Tunnelling and Underground Space Technology 69 (2017) 72–84

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Risk-cost optimised maintenance strategy for tunnel structures

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ARTICLE INFO

Keywords:
Tunnel
Maintenance
Failure mode
Optimization

ABSTRACT

As an essential infrastructure tunnels play an important role in transport network. The functionality of this infrastructure depends on its structural and durability performance. In the climate of an increasing scarcity of resources, infrastructure maintenance is becoming increasingly important. This paper aims to develop a maintenance strategy for tunnels, which determines when, where and what to maintain, to ensure the safe and serviceable operation of tunnel structure with the intention to minimise the total risk. Application of the proposal is presented in a numerical example of a practical case study. It was found that an optimum solution, which can predict when, where and what to maintain for tunnel structure to ensure its safe and serviceable operation during its lifespan, exists. The paper concludes that the proposed framework can equip tunnel operators and asset managers with a tool in developing a risk cost optimised maintenance strategy for tunnels under their management.

1. Introduction

Tunnel is an essential infrastructure that plays a pivotal role in transportation network, economy, prosperity, social well-being, quality of life and the health of its population. In the light of considerable research on maintenance of “aboveground” infrastructure, e.g. bridges, fewer studies on underground infrastructure, e.g. tunnels, have been undertaken. The situation in underground structures can be exacerbated due to more unknowns and uncertainties relating to the factors such as underground water and soil/rock that affect the operation of tunnel infrastructure. In an ageing tunnel system, various potential deficiencies such as seepage, crack, delamination, drainage, convergence and settlement of the lining structure can cause catastrophic failures and economic losses. Most collapses of tunnel structures in the world are related to tunnel deterioration with catastrophic consequences. For instance, in July 1969, three large rocks fell in the Eucumbene Snowy tunnel in Australia (used for water conveyance), completely chocking the tunnel (Jacobs, 1975; Rosin, 2006); in August 1973, a concrete chunk fell in the Steinway Tunnel in New York, causing fire and resulting in one death and many injuries (Russell and Gilmore, 1997) and more recently in December 2012, about 300 ceiling panels in the Sasago tunnel in Tokyo collapsed, killing nine people and injuring two (Kawahara et al., 2014). Therefore, the problem of deterioration is very severe and its consequences have become more and more catastrophic. One apparent solution is to replace the deteriorated infrastructure but this is very costly. The replacement cost for a tunnel is estimated at $250 million/km (Russell and Gilmore, 1997). More importantly, this solution is not sustainable due to the ever-increasing scarcity of resources. In addition, replacement is not always practical for some infrastructure such as tunnels. Therefore, an effective maintenance plan can be a viable means to prevent catastrophic failures of tunnels.

The annual cost of maintenance for tunnels could be as high as $150 K/km (Russell and Gilmore, 1997), which does not include the indirect cost of disruptions, loss of productivity, etc. The cost of tunnel failures is beyond estimate when it involves casualties. Therefore, efficient strategies with minimal cost for maintenance activities are increasingly sought by asset managers to ensure structural reliability, availability and maintainability of these structures (Asakura and Kojima, 2003). The problem is how to determine when, where and what to maintain at minimal risk and with effective cost. A lack of such rational strategy has resulted in a situation where safe structures or components have been routinely maintained unnecessarily, whilst unserviceable or near failure infrastructure has not been maintained in time, leading to failures.

A few strategies for maintaining tunnel structures have been proposed in the current literature. Ai et al. (2014) developed a condition-based maintenance strategy for tunnel structures. The proposed maintenance strategy was based on minimising the total inspection, repair and expected failure cost, with the constraint of limiting the probability

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http://dx.doi.org/10.1016/j.tust.2017.06.008
Received 7 November 2016; Received in revised form 2 June 2017; Accepted 8 June 2017
0886-7798/

of failure below a target level. Although the variation of the lifetime probability of failure for a limit state based on convergence of tunnel lining was provided, little detailed result for the maintenance strategy was given. Yuan et al. (2013) presented a methodology and procedure for condition-based predictive maintenance of tunnels with prefabricated lining rings. The deterioration models for failure modes such as seepage and spalling were based on inspection data collected from typical defects observed in tunnels. The developed empirical analysis involved both risk prediction and damage accumulation for service life determination. The proportional hazard model was used for development of lifetime distribution. Furthermore, system-level risk analysis, and system-level conditional risk for maintenance schedule were used. Through typical defects observed in a case study on a shield tunnel, application of the proposed methodology was demonstrated. Wang et al. (2016) proposed a maintenance framework for shield tunnels based on life cycle cost considering cost of initial construction, inspection and repair. Structural performance in terms of resistance to load ratio and life cycle cost were evaluated as the major deterioration indicators. An ultimate limit state based on maximum flexural stress in which degradation of steel section due to corrosion was considered was used. Furthermore, the uncertainty in the load effect was also considered. First Order Second Moment method was used for calculating the probability of failure. The proposed maintenance framework was applied to the maintenance of a trunk sewerage pipe.

On the other hand, different general frameworks have been proposed to formulate strategies for inspection, maintenance and decision-making for deteriorated structures, using reliability-based optimization (Barone and Frangopol, 2013; Dekker, 1996; Frangopol and Soliman, 2014; Mori and Ellingwood, 1994; Sommer et al., 1993; Stewart, 2001; Thoft-Christensen and Sorensen, 1987). However, a thorough review of the published literature has identified major gaps and deficiencies of the current frameworks as follows. Firstly, most studies consider only a single mode of failure, either in ultimate or serviceability limit state as the assessment criterion (Mori and Ellingwood, 1994). However, structure can fail in different modes. Secondly, only the reliability of a single component rather than the structure as a whole, i.e., structural system, is considered (Sharifi and Paik, 2014). But failure of one component does not necessarily constitute the failure of the structure as system. Thirdly, time-dependent reliability methods have not been fully incorporated in service life prediction and the consequent determination of maintenance time (Frangopol et al., 2004). As it is known, most of failures are not only random but also time variant. Forth, most of the current frameworks deal with maintenance of aboveground structures e.g. bridge. Underground structures are more complicated, and have more interactions with the surrounding environment such as underground water and rock. The purpose of this study is to fill these gaps and address the deficiencies with an innovative approach.

In this paper, a maintenance strategy based on risk cost optimization of tunnel structure during its whole service life is mathematically formulated. An advance time-dependent reliability analysis in which deterioration is modelled as a stochastic process is employed to predict the probability of failure. To facilitate practical application of the formulated maintenance strategy, an algorithm is developed and programmed. An example is given to illustrate the application of the proposed maintenance strategy to an existing tunnel.

2. Formulation of maintenance strategy

A structural system consists of components or subsystems. In this case, failure of a structure can be modelled as a combination of series system for non-redundant components and parallel system for redundant components. Similarly, a component can fail in many modes, some of which reach the ultimate limit state and some reach the serviceability limit state. Thus, component failure should also be modelled as a combination of series system for ultimate failures and parallel system for serviceability failures. This concept can be logically illustrated in Fig. 1. The probability of each failure is determined by a time-dependent reliability method since failure is not only random but also time-variant.

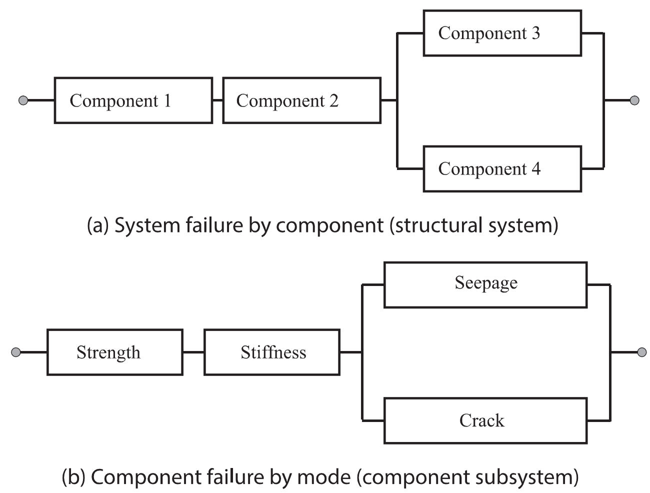

Fig. 1. Concept of system failure.

By combining the concepts of system reliability and optimisation, an innovative maintenance strategy for infrastructure can be developed. The rationale for the proposed maintenance strategy is that, whilst keeping the probability of ultimate failure under control (to ensure safety), only when the probability of serviceability failure is greater than an accepted limit, the maintenance would be warranted. Furthermore, the probability of the whole system failure, which depends on components and failure modes, is also kept below an acceptable threshold. This will ensure that the maintenance action is only performed when there is violation of serviceability limit states such as crack width or water seepage in tunnels. Through limiting the system failure, an upper bound is imposed on the overall system failure.

The merit of this rationale is to minimise, if not eliminate, inspections for possible serviceability failures without compromising the safety of the tunnel. The risk function is based on the probability of system failure and the action takes place on the most influential component as schematically shown in Fig. 2. The problem can then be formulated mathematically using system risk function as follows

$$\begin{aligned} &Minimize:\ Risk = \sum_{i=1}^{N_r}\sum_{j=1}^{N_c}\sum_{k=1}^{N_m} p_{sys}\times C_{jk}\\ &Subject\ to:\ \ p_u(t_i)\leq p_{u,a};\\ &\qquad p_s(t_i)\geq p_{s,a};\\ &\qquad p_{sys}(t_i)\leq p_{sys,a};\\ &\qquad 0\leq t_i\leq t_L \end{aligned} \tag{1}$$

where, t_i is the maintenance time sequence with i refereeing to number of times, j to structural component and k to failure mode. N_r is the number of maintenance actions, N_c is the number of components and N_m is the number of failure modes. C_{jk} is the cost (including interest rate) of failure for j^{th} component due to k^{th} failure mode. p_s and $p_{s,a}$ are the probability and acceptable probability of serviceability failure modes, p_u and $p_{u,a}$ are the probability and the acceptable probability of ultimate failure modes, respectively. p_{sys} and $p_{sys,a}$ are the probability of failure and the acceptable probability of failure for the system. t_L is the lifetime of the structure. The design variables in this optimization are the time of maintenance for each failure mode and component, i.e., t_i. For simplicity, interdependence between failure modes is not included in Eq. (1) to achieve effective practical applications as will be shown in the example.

The number of maintenance actions is given as an input. In each maintenance action, the most influential component within the system is identified. For instance, in a series system the component with the