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Resilience analysis of shield tunnel lining under extreme surcharge: Characterization and field application

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ABSTRACT

A resilient system should have the ability to mitigate the disruption caused by unfavorable environment and to rapidly recover to an acceptable performance level. In this paper, a detailed model to assess resilience of shield tunnel is presented. The performance robustness under disruption and the subsequent recovery rapidity are emphasized in this model. The tunnel horizontal convergence is selected as the performance indicator. The resilience index (Re) is defined by the ratio of the integral of the performance transition function over the integral of the normal performance function. The rationality and applicability of the model is validated by a real case of extreme surcharge on Shanghai metro tunnel. In this case, the performance transition and the normal performance degradation are characterized by the measured data. 70–80% of the normal performance is disrupted due to the surcharge, but only 1% is recovered by unloading of the surcharge in 9 days and 12.4% is recovered after 4 years by the soil grouting in 38 days. It results in a resilience index (Re) between 0.28 and 0.45. The lesson learned from the case indicates that the high vulnerability of lining convergence due to the severe surcharge and the long time duration between recovery measures could result in weak resilient abilities for shield tunnels. The value of resilience index Re could be significantly increased by 73% on average if the recovery duration were shortened.

1. Introduction

In Shanghai, the metro system with a mileage of 538 km takes up 43% of the daily public transportation volume. In operating such a huge system, any disruption is costly and hence of major concern to engineers (Frangopol, 2011). Disruptions and their associated repair works can be caused by different unfavorable environmental conditions (Richards, 1998). Some examples are highlighted below. Chang et al. (2001a) has reported a field case on a shield tunnel for Taipei Rapid Transit System (TRTS) disrupted by an adjacent deep excavation. Large tunnel deformation was measured and cracks at the crown were observed. A road tunnel in Taipei was found to be affected by a slide at a neighboring slope causing severe concrete cracking of the linings (Wang, 2010). Three road tunnels in Korea with severe structural defects caused by environmental disturbance were presented in the paper by Choo et al. (2013). A metro shield tunnel in Shanghai was found to experience a large deformation caused by an unexpected extreme surcharge (Wang and Zhang, 2013). Serious structural defects and the fracture of the steel bolts were detected in this tunnel. In the face of dramatic growth in underground construction, tunnel disruptions due to unfavorable environmental causes, as described above, might be more significant and could be encountered more frequently.

Quite often, the timing for repair measures on disrupted tunnel, e.g., enhancement by steel segments or soil grouting, is vague to engineers, i.e., either too late or too early but without a full estimation of the effect of these measures. It thus may result in a high cost but small effect on the recovery of tunnel performance (Chang et al., 2001b; Ni and Cheng, 2012). In view of this, engineers need to understand the recovery ability of the tunnels in terms of the degree and rapidity before a specific repair measure is implemented. Few studies have been carried out on the performance recovery of tunnels at this moment, possibly because of the limited number of well-documented field cases with measured data (Ni and Cheng, 2010). But even when the measured data are available, the understanding of recovery ability of tunnel is not straightforward due to the absence of a rational model to assess the recovery efficiency. To be more specific, there are no criteria to guide engineers to evaluate the effectiveness of repair measures and their associated time cost (Doherty et al., 2012; Titi and Biondini, 2013).

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In the context of this circumstance, the resilience model might be an appropriate way to provide a full assessment of the system recovery because it includes both the system robustness and recovery rapidity (Ayyub, 2014). Resilience, from US Presidential Policy Directive (PPD-21, 2013), means *"the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions."* It extends from general performance degradation to include the performance disruption under the high-impact, low-chance risks (Blockley et al., 2012). Basically, the system performance within the *resilience* concept is a function of time during the disruption and recovery process. The performance transition with time could indicate both the magnitude of recovered performance and the associated time cost. In this respect, the effectiveness of the repair measures on the system recovery could be evaluated directly. More practically, a generalized metric of resilience, e.g., the integral of the performance transition with time (Cimellaro et al., 2010; Ayyub, 2014), is defined as an index of resilience reflecting the system robustness and recovery rapidity.

Resilience analysis was first formally introduced by Holling (1973) for an ecology system. Later on, the interest in resilience was triggered by the event of 9/11 in US. So far, resilience analysis has been introduced into the water resource system (Hashimoto et al., 1982), infrastructure networks (Henry and Ramirez-Marquez, 2012) and the seismic risk assessment for the bridges (Dong and Frangopol, 2015). However, the resilience of underground structure such as a tunnel is not well studied. We should bear in mind that the disruption for a tunnel is always significant and the subsequent repair work is difficult due to the highly uncertain surrounding environments. In addition, current study on resilience appears to be mostly conceptual with limited demonstration of its applicability in the real world (Sudmeier-Rieux, 2014). Construction of a detailed resilience model and application to an actual field example will allow resilience to be studied in a more concrete way.

Based on the general model proposed by Ayyub (2014), this paper presents a detailed model to assess the resilient ability of a metro tunnel to recover from disruption caused by some unfavorable environmental conditions. The horizontal convergence of the tunnel lining is selected as the performance indicator in this model. The proposed resilience model is applied to the field case reported by Wang and Zhang (2013), in which tunnel disruption is caused by the unexpected extreme surcharge exceeding the design level by seven times. The site information and the repair measures for this case are briefly presented in this paper. The performance transitions from the disruption to the recovery stages are captured by the measured data. For linings in normal conditions, i.e., not subjected to the surcharge, the time-dependent effect is considered in characterizing the performance degradation. The resilience index (Re) is finally characterized by the ratio of the integral of the performance under disruption over the integral of the normal performance. The effects of the repair measures are discussed based on the results of resilience index (Re). The system properties in terms of robustness and the timing for recovery are highlighted in the end of this paper.

2. Frame of resilience analysis for tunnels

Over the long life span of a shield tunnel, the segmental lining structure will age with time in terms of its operational performance (Bader, 2003), which is generally illustrated in Fig. 1 (see the black dashed line). In addition, some high-impact low-chance risk or unfavorable environmental condition may further disrupt the performance at some time t_i (see black arrowed line in Fig. 1). However, the timing of appropriate repair work for these performance losses are quite vague, usually resulting in a high-cost but small-effect recovery in absence of a decision model for Fig. 1 (see details in the field case). In view of this shortage, a resilience frame could assess a tunnel for its ability to absorb disruption caused by unfavorable environments and to recover rapidly from the disruption, and thus could infer a reasonable timing for repair. Detail of the resilience frame for a shield tunnel is given below.

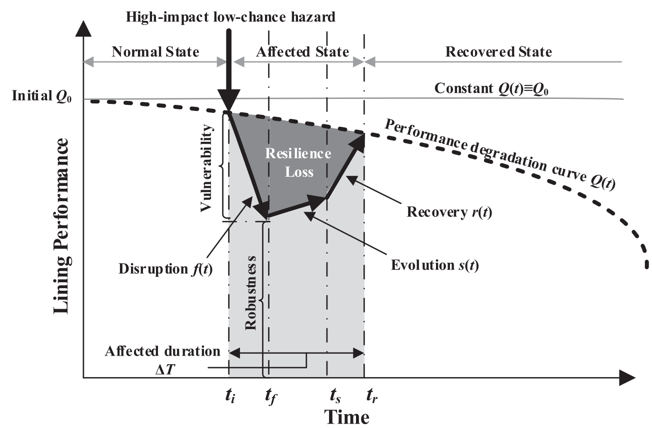

Fig. 1. Schematic of performance transition in resilience analysis for tunnel lining.

2.1. Definition and metric of tunnel resilience

The schematic of performance transition over the whole affected duration ΔT from the time t_i when the unfavorable environmental condition happens to the time t_r when the tunnel recovers to an acceptable level is plotted in Fig. 1 (represented by the arrowed solid line). As the tunnel starts to respond to the environment at time t_i, the performance decreases until time t_f when the significant disruption has been detected. When the recovery measures are applied at time t_s, it helps the tunnel recover to an acceptable level of performance at time t_r. From time t_f to time t_s, it is the period of decision-making for emergency relief and selection of recovery measures. The length of this time period can be varied significantly from case to case. The tunnel might come to a stable but disrupted state as time goes in this period. Hence, it is necessary to define a performance evolution $s(t)$ at this stage that is conceptually different from both the disruption and recovery stages, i.e., $f(t)$ and $r(t)$ in Fig. 1 respectively. Compared to the general schematic of performance transition model proposed by Ayyub (2014), the one presented in this paper is more detailed as this decision-making stage, i.e., $s(t)$, is considered.

Table 1 shows several resilience dimensions involved in this schematic. First, the performance degradation due to the time effect under normal condition is considered (represented by solid dash line in Fig. 1 and denoted as normal performance $Q(t)$). Basically, the normal performance is the target of the acceptable level of the recovered performance in Fig. 1. Second, the performance $f(t_f)$ at time t_f in Fig. 1 stands for the tunnel robustness subjected to the unfavorable environment (hereafter referred to as robust performance), in the meanwhile, the loss of performance compared to the normal performance, i.e., $\text{Vn} = Q(t_f) - f(t_f)$, corresponds to the tunnel vulnerability. Third, the time duration ΔT from time t_i to time t_r stands for the rapidity of the recovery. Note that the rapidity is a crucial dimension for a resilient system (Bruneau et al., 2003). Similar to other infrastructures, the tunnel resilience should have the ability to absorb the disruption of performance, including the high robustness or low vulnerability, and the ability to rapidly recover to an acceptable performance level, including the rapidity and recovery.