Transportation Research Part E 105 (2017) 39–59

Contents lists available at ScienceDirect

Transportation Research Part E

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

Pre-disaster investment decisions for strengthening the Chinese railway system under earthquakes

Yongze Yan [a], Liu Hong [a,b,*], Xiaozheng He [c,d], Min Ouyang [a,b], Srinivas Peeta [c,e], Xueguang Chen [a,b]

[a] School of Automation, Huazhong University of Science and Technology, Wuhan, Hubei 430074, PR China
[b] Key Lab. for Image Processing and Intelligent Control, Huazhong University of Science and Technology, Wuhan 430074, PR China
[c] NEXTRANS Center, Purdue University, 3000 Kent Avenue, West Lafayette, IN 47906, USA
[d] Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, 110 8th St., Troy, NY 12180, USA
[e] Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 30 September 2016
Received in revised form 16 May 2017
Accepted 2 July 2017

Keywords:
Earthquakes
Railway system
Investment decision
Service loss
Genetic Algorithm

ABSTRACT

This study proposes a framework to determine the investment plan to strengthen a railway system which is subject to earthquake hazard. The proposed framework includes four parts: (1) Construct a two-layer (physical layer and service layer) railway network representation; (2) Generate earthquake scenarios based on historical earthquake data; (3) Formulate an investment optimization model to minimize the expected railway system service loss subjected to an investment budget constraint, where the service loss is quantified based on the affected train flow; (4) Solve the optimization model by using Genetic Algorithm. Taking the Chinese railway system (CRS) as an example, the proposed framework has been applied and the results show that the solution of the proposed framework is more responsive to the earthquake impact on railway system compared to topology-based methods. Note that the proposed framework can also be extended to identify pre-disaster investment plans for other transportation systems under natural disasters.

1. Introduction

Railway is one of the most important long-distance transportation modes in many countries since the eighteenth century. In China, about 2.5 billion passengers and 3.4 billion metric tons of cargo were transported by the Chinese railway system (CRS) in 2015 ("Yearbook", 2016). However, China is a country seriously affected by earthquakes, and is suffered from 33% of the serious continental earthquakes, despite it only covers 7% of the land area in the world. Earthquakes can cause railway trains interrupted or delayed, and decrease the functionality of the CRS. Pre-disaster investment to strengthen the railway system can mitigate the impacts of the consequent unpredictable disruptions (Orcesi and Frangopol, 2011). However, the budget for pre-disaster investment is typically limited. From a pure monetary perspective, it is neither affordable nor acceptable to strengthen the entire railway system, especially for large scale ones such as the CRS whose rail mileage is more than 100,000 km. Thus, the challenge is how to strengthen a subset of the railway components through investment under limited budget constraint in a planning context to retain railway service after disasters.

This problem belongs to the domain of disaster management, which can be analyzed as a three-stage process: pre-disaster investment to strengthen the system (Hong et al., 2015, 2017; Ouyang and Fang, 2017; Ouyang et al., 2017;

* Corresponding author at: School of Automation, Huazhong University of Science and Technology, Wuhan, Hubei 430074, PR China.
E-mail address: liu.hong@hust.edu.cn (L. Hong).

http://dx.doi.org/10.1016/j.tre.2017.07.001
1366-5545/

Peeta et al., 2010; Wang et al., 2012, 2013), post-disaster adaptive response to minimize the system loss (Corman and D'Ariano, 2012; Corman et al., 2014; Gao et al., 2016; He and Peeta, 2014; He et al., 2015; Jespersen-Groth et al., 2009; Samà et al., 2017; Zhan et al., 2016) and post-disaster re-construction to recover the system (Yan and Shih, 2009). Pre-disaster investment in a railway system plays an essential role in system protection as it entails the need to strengthen the railway components to decrease their failure probabilities under disasters. In order to assess the effect of an investment plan, future disasters should be estimated first, and then the damage state of each affected system component under disasters is estimated respectively with the consideration of pre-disaster investment plan on weak components, the system performance after disasters can be calculated based on the post-disaster states of all components, and finally the effectiveness of an investment plan can be assessed in terms of the improvement ratio of system performance under all these disasters.

Compared to other natural disasters, such as floods and hurricanes, earthquakes are hard to predict precisely. In order to estimate the seismic effect on system components, several alternative methods have been developed, including Probabilistic Seismic Hazard Analysis (PSHA), historical earthquakes based analysis, and Monte-Carlo simulation based analysis. The PSHA provides the annual rate of exceeding some level of earthquake ground shaking at a site for a range of intensity levels, which has been widely used for almost 50 years by governments and industries (Mulargia et al., 2017). Poljanšek et al. (2012) used PSHA to estimate the post-disaster state of the components of European gas and electricity networks, and studied their seismic vulnerability from a topological point of view. The historical earthquakes based analysis can also be used to generate scenarios. Tantala et al. (2008) used three different magnitude earthquakes located at a historic epicenter, namely, the M5.2 quake in NYC in 1884, to estimate the seismic effect on the buildings in New York City Metropolitan Region. Bommer et al. (2002) modified historical earthquake catalogue to estimate the seismic loss of different type of buildings in Turkish. The Monte–Carlo simulation based analysis is commonly used to generate synthetic earthquake catalogues in the commercial sector (Crowley and Bommer, 2006). Windeler et al. (2004) used Monte–Carlo simulation method to present seismic risk for residential buildings in the western United State. Among the three methods, the PSHA is useful when analyzing the seismic risk of single facility, but it cannot reflect the correlation of ground motion intensities of different components in a network, so it is unsuitable for seismic analysis of transportation system distributed in a larger area. Inspired by Crowley and Bommer (2006), and considering the large-scale feature of the CRS, the Monte–Carlo simulation based analysis is adopted in this paper.

The post-disaster states of railway components are estimated by fragility analysis under a specific earthquake scenario, and these components include railway stations (Carpinteri et al., 2016), tunnels (Yang et al., 2013), bridges (Banerjee and Chi, 2013; Jia et al., 2013; Mackie et al., 2012; Ramanathan et al., 2015; Siqueira et al., 2014) and embankments (Li et al., 2009). Masanobu et al. (2000) examined the fragility curves of a bridge by two different approaches: the time-history analysis and the capacity spectrum method. Karim and Yamazaki (2007) developed fragility curves for isolated bridges and compared them with the ones of the non-isolated systems. Argyroudis and Pitilakis (2012) constructed the fragility curves for shallow metro tunnels in alluvial deposits. Maruyama et al. (2010) constructed the fragility curves of expressway embankments in Japan using statistical analysis. For the long railway tracks between two stations in the CRS, the ground motion intensity is varying at different sites along the track, because different sites may have different epicentral distance. To calculate the post-disaster states of the whole railway track, this paper adopts the method used for pipelines (Duenas-Osorio et al., 2007). This method divides a railway track into many small segments, the failure probability of each segment is calculated based on its fragility curve and the ground motion intensity, and the failure probability of the whole railway track is synthesized from that of all its segments. The fragility curves of railway stations and railway segments used in this paper are obtained from HAZUS (FEMA, 2004).

Based on the post-disaster states of all railway components, the system performance under disasters can be calculated. Topological metrics are used to measure railway system performance in some related works (Wang et al., 2012), such as average shortest path length (Zhou and Wu, 2010), network efficiency (Luo et al., 2014), size of the giant component (Osei-Asamoah and Lownes, 2014; Wang et al., 2013) and connectivity (Hong et al., 2017; Ouyang et al., 2015). Purely topological metrics do not consider the flow in the system, different topological metrics may obtain contradictory results when estimating the system performance (Ouyang and Fang, 2017; Zhang et al., 2015). Ouyang et al. (2014) compared the topology based model and real train flow model in railway system for the vulnerability analysis. Passenger flow can also be used to assess transportation system performance, but the related data is often hard to obtain, especially for large transportation system like the CRS. As an alternative, the affected trains is used to estimate the railway system performance in this paper.

These aforementioned studies deal with some aspects of the problem in this paper, but few of them integrate the above models for different aspects as a comprehensive framework to solve the problem. Peeta et al. (2010) proposed a stochastic program based method to make a pre-disaster investment decision for strengthening highway system under earthquake risk, but this work did not consider the earthquake scenarios and component fragilities, with the link failure probabilities given in advance. Hong et al. (2015) proposed a methodology to quantitatively assess the railway system vulnerability under floods using historical data, but they did not consider the budget constraint for pre-disaster investment. To the best of the authors' knowledge, there is little work on system level pre-disaster investment analysis for large-scale railway systems under earthquakes with the consideration of the investment budget constraint.

This paper develops a general framework for pre-disaster investment problem of railway systems under earthquakes and applies the framework to the CRS. In the framework, the railway system is modeled as a two-layer network, which is useful to clearly estimate the damage states of railway components and assess the whole system loss by the affected train flow