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Optimal Critical Infrastructure Retrofitting Model for Evacuation Planning

Yuval Hadas [a], Riccardo Rossi [b,*], Massimiliano Gastaldi [b], Carlo Pellegrino [b], Mariano Angelo Zanini [b], Claudio Modena [b]

[a]*Bar-Illan University, Department of Management, Max ve-Anna Webb street, Ramat Gan 5290002, Israel*
[b]*University of Padova, Department of Civil, Environmental and Architectural Engineering, Via Marzolo 9, Padova 35131, Italy*

Abstract

In emergency situations, it is necessary to safely evacuate the population in order to save lives. The road network infrastructure is vulnerable for extreme events, and as a result its ability to supply the required capacity can be seriously hampered. Hence, it is crucial to identify those critical segments which prohibit safe evacuation, and find an optimal retrofit scheme at the network level in order to minimize evacuation time. This work introduces an emergency evacuation model that considers infrastructures vulnerability, event location and magnitude, road network, transportation demand and evacuation areas in order to identify the critical infrastructures and recommend budget allocation for increasing network capacity for minimizing evacuation time, given budget alternatives. The infrastructures' analysis was based on the knowledge about mechanics characteristics of a set of bridges, and about a set of possible seismic scenarios related to the area of interest. By using fragility curves of bridges, the damage state of them has been assessed. By making a series of hypotheses on how a bridge damage state can influence links' functionality, reduced capacity was assigned to the road network. The result is the estimation of the retrofit cost needed for a specific seismic scenario, considering the most effective retrofit intervention type, previously identified for each bridge. The infrastructures' analysis results were used by the evacuation model for optimal budget allocation of retrofits strategies in order to attain a desired evacuation time frame. The procedure has been applied to an urban network in north Italy.

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Keywords: Evacuation; Emergency; Network rehabilitation; Earthquake; Road network capacity; Bridges; Accessibility

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1. Introduction

In emergency situations it is necessary to safely evacuate the population, if such an action will save lives. The road network infrastructure is vulnerable for extreme events, and as a result its ability to supply the required capacity, when

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needed most, can be seriously hampered. Hence, it is crucial to identify those critical segments which prohibit safe evacuation, and find an optimal retrofit scheme at the network level in order to minimize evacuation time. The main aim of this work is to develop an emergency evacuation model that considers infrastructures vulnerability (in particular bridges), event location and magnitude, road network, transportation demand and evacuation areas in order to identify the critical infrastructures and recommend budget allocation for increasing network capacity for minimizing evacuation time, given budget alternatives. Evacuation analysis requires a multidisciplinary approach integrating transportation, structural engineering, operations research, and social sciences. We focus our work in particular in the field of seismic vulnerability assessment of network elements like bridges, considered to be the most vulnerable elements in transportation networks (Nicholson & Du 1997; Franchin, Lupoi, et al. 2006; Franchin, Pinto, et al. 2006), and the field of network design. The paper is organized as follows: 1) an overview of the theoretical background required for this type of analyses is described, 2) a description of the integrated procedure with some details about its components is provided, 3) a case study, and 4) Concluding remarks and future research directions.

2. Theoretical background

This section summarizes the main concepts related to the structural and transportation key issues used in this work: in particular, r the first part introduces some concepts on seismic vulnerability assessment of infrastructures whereas the second describes the main existing literature issues concerning evacuation optimization models and approaches.

2.1. Seismic vulnerability assessment

The efficiency and reliability of a transportation system have a significant influence on the economy of a territory; indeed, the system must be able to guarantee accessibility and allow the safe and smooth 'movement' of people and goods. With reference to emergency situations, the first requirement is to investigate the effects on infrastructures by extraordinary events (specifically, earthquakes), and to identify the connections between these physical and mechanical impacts and the functional characteristics both of single components and of the road network as a whole. It is important that the transportation system remain operative or that its function be repaired or restored as soon as possible (Nicholson & Du 1997; Franchin, Lupoi, et al. 2006). In particular, past experience has shown too often that earthquake damage to road network components (e.g., bridges, tunnels, retaining walls, etc.) can severely interrupt traffic flow, thus negatively impacting the economic activity of a region as well as on post-earthquake emergency response, evacuation and recovery activities (Franchin, Pinto, et al. 2006; Lupoi & Franchin 2006; Schotanus et al. 2004; Franchin, Lupoi, et al. 2006). Past works have focused on seismic performance assessment of individual components of the road network (Banerjee & Shinozuka 2007), and neglected to pay attention to system performance assessment and to the optimal economic allocation in the network e in order to improve/retrofit the components (Pellegrino & Modena 2010; Zanardo & Pellegrino 2004; Gastaldi et al. 2013; Carturan et al. 2013; Banerjee & Shinozuka 2007), which is crucial for fast evacuation of the population, if needed. Hence, it is required to assess the seismic vulnerability of road network elements; in this work we refer in particular to bridges. Bridges have been proven to be the most vulnerable elements in transportation networks during earthquakes (Auza et al. 2010; Banerjee & Shinozuka 2007; Pellegrino & Modena 2010; Zanardo & Pellegrino 2004), therefore their seismic vulnerability assessment is necessary for a proper planning of the emergency response and to define priority on retrofit interventions. Fragility curves allow assessing bridge seismic vulnerabilities (Carturan & Zanini 2014; Zanini & Pellegrino 2013; Lee et al. 2007; Padgett & DesRoches 2008; Moschonas & Kappos 2009; Shinozuka et al. 2003), taking into account uncertainties of the variables and using probabilistic distributions to describe the properties of the materials composing the structure. These curves can be developed empirically as well as analytically. Empirical curves are usually developed based on the damage reports from past earthquakes. Whereas actual bridge damage and ground motion data are not available, analytical curves can be derived to assess the performance of bridges (Nielson & DesRoches 2007). As described in Risk-UE 2004 (Mouroux & Brun 2006) reports, empirical fragility curves are usually based on bridge damage data from past earthquakes; analytical fragility curves are instead developed through seismic analysis of the structure.