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Vulnerability assessment and mitigation for the Chinese railway system under floods

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A B S T R A C T

The economy of China and the travel needs of its citizens depend significantly on the continuous and reliable services provided by its railway system. However, this system is subject to frequent natural hazards, such as floods, earthquakes, and debris flow. A mechanism to assess the railway system vulnerability under these hazards and the design of effective vulnerability mitigation strategies are essential to the reliable functioning of the railway system. This article proposes a comprehensive methodology to quantitatively assess the railway system vulnerability under floods using historical data and GIS technology. The proposed methodology includes a network representation of the railway system, the generation of flood event scenarios, a method to estimate railway link vulnerability, and a quantitative vulnerability value computation approach. The railway system vulnerability is evaluated in terms of its service disruption related to the number of interrupted trains and the durations of interruption. A maintenance strategy to mitigate vulnerability is proposed that simultaneously considers link vulnerability and number of trains using it. Numerical experiments show that the flood-induced vulnerability of the proposed representation of the Chinese railway system reaches its maximum monthly value in July, and the proposed vulnerability mitigation strategy is more effective compared to other strategies.

1. Introduction

Railway systems have played a key role in the economic and social development in many countries since the nineteenth century. In 2012, about 1.89 billion passengers and 3.89 billion metric tons of cargo were transported by the Chinese railway system (CRS) [1]. Here, CRS includes both the regular and high-speed railway networks, whose links typically run in parallel. Disruptions in a railway system can have severe consequences, such as direct damage and indirect loss [2]. Floods represent one of the most important natural hazards, and cause at least one-third of the total losses due to all natural hazards in the world [3]. China is a country prone to flood hazards. Two-thirds of the Chinese land area faces the threat of floods, which can disrupt the CRS and lead to enormous economic losses. From 2000 to 2010, the average spending on flood-related maintenance in the CRS was about $15 million per year, and the indirect loss caused by railway disruption was about $37.5 million per year [1]. Hence, an assessment of the vulnerability of the CRS under floods and the design of effective vulnerability mitigation strategies are critical for the reliable functioning of the CRS and the protection of its infrastructure.

Studies from different domains define system vulnerability differently [4–8]. As a synthesis of the available literature, this article considers that the vulnerability is associated with a disruptive event and quantified by the performance drop of the system under the event. For the vulnerability analysis of infrastructure systems, many approaches exist in the literature to address this issue [9], such as agent based approaches [10–15], system dynamics based approaches [16–20], network based approaches [21–25], and others. The agent based approaches use agents to represent components in an infrastructure (such as electric transformers or generators) or important players (such as government or weather) related to system operation. A set of rules is used in agent-based approaches to describe agents' behaviors and their interactions with the environment and capture system performance response under disruptive events. Discrete-event simulations are used in agent based approaches to provide scenario-based vulnerability analysis and the effectiveness

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assessment of different vulnerability mitigation strategies. The system dynamics approaches use feedback loops, stocks, and flows to model the dynamic and evolutionary behavior of infrastructure systems under disruptive scenarios to analyze the effects of policy and technique factors on system evolution in the long term and provide investment recommendations to mitigate vulnerability. The network based approaches model each involved system as a network, which enables capturing the topological features of infrastructure systems and flow characteristics, identifying the critical system components, and providing suggestions on mitigation strategies at detailed topological levels. As the Chinese railway system is distributed over a large-scale area and the flood hazards are affected by the geographical location, modeling the flood impact on the railway system requires describing the railway system at a topological level. Hence, this article uses a network-based approach to model flood-induced railway vulnerability.

To assess the railway system vulnerability at the topological level, some studies analyze the topological characteristics of railway systems of various countries (India [26], Spain [27] and China [28]) using complex network theory [29,30]. They describe the railway system through a graph, with nodes representing railway stations and links representing the relationships between stations. Using this method, Wang et al. [31] discuss the topological properties of the CRS using two models and illustrate that the CRS exhibits properties such as hierarchical structure and small-world behavior. Derrible and Kennedy [32] analyze the complexity and robustness of 33 metro systems in the world based on network science methodologies, and conclude that robustness is related to the number of cycles in the network. They also provide recommendations to increase the system robustness at a macro level. Zhang et al. [33,34] discuss the vulnerability of the China high speed railway network and the Shanghai subway network. They use transport topological efficiency loss and connectivity to describe the vulnerability of a railway network under random and intentional attacks. These studies are usually aimed at random failures or intentional attacks, but there exists another type of disruptive events, called natural hazards, which disrupt the railway system in different ways. These hazards can attack several infrastructure components simultaneously, and each component may have specific failure probabilities corresponding to the type of natural hazard. Chang and Nojima [35] introduce a method to analyze the post-disaster performance of the railway system under earthquake scenarios, which is evaluated in terms of the total length of functional railway line and the total distance-based accessibility. Moran et al. [36] describe a documentation procedure to characterize the structural damage of railway infrastructure components and associated operational effects under the impact of floods.

While there is little work on system level vulnerability analysis of railway networks under natural hazards, there exist many network-based system-level vulnerability studies on other types of transportation and infrastructure systems under natural hazards. Nagurney et al. [37] propose environmental link importance indicators to describe the environmental impacts of the degradation in road network link capacities. Peeta et al. [38] assess the vulnerability of highway networks subject to random failures under earthquake, and propose a method to make pre-disaster investment decisions for strengthening the highway network. Jenelius and Mattson [39] present a method to analyze the vulnerability of road networks under area-covering disruptions. In it, the road network is covered using a grid of uniformly shaped and sized cells, where each cell represents the spatial extent of a disrupting event. Sohn [40] uses an accessibility perspective to study the vulnerability of a highway network under flood damage by evaluating the significance of its links. More comprehensive vulnerability studies of various infrastructure systems under natural hazards include the seismic vulnerability analysis of power grid and water pipeline system in Shelby County, TN, USA [41–45], European gas and electricity systems [46], the hurricane vulnerability analysis of power grid and gas system in Harris County, TX, USA [47–50], and the lightning vulnerability of the IEEE 118 power grid [51].

The aforementioned vulnerability studies are aimed at different systems and different types of hazards, but illustrate a common modeling framework. This framework includes the following steps: (1) modeling the hazards of concern to generate a hazard scenario; (2) estimating component failure probabilities under the hazard scenario; (3) comparing each component failure probability with a uniformly distributed random number to produce a damage event which describes the damage state of each component; and (4) modeling and analyzing system performance response under the initial component damage or the specific event, and computing the system performance drop under the event, which is labeled the vulnerability under the event. The procedure is repeated under different events generated using the random number, and the average computed vulnerability value across the events is regarded as the vulnerability under that specific hazard. This article applies this framework to propose an approach to quantitatively assess the vulnerability of a railway system under flood hazards by using historical flood data and geographic information systems (GIS) technology. This method consists of four parts that are illustrated using the CRS: (i) a network representation of the CRS is provided and some of its topological properties are discussed, (ii) flood event scenarios are generated through Monte Carlo simulation using historical flood event data for the past 30 years in China, (iii) the railway link vulnerabilities are estimated based on flood-induced railway disruption event data for the past 30 years, and (iv) the concept of railway service disruption is introduced and used to quantify the railway system vulnerability.

Also, note that for the railway vulnerability quantification, in the literature, many studies use purely railway topological models and metrics, but recent studies show flow is a key factor influencing system vulnerability [52]. Ouyang et al. [53] compare two complex network based models, including a purely topological model which does not consider train flow and a shortest path model which considers train flow running along the shortest paths, with a real train flow model. Results in [53] show that the complex network based models can approximate the real flow model well to produce railway vulnerability under single component failures, but not well under multiple component failures. Natural hazards, such as floods and earthquakes, almost always affect large areas and many components of the system simultaneously. Hence, this article uses a real train flow model to assess the flood-induced railway vulnerability.

The remainder of the article is organized as follows. Section 2 introduces the vulnerability assessment methodology for railway systems under floods, including a network representation of the railway system, the generation of flood event scenarios, a method to estimate railway link vulnerability, and a quantitative system-level vulnerability value computation approach. Section 3 applies the proposed methodology to analyze the vulnerability of the CRS. It also proposes a maintenance strategy for the CRS vulnerability mitigation. Numerical examples are discussed to compare the effectiveness of various vulnerability mitigation strategies with the proposed one. Section 4 provides some concluding comments and potential directions for future research.

2. Vulnerability assessment of a railway system under floods

According to the literature review introduced in Section 1, the proposed approach includes a network representation of the railway system, the generation of flood event scenarios, a method to estimate railway link vulnerability, and a quantitative system-level vulnerability value computation model.