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Simple method for real-time seismic damage assessment of bridges

I. Anastasopoulos [a,*], P.Ch. Anastasopoulos [b], A. Agalianos [a], L. Sakellariadis [a]

[a] University of Dundee, UK; formerly National Technical University of Athens, Greece
[b] Dept. of Civil, Structural and Environmental Engineering, University at Buffalo, The State University of New York; Institute for Sustainable Transportation and Logistics; and Engineering Statistics and Econometrics Application Research Laboratory, USA

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ABSTRACT

Seismic damage of bridges may pose a severe threat to motorway users, and preventive closure until post-seismic inspection may be viewed as the only safe option. However, such a measure may incur pronounced losses by obstructing transportation of rescue teams. On the other hand, allowing traffic on earthquake-damaged bridges is a difficult decision with potentially dire consequences. Hence, the main dilemma for the motorway administrator is whether to interrupt the operation of the network, calling for timely development and implementation of a RApid REsponse (RARE) system. The development of such a RARE system requires an effective means to estimate the seismic damage of motorway structures in real time. This paper contributes towards such a direction by introducing a simple method for real time seismic damage assessment of motorway bridges. The proposed method requires nonlinear dynamic time history analyses using multiple seismic records as seismic excitation. Based on the results of the analyses, statistical models are estimated, and nonlinear regression equations are developed to express seismic damage as a function of statistically significant intensity measures (IMs). Such equations are easily programmable and can be employed for real-time damage assessment, as part of an online expert system. In the event of an earthquake, the nearest seismic motion(s), recorded by an online accelerograph network, will be used in real time to estimate the damage state of motorway structures, employing the developed equations. The efficiency of the proposed method is demonstrated using a single bridge pier as an illustrative example. Based on finite element (FE) analysis results, three nonlinear regression models are estimated correlating three damage indices (DIs) with statistically significantly IMs.

1. Introduction

Under normal conditions, the safety of motorway users is mainly related to the quality of the road network (road geometry, traffic characteristics, pavement condition) and the behavior of drivers [4–6,8,38,44,48]. In the event of a strong earthquake, the safety of motorway users is directly related to the seismic performance of motorway infrastructure. Structural damage, such as the bridge collapses of Fig. 1a and b during the devastating 1994 Northridge [12,26] and 1995 Kobe earthquakes [27,30], may pose a severe threat to the users of the transportation network as dramatically illustrated in Fig. 1c. In this particular case, a bus traveling on Hanshin Expressway No. 3 during the Kobe earthquake marginally stopped in front of a collapsed bridge span. The consequences of a 14 m free-fall would have been detrimental to the bus and, most importantly, to its passengers.

Even if a motorway bridge is still standing after the main shock, it may be severely damaged and therefore prone to collapse when subjected to aftershocks [23]. Preventive closure of the motorway until post-seismic inspection may seem as the safest option. However, such closure will unavoidably lead to serviceability deterioration (Fig. 1d), and may also incur pronounced losses by obstructing transportation of critical groups, such as rescue teams. In addition, such an action would prevent the use of the motorway as an evacuation path. On the other hand, allowing traffic on earthquake-damaged bridges is a difficult decision with potentially dire consequences. Maintaining the network in operation without inspection may jeopardize the safety of users and rescue teams, since some structures may already be at a critical state. Hence, the main dilemma for the motorway administrator will be whether to interrupt the operation of the network.

But even if structural damage is not substantial, the lack of coordinated action on behalf of the motorway administrator may increase the feeling of insecurity and resentment to the motorway users. This can in turn increase the generalized sense of panic, and further disrupt the operation of the network, or even result in additional injuries (or even worse, fatalities). Although the direct consequences of a strong earthquake cannot be easily avoided (as they would probably require substantial expenditure for rehabilitation), the

* Corresponding author.

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Fig. 1. Structural damage of motorway bridges during: (a) the 1994 Northridge earthquake, and (b) the 1995 Kobe earthquake; (c) bus traveling on Hanshin Expressway Route No. 3 marginally stopping before a collapsed bridge span; and (d) deterioration of serviceability due to closure of road segments.

indirect consequences can be effectively mitigated through timely development and implementation of a RApid REsponse (RARE) system. The objectives of such a RARE system are (a) to ensure the safety of motorway users and minimize the levels of distress, (b) to minimize closure of the motorway, and (c) to optimize the post-seismic serviceability of the motorway.

Several emergency response systems have been developed worldwide (e.g., [21]). Such systems can be classified with respect to the scale of the reference area as global or local. Apart from major global earthquake management systems, such as the Global Disaster Alert and Coordination System (GDACS, www.gdacs.org; [17]) and WAPMERR (www.wapmerr.org), several local systems have been developed to estimate the damage and casualties in near-real time for large cities such as Tokyo, Istanbul, and Naples [20]. The majority of such systems employ recordings from strong motion networks to characterize seismic events and estimate the damage by use of known inventory of elements exposed to hazard and associated vulnerability relationships. With respect to transportation networks, there have been some attempts to apply seismic risk assessment to motorway systems such as the one in the Friuli-Venezia Giulia region of NE Italy [16].

Despite the considerable work on the subject, to the best of the authors' knowledge, there are no documented efforts to develop a RApid REsponse system for motorway networks. The development of such a RARE system requires an effective means to estimate the seismic damage of motorway components (such as bridges, tunnels, retaining walls, cut slopes, and embankments) in real time, immediately after the occurrence of a seismic event, which is the scope of the present paper. Such real time estimation of the seismic damage is of the utmost importance: (i) to rationally decide whether there is a need for emergency inspection, and (ii) to rationally allocate inspection teams, allowing for minimum disruption of traffic operations and optimization of post-seismic motorway serviceability. The paper applies an inter-disciplinary approach, combining finite element (FE) simulations with statistical modeling.

2. Overview of the RARE system

A RARE system is currently being developed as part of a European research project, using the Attiki Odos Motorway (Athens, Greece) as a case study. The detailed description of the system is not within the scope of this paper, but a brief overview is considered necessary to put the work presented herein into context. The four main steps that are required for the preparation (before the earthquake) of the RARE system are sketched in Fig. 2.

First of all (Step 1), a comprehensive GIS database of the motorway network is required, including all the necessary information to describe the motorway and its key components: geographic distribution; location of the various structures; typologies; geotechnical, tectonic and topographic conditions; and traffic capacities. Moreover, a carefully-documented database of motorway structures is essential, focusing on the most commonly observed typologies of each element at risk (bridges, cut-and-cover and bored tunnels, retaining structures, cut slopes, and embankments). If resources were unlimited, each motorway structure could be equipped with a state-of-the-art monitoring system, which could provide a direct assessment of the seismic damage.