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Seismic analysis of motorway bridges accounting for key structural components and nonlinear soil–structure interaction

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ABSTRACT

The paper introduces an efficient methodology to analyze the seismic performance of motorway bridges. Rigorous 3D models of a typical overpass bridge are developed and used to assess the efficiency of the proposed method. Fixed-base conditions are initially considered to focus on the effect of key structural components. The proposed simplified model is composed of a SDOF system of a pier with lateral and rotational springs and dashpots connected at the top, representing the deck and the abutment bearings. Its definition requires section analysis of the pier, and computation of spring and dashpot coefficients using simple formulas. It is shown that the lateral and rotational restraint provided by the deck and the abutment bearings is not at all negligible and should be taken into account. The simplified model is extended to account for nonlinear soil–structure interaction, replacing the soil–foundation system with horizontal, vertical, and rotational springs and dashpots. While the horizontal and vertical springs and dashpots are assumed elastic, the nonlinear rotational spring is defined on the basis of non-dimensional moment–rotation relations. The simplified model compares well with the full 3D model of the bridge–abutment–foundation–soil system, and is therefore considered a reasonable approximation.

1. Introduction

Motorway networks are indispensable for day-to-day life in modern societies. They are typically composed of various components, including bridges, tunnels, and embankments. Bridges are generally acknowledged to be the most vulnerable [32]. Their severe damage or collapse, such as that of the Fukae section (Fig. 1a) during the 1995 Kobe earthquake [25], may pose a severe threat to the motorists (Fig. 1b). Even if the main shock does not lead to collapse, a severely damaged bridge may be unsafe during subsequent aftershocks [16]. In such a case, emergency inspection is necessary and preventive closure of the motorway may be the only safe option. However, such an action will unavoidably lead to obstruction of rescue operations, and may inflict severe indirect losses. Hence, there is an urgent need for development and implementation of emergency response systems for motorway networks.

A variety of emergency response systems have been developed so far, including global earthquake management systems (GDACS, www.gdacs.org, [12]; WAPMERR, www.wapmerr.org; [14]), and local systems for real-time damage assessment at the city level [13]. In the case of transportation systems, there have been some first attempts (e.g., [11]), but to the best of our knowledge, there are no well documented emergency response systems for motorway networks. Such a RApid REsponse (RARE) system is currently being developed, using the Attiki Odos Motorway (Athens, Greece) as a case study. As discussed in [5], the development of such a RARE system requires: (a) a comprehensive GIS database of the motorway, including the locations and typologies of the various structures; (b) a network of accelerographs to record the seismic motions at characteristic locations along the motorway; and (c) a real-time damage assessment method.

Such a method has been outlined in [5], combining finite element (FE) simulations with advanced statistical modeling. For each bridge type, the method requires: (i) nonlinear dynamic time history analyses with an adequately large number of seismic excitations; (ii) development of a dataset of the seismic damage, expressed by appropriate damage indices (DIs) as a function of the seismic excitation, expressed by a variety of intensity measures (IMs); and (iii) development of a nonlinear regression model, expressing the seismic damage (using one or more DIs) as a function of a number of statistically significant IMs. In contrast to previous research, which aimed at identifying efficient IMs (e.g., [23,6]), the proposed method develops nonlinear regression models, combining an optimum number of statistically significant IMs.

Previous studies have shown that a single IM is not always adequate to capture all of the characteristics of a seismic motion (e.g., [20]). In [5], this was demonstrated using an idealized

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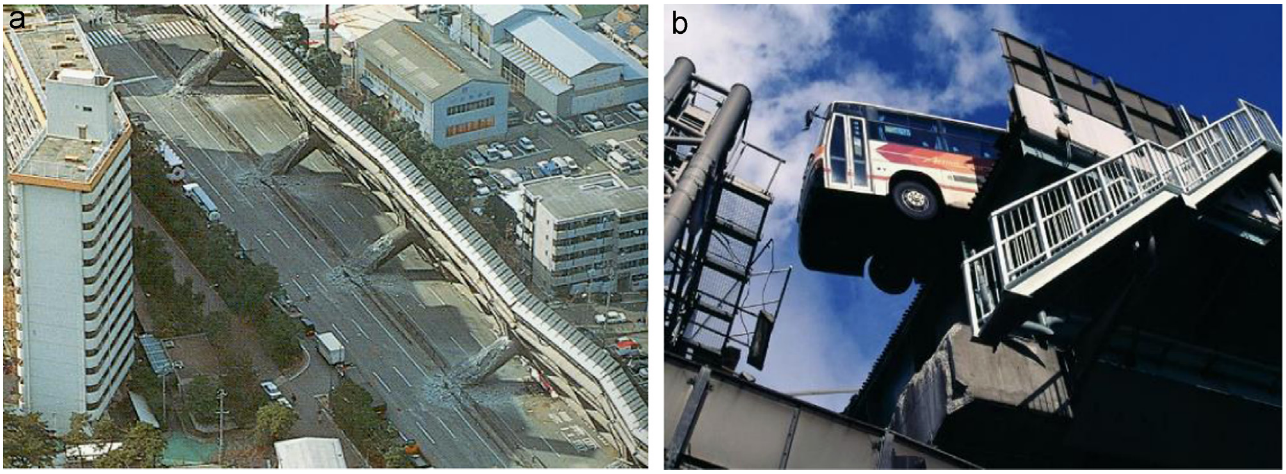

Fig. 1. Direct and indirect consequences of an earthquake: (a) collapse of the Fukae section of Hanshin Expressway Route No. 3 during the 1995 Kobe earthquake; and (b) bus stopping just before a collapsed bridge span.

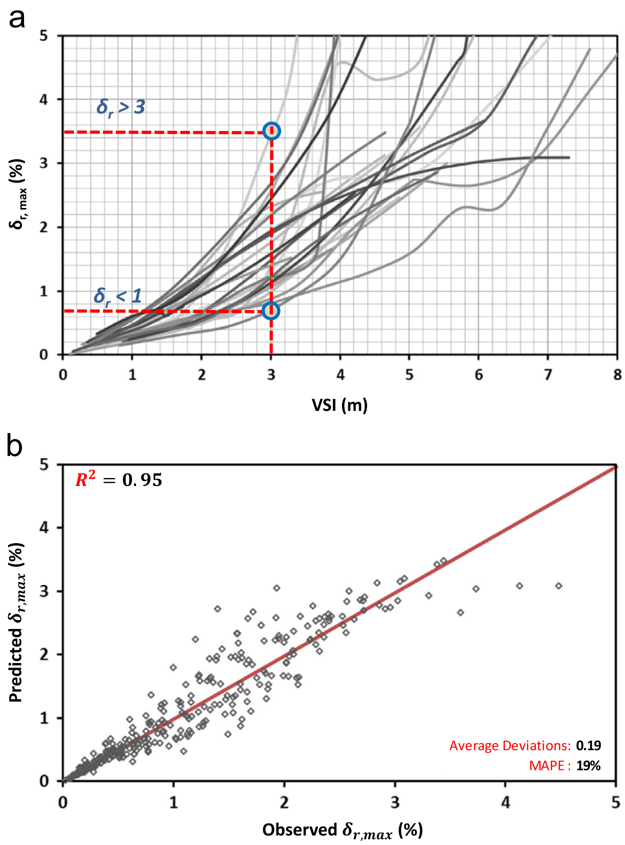

Fig. 2. Seismic performance of an idealized bridge pier [5]: (a) correlation of typical DI (maximum drift ratio $\delta_{r,max}$) with one of the best IMs (*VSI*); and (b) observed vs. predicted $\delta_{r,max}$ using then onlinear regression model equation.

(single) bridge pier as an illustrative example. One such example is shown in Fig. 2a, referring to the correlation of the maximum drift ratio $\delta_{r,max}$ (a typical DI):

$$\delta_{r,\,max} = \frac{\delta_{max}}{h} * 100\% \tag{1}$$

with one of the most efficient IMs, the Velocity Spectrum Intensity, *VSI* [34]. It is worth observing that for $VSI = 3$ m, the maximum drift ratio $\delta_{r,max}$ varies from less than 1% (minor damage) to more than 3% (severe damage or collapse).

An example of the efficiency of the nonlinear regression equations [5] is depicted in Fig. 2b, which compares the observed $\delta_{r,max}$ to the predicted value, according to the following equation:

$$\delta_{r,\mathrm{max}} = \mathrm{EXP}\left[\begin{array}{c} 0.70612 * LN(PGA) + 12.97257 * \frac{1}{PGV} - 2.50142 * \frac{1}{\sqrt{PGD}} - 3.18861 * A_{RMS}{}^2 + \\ + 1.46808 * \frac{1}{\sqrt{D_{RMS}}} - 0.18791 * \frac{1}{\sqrt{I_c}} - 11.8121 * \frac{1}{\sqrt{S_E}} + 212.77053 * \frac{1}{CAV} + \\ + 0.10551 * \sqrt{VSI} - 0.04486 * \sqrt{H_I} - 0.02203 * \frac{1}{SMA} + 3.05564 * \frac{1}{SMV} + \\ + 0.1741 * LN(T_P) - 0.28233 * \frac{1}{T_{mean}} + 0.18476 * \sqrt{D_{sig}} \end{array}\right] \tag{2}$$

where *PGA*, *PGV*, and *PGD*: peak ground acceleration, velocity, and displacement; A_{RMS} and D_{RMS}: RMS acceleration and displacement; *IC*: characteristic intensity; S_E: specific energy density; *CAV*: cumulative absolute velocity; H_I: Housner intensity; *SMA* and *SMV* sustained maximum acceleration and velocity; T_P and T_{mean}: predominant and mean period; and D_{sig}: significant duration. The efficiency of the equation is expressed additionally in terms of Adjusted R-squared (R^2), average deviation, and mean absolute percentage error (*MAPE*):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n} |PE_i| \tag{3}$$

where $PE_i = 100\% \left(Y_i - \hat{Y}_i\right) / Y_i$ is the percentage error for observation *i* of the actual damage index value *Y*, and the model-estimated damage index value $\hat{Y}_i$, for observation. From such results, it can be concluded that the nonlinear regression model equations reduce significantly the deviations between the predicted and the observed results.

Such equations are easily programmable and can be employed for real-time damage assessment. As sketched in Fig. 3, in the event of an earthquake the real-time system will record seismic accelerations at various locations along the motorway. This way, the seismic motion will be available in real time, right after the occurrence of the earthquake. For each bridge (or other kind of structure), the nearest record(s) will be used to assess the seismic damage employing the developed equations. Such knowledge of the seismic excitation is a major difference to traditional risk assessment, in which case the seismic excitation cannot possibly be predicted, and hence probabilistic approaches are much more appropriate.

Still though, developing such equations for all the bridges of a motorway requires quite substantial computational effort. For example, for the idealized bridge pier that was analyzed in [5], about 350 nonlinear dynamic time history analyses were required