014) and researches (Mair, 2008). Equation 2 is denoted as the performance index $Q_n(t)$ by a normalization transformation form with ΔD, where ΔD_0 is the initial convergence deflection when the tunnel lining is constructed and $\Delta D(t)$ is the convergence at time t which can consider the degradation effect with time.

$$Q_n(t) = \frac{\Delta D_0}{\Delta D(t)} \tag{2}$$

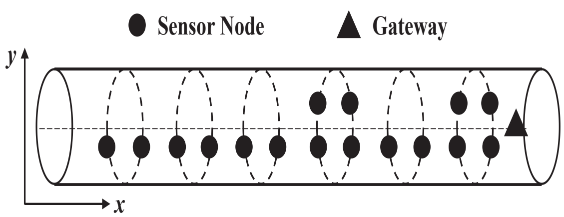


Figure 3. WSN deployment in a shield tunnel

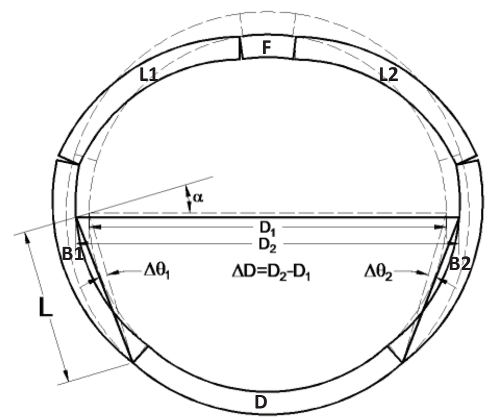


Figure 4. Transformation model for horizontal convergence of shield tunnel

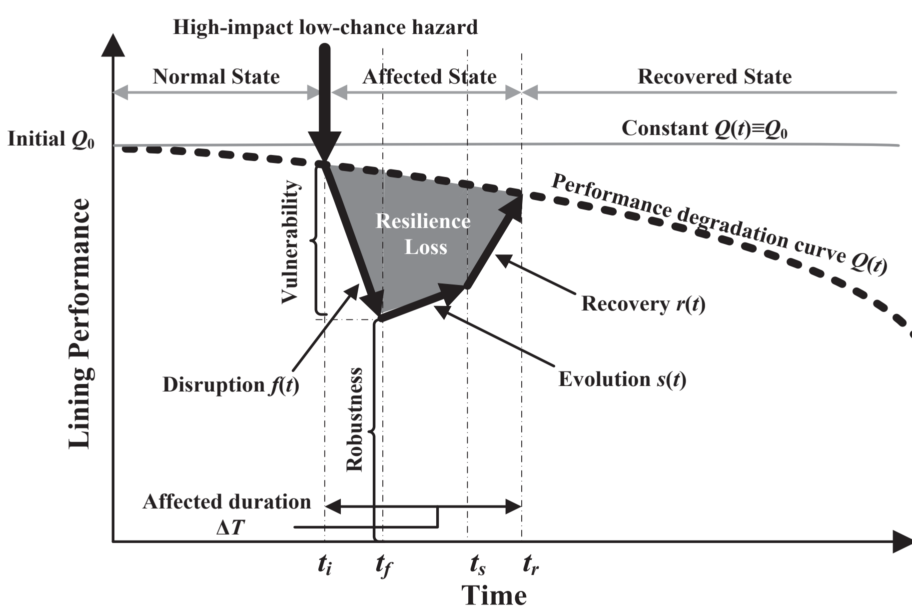


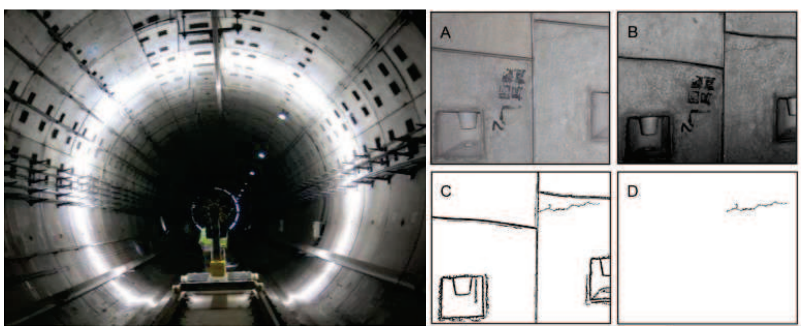
Figure 5. Definition of convergence resilience for tunnels

Figure 5 has illustrated the concepts of lifetime performance evolution for tunnel convergence. In general, there are three stages including before hazard, after hazard but before fully recovery, and finally after fully recovery. The resilience assessment is mainly focusing on the performance changes for the second stage, i.e., a stage when a hazard is recognized and recovery measures are implemented, but the full recovery is not achieved.

5 Application Example: Metro tunnel in Shanghai

In Shanghai, from time to time, there are often some extreme surcharges loading on the ground surface above the metro tunnel. The surcharge will cause several serious defects including large convergence, crack, and seepage in the metro shield tunnel lining. Hence, the integrated inspection and monitoring plans are necessary to ensure the structural safety of the metro networks. Here, an example of the surcharge case for metro line 2 is briefly discussed following the non-intrusive inspection, real-time monitoring and resiliency analysis during the repair work for the disrupted tunnel by the extreme surcharge. The detailed information of the surcharge and disruption of the deformational performance of the lining structures could be referred to the paper by authors (Huang, et al., 2017a).

5.1 *Inspection*



(a) Site photo (b) Inspected concrete crack

Figure 6. On-site inspection by using MTI-100 for metro line 2

In order to ensure the safety of tunnel operation, the MTI-100 has been applied into the shield tunnels of metro line 2 for a full inspection of the tunnel defects and sensing the environmental impact in advance. Figure 6 shows the on-site inspection by moving the MTI-100 vehicle in the metro tunnel. In Figure 6(a), man-power is used to move the vehicle and then the line camera (CCD camera) is scanning along the alignment of the tunnel lining inner surface. Figure 6(b) shows the inspected concrete cracks. In Figure 6(b), image A shows the raw photo captured by the camera, image B and image C is the image processing for the cracks, and image D is the final extraction of the crack in terms of the crack width, length and directions. Details could be referred to the paper by authors (Huang, et al., 2017b).

5.2 *Monitoring*

One monitoring sections of disrupted tunnel at ring No. 433 is selected to measure the convergence development during the repair work, i.e., soil grouting at side of spring line of tunnel. The segmental lining for this metro tunnel has an outer diameter *D* of 6.2 m and a wall thickness of 0.35 m. The tilt sensor was installed on the inner surface of lining L1, B1, L2 and

B2. Total of four MEMS tilt sensors were installed within one ring. In the meanwhile, one laser distance meter sensor was installed on B1 at the same level of tunnel center. Target of laser distance meter was installed on B2 at the same level. Tilt sensors measured the rotation of segmental lining during the soil grouting. Figure 7 shows the tilt data of Ring 433 on 18th June, 2014. It indicates that the horizontal convergence become smaller during the grouting.

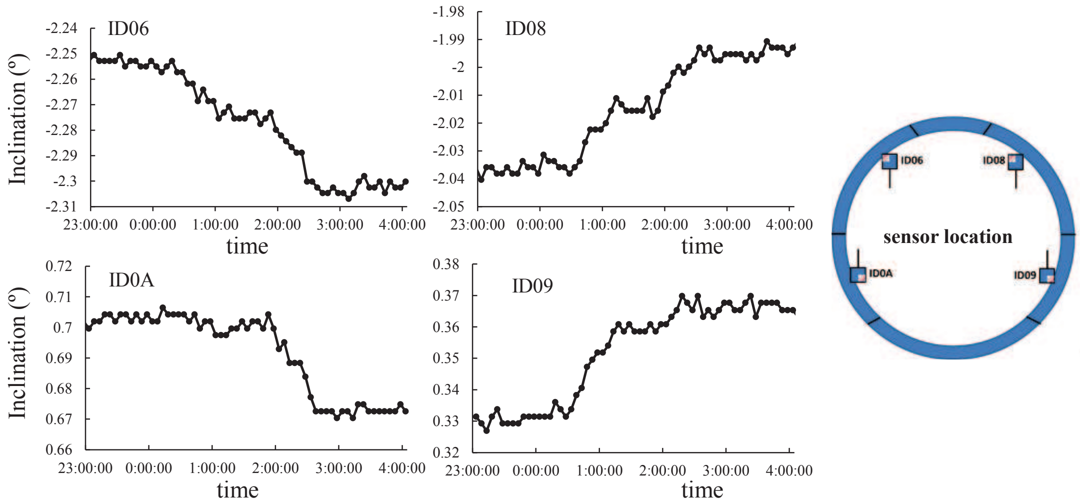


Figure 7. Tilt data of Ring 433 on 18th June

5.3 *Resiliency Analysis*

The proposed resilience analysis model has been applied to the same accident for Shanghai metro tunnel, i.e., extreme surcharge loading on the ground surface above the under-passed metro line 2. For this case study, the effect of real-time monitoring on improving the tunnel resilience can be explicitly demonstrated from a mathematical point of view. It should be noted that the WSN system was applied for the disrupted tunnel only during the recovery (soil grouting) stage. Hence, the integrated performance transition curves along with the disruption and decision making stages are estimated by the traditional monitoring system (e.g., total station). Figure 8 illustrates the integrated convergence performance transition of lining ring No. 433 due to the extreme large surcharge loading. A best-fitted performance transition curve is obtained by using the measured data with a coefficient of determination (R2) for this curve equal to 0.89 (sample size n equal to 101). Almost six years has been passed since the occurrence of the disruption until the complete of the recovery. The delay of the reaction has resulted in a small resilience index Re at 0.34. It means that 66% of the total performance has been lost because of the extreme surcharge and also because of the slow reaction. The stop of monitoring is mainly because the lining is observed in a disrupted but stable status. The lining is regarded by maintenance engineers to be safe at that time resulting in the stop of monitoring. However, almost three years later engineers want to enhance the serviceability in deformation of tunnel lining. That is the reason for a grouting treatment after almost six years, which definitely lost the rapidity of recovery.

If the tunnels has been instrumented by the WSN system before the disruption. In that case, the reduction of performance due to extreme surface loading could be captured once it starts to occur. Suppose the tunnel disruption can be detected within 80 days after the surcharge loading on the ground, the tunnel would have only 11% loss of the performance and could be recovered fully and quickly by the soil grouting. In this artificial case, the calculated resilience index Re is

0.94, significantly larger than the previous value at 0.34 for the real case. This comparison is visually explained by Figure 9. Hence, a timely detection of the disruption by applying the real-time monitoring, could reduce the vulnerability at the beginning of the disruption and subsequently increase the resilience with much lower time cost.

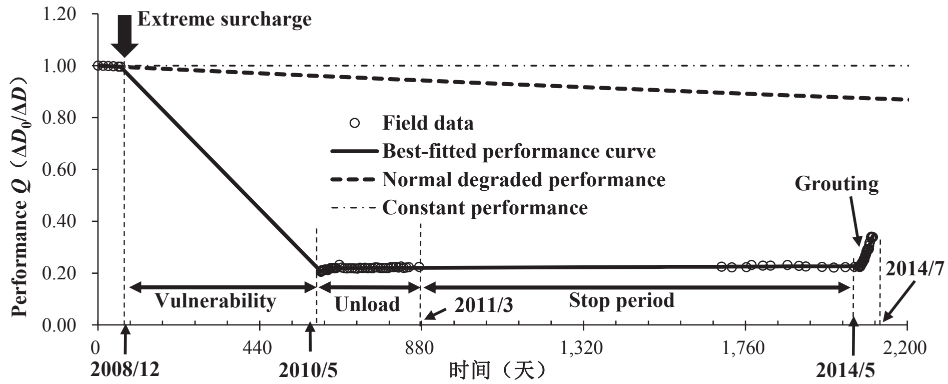


Figure 8. Measured performance transition for tunnel convergence

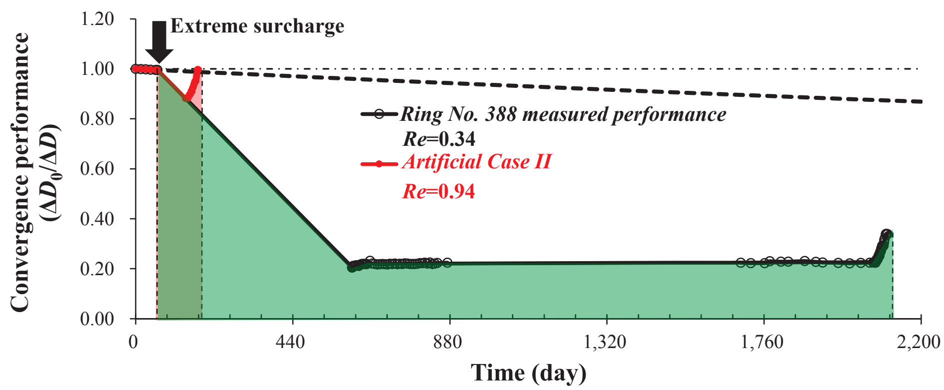


Figure 9. Comparison of the resilience between real case and artificial case

6 Conclusions

With the number of operational tunnels is increasing rapidly, the preventive maintenance associated with the inspection and monitoring strategies are of great necessity to ensure the structural safety for infrastructural system in long-term. This paper presents a rational framework for the non-intrusive inspection and real-time monitoring for the preventive maintenance in the sense of resiliency philosophy for the tunnels. The moving vehicle of the CCD camera based inspection system could well capture the tunnel structural defects with the precision of cracks at 0.3mm with a moving speed at 5km per hour. The WSN-based monitoring system could capture the tunnel deformational response in real-time. A resiliency analysis model combined with the inspected and monitored data could be of great help to understand the resilience of the tunnel structural behaviors. A rational repair strategy in terms of the optimized recovery timing and recovery measures could be derived with the proposed resiliency analysis model. The illustrated real case application example shows the well validation of the proposed integrated resiliency model using the above inspection and monitoring techniques.

7 Acknowledgement

This study is substantially supported by the Natural Science Foundation Committee Program (No. 51538009, 51608380), by the International Research Cooperation Project of Shanghai Science and Technology Committee (No. 15220721600) and also by the Peak Discipline Construction on Civil Engineering of Shanghai Project. Hereby, the authors are grateful to these programs.

8 References

Ayyub, B. M., Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making, Risk Analysis, 34(2), 340-355, 2014.

Bennett, P. J., Kobayashi, Y., Soga, K., and Wright, P., Wireless Sensor Network for Monitoring Transport Tunnels, Geotechnical Engineering, 163(3), 147-156, 2010.

Blom, C. B. M., Horst van der, E. J., and Jovanovic, P. S., Three-dimensional Structural Analyses of the Shield-driven "Green Heart" Tunnel of the High-Speed Line South, Tunnelling and Underground Space Technology, 14(2), 217-224, 1999.

Huang, H. W., and Zhang, D. M., Resilience Analysis of Shield Tunnel Lining Under Extreme Surcharge: Characterization and Field Application, Tunnelling and Underground Space Technology, 51, 301-312, 2016.

Huang, H. W, Shao, H., Zhang, D. M., and Wang, F., Deformational Responses of Operated Shield Tunnel to Extreme Surcharge: A Case Study, Structure and Infrastructure Engineering, 13(3), 345-360, 2017a.

Huang, H. W., Sun, Y., Xue, Y. D., and Wang, F., Inspection Equipment Study for Subway Tunnel Defects by Grey-scale Image Processing, Advanced Engineering Informatics, 32, 2017b.

Huang, H. W., Xu, R., and Zhang, W., Comparative Performance Test of an Inclinometer Wireless Smart Sensor Prototype for Subway Tunnel, International Journal of Architecture, Engineering and Construction, 2(1), 25-34, 2013.

Mair, R. J., Tunnelling and Geotechnics: New Horizons, Geotechnique, 58(9), 695-736, 2008.

Montero, R., Victores, J. G., Martínez, S., Jardón, A., and Balaguer, C., Past, Present and Future of Robotic Tunnel Inspection, Automation in Construction, 59, 99-112, 2015.

Richards, J. A., Inspection, Maintenance and Repair of Tunnels: International Lessons and Practice, Tunnelling and Underground Space Technology, 13(4), 369-375, 1998.

Yuan, Y., Jiang, X., and Liu, X., Predictive Maintenance of Shield Tunnels, Tunnelling and Underground Space Technology, 38, 69-86, 2013.

Ministry of Transport of the People's Republic of China (MTPRC), Code for design of road tunnel JTG/D70-2014, China Communications Press Co., Ltd., Beijing, China, 2014.

Soga, K., Ledesma, A., Roncaglia, A., and Vanicek, I., Micro-measurement and monitoring system for ageing underground infrastructure (Underground M3), Crc Press-Taylor & Francis Group, Boca Raton, USA, 2012.

Gavilán, M., Sanchez, F., Ramos, J. A., and Marcos, O., Mobile Inspection System for High-resolution Assessment of Tunnels, Proceeding of the 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-6). Hong Kong, China, 2013.

Huang, H. W., and Zhang, D. M., Quantitative Geotechnical Risk Management for Tunneling Projects in China, Proceeding of the 5th International Symposium of Geotechnical Safety and Risk (ISGSR-5), 61-75, Rotterdam, the Netherlands, 2015.

Zhang, D. M., Huang, H. W., Hu, Q. F., and Zhang, Y. J., How Smart Sensoring Improve Tunnel Resilience: from Theoretical Model to Future Application, Proceedings of the International Conference on Smart Infrastructure and Construction, 721-726, Cambridge, UK, 2016.