Tunnelling and Underground Space Technology 38 (2013) 69–86

Contents lists available at SciVerse ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Predictive maintenance of shield tunnels

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ARTICLE INFO

Article history:
Received 28 December 2012
Received in revised form 20 April 2013
Accepted 12 May 2013
Available online 13 June 2013

Keywords:
System risk
Predictive maintenance
Condition based maintenance
FMEA
Damage accumulation model
Weibull distribution

ABSTRACT

Scientific maintenance methodologies are specially needed to enhance system reliability and safety, reduce maintenance manpower, spares, and repair costs, eliminate scheduled inspections, and maximize lead time for maintenance and parts procurement. This paper systematically presents a comprehensive methodology and framework for aggressive inspection and condition based predictive maintenance of a shield tunnel consisting of prefabricated lining rings. The framework consists of six components: maintenance purposes, data, modeling and simulation, documentation, managerial schedule, and inspection/maintenance behaviors. These components are interpreted in details as nine necessary parts in a predictive maintenance strategy. The failure mode and effect analysis approach is employed in developing a predictive maintenance strategy for a tunnel structure, with the purpose of prioritizing possible defects in the tunnel in order to facilitate the decision making on predictive maintenance. The system-level lifing analysis method is proposed for the proactive maintenance of the tunnel system. The method includes data preprocessing, risk model establishment, quantitative model validation, empirical lifing analysis, and system-level maintenance schedule. The empirical lifing analysis involves both risk prediction and damage accumulation models for service limit determination, system-level risk analysis, and system-level conditional risk for maintenance schedule. The proposed methodology is demonstrated with the inspection data collected for six typical defects observed in real-world shield tunnels.

1. Introduction

A large number of infrastructure systems like tunnels around the world have been in service for decades, for instance, a majority of transit systems in US are over 50 years old (FTA, 1997). The critical components and subsystems in such an ageing system as tunnel contain various potential deficiencies such as seepage, spalling, crack, concrete delamination, steel corrosion, drainage, and decay of the lining structure in the tunnel (Yuan et al., 2012). These defects may result in fatal incidents and huge loss of life and properties. For instance, concrete spalling in the lining structure has become an increasingly significant issue in underground engineering (Delatte et al., 2003; Russell and Gilmore, 1997). In particular, the water leakage in the concrete lining structure of a tunnel usually causes corrosion in steel reinforcement, which leads to concrete spalling due to the increasing volume of the steel embedded in the concrete. Concrete spalling in a tunnel may even result in severe damage or fatal incident if not monitored continuously. A well-known severe incident resulting from concrete spalling occurred at New York City in August, 1973 when the concrete delaminated from the archway of the Steinway Tunnel. The falling concrete struck an 11-car passenger train, resulting in one passenger died and many injured from the incurring fire. As pointed out by Russell and Gilmore (1997), this tunnel accident would be avoided if an aggressive inspection and maintenance program was implemented to repair the concrete spalling prior to its delamination. This paper exploits a system engineering methodology for aggressive inspection and condition based predictive maintenance of shield tunnels consisting of prefabricated ling rings.

Maintenance activities and philosophy are playing an increasingly important role on ensuring structural reliability, safety, availability and maintainability as well as optimizing operating cost of a modern engineering system such as tunnels. Scientific maintenance methodologies are specially needed to enhance tunnel reliability and safety, reduce maintenance manpower, spares, and repair costs, eliminate scheduled inspections, and maximize lead time for maintenance and parts procurement. Over the past two decades, a plenty of approaches have been proposed to study maintenance philosophies (e.g., Amari et al., 2006; DoD, 2008; Pinteton and Herz, 2008; Tinga, 2010). The maintenance requirement also becomes a significant part in the specifications of the inspection and grading approaches for transportation tunnels (e.g., FTA, 1997; FHWA, 2004) in the past decade. Non-destructive inspection, traditional schedule-based maintenance, and repair technologies have also investigated for tunnel structure (see e.g.,

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http://dx.doi.org/10.1016/j.tust.2013.05.004

Haack et al., 1995; Richards, 1998; Asakura and Kojima, 2003). In particular, the International Tunneling Association (ITA) established a working group to study new technologies on the maintenance and repair of underground structures (Richards, 1998). More recently, Nývlt et al. (2011) employed the probabilistic risk analysis concept well-founded in other industries for risk assessment and cost minimization of highway tunnel management. However, to the best knowledge of the authors, there is no literature to systematically present the condition based predictive maintenance method for shield tunnels.

Based on the determination of the inspection interval, maintenance philosophies may be classified into three categories: corrective, preventive, and predictive. Pinteton and Herz (2008) introduced fundamental elements of maintenance for engineering systems and provide a summary of the evolution path of maintenance management and philosophies over time. Also DoD (2008) and Jiang (2010) presented the major features of the three maintenance philosophies. Basically *corrective maintenance* is applied to restore the operability of an engineering system after a defect or failure is observed during the routine inspection. Corrective maintenance is usually carried out where the consequences of failures or wearing out are not significant. *Preventive maintenance* is aimed at preserving the useful life of components, avoiding premature failures, and minimizing any impact on operational requirements. It is carried out on those components where a defect or failure will result in expensive or unacceptable consequences. In a preventive maintenance, systematic inspection is applied to identify impending problems and incipient defects or failures, and scheduled maintenance is applied to prevent component failure or further degradation.

Predictive maintenance is an advanced preventive approach where maintenance is deferred until it is actually needed. The objective of this approach is to monitor the system in a way that incipient faults (such as cracks, seepage, or spalling that has initiated in tunnels) are detected, identified and tracked well before they can cause a component to have performance degradation or failure. Actual maintenance activities are performed only when the faults have propagated to some unacceptable level, or the faults have caused system performance to deteriorate to an unacceptable level. In this approach, the remaining life of components or systems is used to determine when the maintenance should be performed. The monitoring activity can be discrete (e.g., periodic inspections) or continuous (e.g., monitoring dynamics or performance of the system). There are roughly two main types of predictive maintenance activities, namely, condition based maintenance (CBM) and prognostics and health management (PHM). The former usually takes advantage of data-driven or physics-based reliability models for risk-based inspection and predictive maintenance of engineering structures. Whereas the latter usually utilizes sensor data continuously collected from monitored operating systems to develop strategies for real-time monitoring, diagnostics and prognostics of structural performance.

Condition based maintenance techniques provide the assessment of the system condition based on the collected historical data through periodical inspections. Its aim is to determine required maintenance activities prior to any predicted failure. Over the past decade the CBM has received increasing attention from industry, academia, and government in a wide variety of engineering fields such as aerospace, automotive, civil, energy, and mechanical engineering (e.g., Cheng and Plumtree, 1998; Coh et al., 1989; Engel, 1993; Ihara and Tanaka, 2007; Rudra and Jennings, 1994; Seweryn et al., 2008; Szusta and Seweryn, 2010; Tinga, 2010; Yang and Younis, 2005; Younis and Knight, 2010; Walls and Quigley, 2001). Fig. 1 illustrates basic concepts of applying a probabilistic damage prediction model for maintenance interval schedule (Fig. 1a), limit status definition (Fig. 1b), and performance degradation status (Fig. 1c) of a tunnel. With the ageing and usage of an engineering system such as tunnels, historic damage data for a given failure mode (e.g., crack or seepage) are usually collected from the field inspection periodically (solid dots in Fig. 1a). These damage data points generally follow a statistical distribution (e.g., Weibull or lognormal distribution, see the dash curves in Fig. 1a) at any given inspection time. The damage indicator at the same location in a section or segment of the tunnel should increase over the operating time, assuming no maintenance activities conducted prior to its service limit. As such, all damage data historically observed for a given failure mode should display a monotonically increasing trend as the operating time increases due to the damage accumulation. The percentiles of damage at various inspection intervals can be estimated from the inspection data, shown as P_x curves in Fig. 1a, where the subscript x represents the percentage of the damage along the operating time. If a damage limit is predefined for a given failure mode based on probabilistic limit design theory (the dash line in Fig. 1a), the time-to-failure or the residual useful life of the tunnel segment can be estimated from the damage accumulation curve at different percentages. The obtained results can be then used to schedule next inspection time in order to ensure the tunnel in a safe operating condition.

In the condition based predictive maintenance of a shield tunnel, the service conditions of its prefabricated lining structure can be categorized intro three levels: initial degradation, serviceable, and repairable. Given a performance indicator such as structural deflection, the service conduction of the tunnel structure can be defined and evaluated based on the probabilistic theory, considering uncertainty (Fig. 1c).Their corresponding service limits may be determined according to the probability of structural damage, which is calculated from service condition based reliability or performance model of the structure, as shown in Fig. 1b and c. Different services conditions as well as their deviation from the design condition will determine the structural performance of a tunnel in operation. The initial degradation limit may be decided when the probability of failure reaches up to an acceptable small level. In addition, the structure does not need to be repaired before its failure probability reaches to an acceptable service limit. After then, the structure should be repaired any time before its probability of failure reaches to the repairable limit. If the damaged structure is not repaired before repairable limit, the structure may not be repairable any more. Note that the durability may be considered as another category in the condition assessment, as discussed in Yuan et al. (2012), which is beyond the scope of this study.

In the following sections, the framework and architecture of condition based predictive maintenance is first presented at a system engineering perspective. The components of maintenance framework are then interpreted in details as nine necessary parts in a predictive maintenance strategy, such as failure modes and effective analysis, data pre-process, reliability modeling, and system-level lifing analysis. The empirical lifing analysis involves both risk prediction and damage accumulation models for service limit determination, system-level risk analysis, and system-level conditional risk for maintenance schedule. Next, the proposed methodology is demonstrated with the inspection data collected for six typical defects observed in real-world shield tunnels. Finally, concluding remarks are provided.

2. Predictive maintenance architecture of a tunnel

Routine maintenance methodology is being widely used for shield tunnels consisting of prefabricated lining structures. This maintenance approach is often inefficient, ineffective, and inaccurate. This study exploits a system engineering methodology for aggressive inspection and condition based predictive maintenance