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Susceptibility of existing and planned Chinese railway system subjected to rainfall-induced multi-hazards

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ABSTRACT

Rainfall-induced flooding, landslides, and debris flows have been the main natural hazards that impact on the safety and operation of the Chinese railway system. With the rapid increase of railway length and passengers over the past 20 years, a better understanding of susceptibility of railway infrastructures to rainfall-induced hazards is urgently needed, in particular because extreme precipitation has increased in many parts of China. This paper provides a quantitative approach for susceptibility assessment of transportation system subjected to natural hazards at a relatively large scale. The susceptibility of both existing and planned Chinese railway system subjected to rainfall-induced multi-hazards is quantitatively analyzed using a machine learning method (Random Forest) and historical disaster events triggered between 1980 and 1998. The main environmental and climatic factors that influence the safety of the railway system are identified and ranked. Susceptibility maps illustrate the hotspot zones of both existing and planned railways in China that need significant attention and preventative action to reduce potential losses and disruption of operation.

1. Introduction

With the rapid increase of railway infrastructure construction over the past 20 years, the length of railway tracks in China reached 112,000 km by the end of 2014, across diverse geomorphic and climatic regions. Meteorological hazards, such as strong winds, extreme rainfall, and blizzards, pose a significant risk to the operation and safety of trains. Among these, rainfall-induced floods, landslides, and debris flows have been the main natural hazards that impact the railway system, and have caused severe infrastructural damage and indirect economic loss. An annual average of over 100 disruptions of train operation due to flooding were reported between 1972 and 1992 (Ma and Zhang, 1992). Furthermore, annually an average of over five fatal accidents were caused by rainfall-induced hazards (Ma and Zhang, 1992). In the context of global climate change, there is an increasing trend of extreme weather and climate events (IPCC, 2012), which causes specific long-term threat in the transport sector (Mattsson and Jenelius, 2015). As noted by the 'Sendai framework for disaster risk reduction 2015-2030', promoting the resilience of new and existing critical infrastructures to ensure that they remain safe, effective, and operational during and after disasters is one of seven global targets over the next decade. There is therefore an urgent need to investigate the spatial and temporal patterns of the railway rainfall-induced disasters and railway infrastructure susceptibility on a large scale, to enable railway infrastructural planners and managers to decide

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on effective interventions, investment, and emergency planning to maintain robust railway infrastructure systems across the country.

Heavy rainfall can cause direct damage to railway embankments by increasing pore pressures that lead to a reduction in the shear strength of the soil and consequently result in progressive failure of slopes. Flood disaster of railway lines indicates that the tracks are inundated by water flow and may cause, for example, the washing away of ballast, slope failures, sediment, and breaches of embankment. Landslides of the slope (i.e., fall of soils, rocks and earth) and debris flow in gullies (i.e., moving mass of mud, sand, soil, rock, water and air that travels down a slope) can affect railway lines by destroying and obscuring railway segments. Therefore, when we assess the risk of railway lines subject to rainfall-induced hazards, various factors, including meteorological, geographical, geological, and hydrological characteristics, should be taken into account.

A variety of deterministic methods, from analytical to numerical models, have been used to analyze the susceptibility of infrastructures subject to rainfall-induced hazards. Deterministic methods require knowledge of the physical processes of the phenomenon and depend on engineering or theoretical principles. For example, the numerical analysis of slope failure is typically based on slope stability analysis using the strength reduction technique or limit equilibrium method to determine the critical slip surface and safety factor, as well as to investigate the triggering mechanisms and contributing factors (Chandrasekaran et al., 2013; Ali et al., 2014; Raj and Sengupta, 2014; Xu and Zhang, 2010; Casagli et al., 2006). These analyses, however, require sufficient information about the local geology, weather, hydrology, soil constitutive and engineering properties for a physical model of a specific site. This often involves site investigations and laboratory tests to provide basic data required for the analysis. Meanwhile, the results are often sensitive to the selected models and the variation of input parameters. Compared with slope failure analysis, the simulation of the debris flow process is more challenging. Debris flows are gravitational mass movements of rock incorporated in a fluid matrix of fine sediments suspended in water (Takahashi, 1981). The complex dynamic mechanism of the debris flow and the interaction between the environment and flow materials leads to spatial and temporal variations that make it relatively difficult to simulate. Existing numerical methods for simulating the dynamical debris flow process are based on many assumptions and simplifications (Han et al., 2015; D'Aniello et al., 2014; Rosatti and Begnudelli, 2013). Nevertheless, these methods provide insights into the physical process of hazards and ways to examine the safety of specific sites.

When susceptibility assessment of the transportation system at regional or national scale is required, analytical or numerical methods are inapplicable because detailed characterization data and high computational capacity may not be available. Forzieri et al. (2018) pointed out that quantifying the effects of climate hazards on infrastructures in a large scale is a complex task because of incomplete scientific methodologies and limited understanding of vulnerabilities of infrastructures. In literatures, the susceptibility of infrastructures to climate related hazards are primarily presented in qualitative and descriptive terms when it comes to large scale (Michaelides et al., 2014; Wu et al., 2013; Tao et al., 2017; Forzieri et al., 2018). Some researchers tried to quantitatively assess the susceptibility of infrastructures to climate-related hazards. Misnevs et al. (2015) performed meteorological risk assessment of Latvian railway. The level of hazard vulnerability is calculated by multiplying hazard criticality and vulnerability. For example, the hazard criticality of rainfall amount less than 100 mm during the period from 12 to 48 h is defined as 40%, while the failure probability of embankment with contaminated pipe culverts is defined as 60%, thus resulting a hazard vulnerability risk level of 0.24. However, both the hazard criticality and failure probability of infrastructure are determined based on experience or expert survey, which makes the result less objective. Muriel-Villegas et al. (2016) investigated the transportation networks subject to natural hazards, the road link weakness is defined as the number of failures per day based on the historical dataset of road closure, while lacks a deep insight from historical data.

In this study, we seek to address this gap by providing an approach that can learn from historical hazard data, reveal relationships of environmental features and hazard occurrence, and use this relationship to make susceptibility assessment of infrastructures in a large scale. Machine learning methods (Al-Jarrah et al., 2015; Ayalew and Yamagishi, 2005; Xu et al., 2013), by learning from historical data to recognize complex patterns and build a model that can make predictions, offer a new approach for mapping the susceptibility of infrastructures over large regions. Machine learning method has the following advantages: (1) It is a powerful data-driven and self-adaptive computational tool that can capture nonlinear relationship and complex underlying characteristics; (2) There is no necessity to mathematically describing or make assumptions for the underlying physical processes; (3) It can work with different types of variables and can handle data from various scales; (4) It can give a high degree prediction accuracy. Random Forest (RF) algorithm, introduced by Breiman (2001), is one of the most popular and most powerful machine learning algorithms, especially when working with multi-variable and non-linear patterns. In recent years, researchers in different fields have begun to use RF algorithm for classification, influential factors ranking, and model cross comparison (Diaz-Uriarte and De Andrés, 2006; Catani et al., 2013; Rodrigues and Riva, 2014). The RF method shows better performance compared with traditional regression methods (Miao and Wang, 2015; Rodrigues and Riva, 2014), and its results are better interpreted compared with other machine learning approaches, such as Artificial Neural Network (Prasad et al. 2006). In this study, we analyze the susceptibility of the Chinese railway system subjected to rainfall-induced multi-hazards using documented rainfall-induced disaster events and RF algorithm. We believe that the proposed approach adds values in the following ways:

(1) We combine machine learning method and historical hazard data for quantitatively assessing susceptibility of transportation infrastructure to rainfall-induced hazards. Different from existing approaches, this method reveals underlying relationships between specific environmental features and the occurrence of hazards by learning from historical data, and this relationship can be further used to assess the failure susceptibility of infrastructure.
(2) This is the first time that a quantitative hazard susceptibility analysis of Chinese railway infrastructure is performed, which not only benefits and facilitates further risk analysis and disaster management of Chinese railway, but also offers insights into the meteorological hazards impact on railway infrastructure, raise awareness, and foster better adaption strategies worldwide.