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On the development of a Rapid Response System for Motorways

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ABSTRACT

In the event of a strong earthquake, severely damaged motorway infrastructure may pose a threat to motorists, and preventive closure may be considered as the safest decision. However, this may lead to indirect losses by obstructing rescue teams, and the motorway administrator will face the dilemma whether or not to interrupt network operation. This calls for timely development and implementation of a RApid REsponse (RARE) system. This paper outlines the key aspects of such a framework, introducing a simple method for real time seismic damage assessment of motorway structures. The method requires nonlinear dynamic time history analyses. Based on the results of the analyses, 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. The efficiency of the proposed method is demonstrated using a bridge as an illustrative example.

Introduction

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, may pose a severe threat to the users of the transportation network. Preventive closure of the motorway until post–seismic inspection may seem as the safest option. However, such closure will unavoidably lead to serviceability deterioration, 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.

Although the direct consequences of a strong earthquake cannot be easily avoided (as they would probably require substantial expenditure for rehabilitation), the 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 panic, (b) to minimize closure of the motorway, and

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(c) to optimize the post-seismic serviceability of the motorway.

Several emergency response systems have been developed worldwide (e.g., Erdik et al., 2011; De Groeve et al., 2006). 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 (Codermatz et al., 2003). 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 advanced econometric modelling.

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 four main steps that are required for the preparation (before the earthquake) of the RARE system are described herein.

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, traffic capacities, etc. Moreover, a carefully-documented database of motorway structures is essential, focusing on the most commonly observed typologies of each element at risk. 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. An alternative is to install a network of accelerograph stations (Step 2), which will record the seismic motions at characteristic locations along the motorway. The latter will be used as the basis to estimate the expected seismic damage employing the proposed rapid damage assessment system. The design of such an online architecture requires strategically optimized selection of station locations, calling for a trade-off between the installation cost and the quality of real-time data (i.e., the seismic records). Obviously, an adequately large number of instruments is required in order to ensure adequate geographic coverage.

Then (Step 3), for each class of structures, nonlinear dynamic time history FE analysis is performed using multiple seismic records as seismic excitation. Each record is scaled to PGA ranging from 0.1 to 1 g (or more, if necessary). The output of the numerical analysis is the damage of the structure as a function of the seismic excitation. The damage is expressed with one or more damage indices, such as the drift ratio δ_r. Finally (Step 4), for all seismic excitations the corresponding intensity measures (*IMs*) are computed, and based on the results of the FE analyses a dataset correlating one or more damage indexes with *IMs* is developed. The latter is then used to develop a multivariate econometric model, expressing the seismic damage (using one or more of the damage indexes) as a function of the most statistically significant IMs.

As schematically illustrated in Figure 1, in the event of an earthquake the real-time system will record seismic accelerations at various locations along the motorway. This way, the seismic excitation will be available in real time, right after the occurrence of the seismic event. For each structure, the nearest record(s) will be used to assess the seismic damage employing the simplified approximate method of this paper.

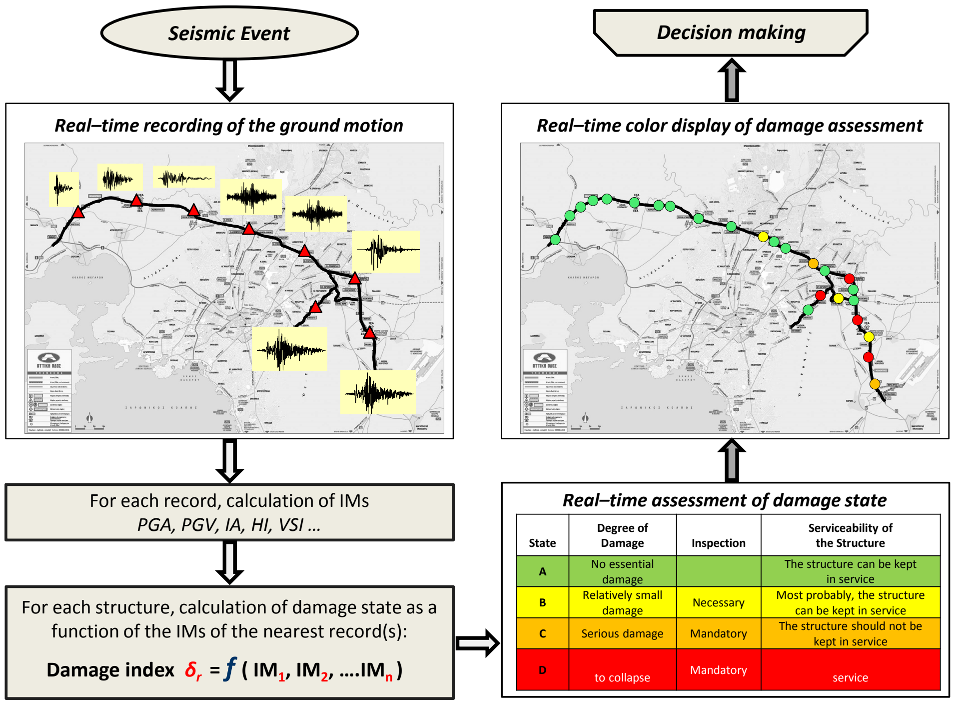

Figure 1. Schematic illustration of the application of the RARE system during a seismic event.

As discussed in more detail in the next section, the proposed method estimates the damage state (e.g., no essential damage, relatively small damage, serious damage, severe damage up to collapse) on the basis of easily programmable multivariate equations. The latter correlate the damage state with a number of statistically significant intensity measures (IMs), which are easily programmable to be computed in real time for the nearest record(s). For each structure or class of structures, the multivariate equations are estimated making use of FE simulations. Subsequently, the proposed methodology is presented using a simple bridge structure as an illustrative example.

Problem Definition and FE Modelling

In order to demonstrate the efficiency of the proposed method, a single bridge pier is used as an illustrative example (Figure 2), inspired by the Fukae bridge which collapsed during the 1995 Kobe earthquake (Anastasopoulos et al., 2010). The deck, of mass m = 1200 Mgr is supported by a RC pier of height h = 12 m and diameter d = 3 m. The pier is designed according to the Greek Seismic Code (EAK 2000) for design acceleration A = 0.24 g, considering a behavior factor q = 2. The elastic fixed-base period is T = 0.48 sec, yielding design spectral acceleration SA = 0.3 g, and design bending moment $M_D \approx 43$ MNm.

The seismic performance of the bridge is simulated employing the FE method, using the numerical code ABAQUS (2011). The nonlinear behavior of the RC pier is simulated with an appropriately calibrated kinematic hardening model with a Von Mises failure criterion and associative flow rule. Although the model is mainly intended to stimulate the inelastic behavior of metals subjected to cyclic loading, its parameters can be calibrated to match the moment–curvature (M–c) response of the RC pier (Gerolymos et al., 2005). The parameters of the model are calibrated against the results of RC section analysis using the USC_RC software (2001). The result of the calibration procedure is shown in Figure 2.

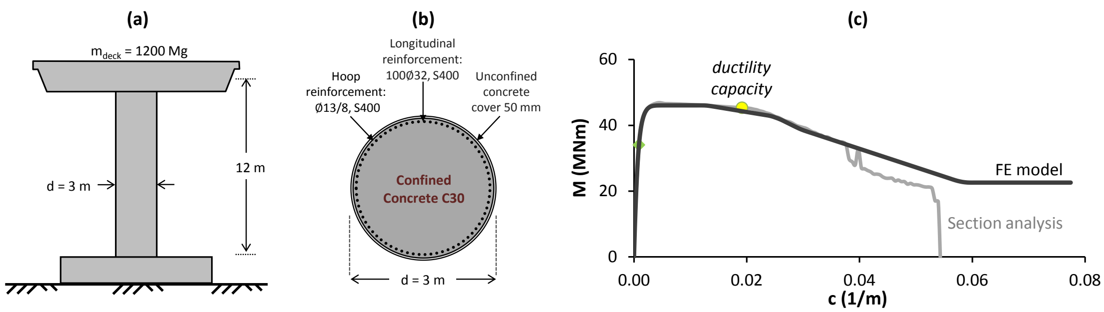

Figure 2. Bridge pier used for the analyses: (a) key characteristics; (b) pier cross-section and reinforcement details; and (c) FE model calibration against moment–curvature (*M*-*c*) response.

The bridge's seismic response is investigated through nonlinear dynamic time history analysis. To cover a wide range of strong motion characteristics, 30 real records from earthquakes of various intensities and kinematic characteristics are used as seismic excitation. Each record is scaled to PGA ranging from 0.1g to 1g, yielding a dataset of 300 seismic excitations.

Correlation of Seismic Damage with Intensity Measures

Based on the results of the FE analyses, three different damage indices (DIs) are used to express the seismic damage of the bridge pier: (a) the maximum drift ratio, $\delta_{r,max}$ (%), (b) the residual drift ratio, $\delta_{r,res}$ (%) and (c) the ratio of ductility demand over ductility capacity, μ_d/μ_c .

In order to assess the seismic damage of the pier, influential factors affecting the three DIs are identified, through estimation of three nonlinear regression models, as discussed in the next section. As explanatory parameters, the IMs that statistically significantly affect the DIs are used. In contrast to past research that has investigated the correlation between a DI and one IM at a time, the presented statistical models identify the causal relationships instead, accounting simultaneously for all possible factors that can have an effect on the expected values of the DIs.

A total of 19 popular IMs found in the literature (PGA, PGV, PGD, I_A, I_H, A_{RMS}, V_{RMS}, D_{RMS}, I_C, S_E, CAV, SMA, SMV, ASI, VSI, A_{95}, $T_{P,}$ D_{sig}, T_{mean}) as described in detail in Garini & Gazetas (2013) are selected for analysis. These are computed for all seismic excitations, yielding a dataset of the 3 DIs (FE analysis output) as a function of the 19 IMs (computed directly). It is emphasized that the same analysis can be conducted using a different, possibly more sophisticated, FE model and/or a different set of IMs.

Effectiveness of a single IM

The results of the FE simulations are aggregated and classified in a database including the 3 DIs as a function of the 19 IMs for each one of the 300 acceleration time histories (Agalianos & Sakellariadis, 2013). A typical graph that shows this correlation as obtained from the analyses is shown in Figure 3 indicatively for μ_d/μ_c with A_{RMS}. From this graph it becomes evident that a single IM is a poor index of the seismic damage of the pier, as expressed through the DIs. Observe that for A_{RMS} = 0.1 g, the μ_d/μ_c varies from less than 0.1 (minor damage) to more than 2 (collapse). The obtained results are quite similar for all possible combinations between DIs and IMs. Therefore, it can be concluded that a single IM cannot be used to predict the structural damage, even for this very simple case of a SDOF system.

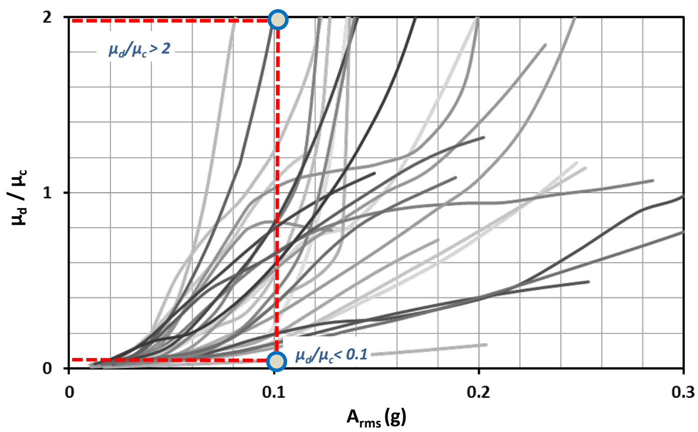

Figure 3. Correlation of μ_d/μ_c as obtained from the FE simulation with A_{rms}.

Non-Linear Regression Models of Damage Indices

As discussed above, predicting a DI using a single IM is inefficient. Even in the case that such an approach may provide reasonable results, the true unmasked effect of the IM on the DI is not captured. This omitted variables bias (Washington et al., 2011), is a serious misspecification error that occurs when omitted independent variables are correlated with an included independent variable, and leads to biased parameter estimates, and in turn to erroneous inferences and inefficient estimators. It is therefore of great importance to provide well specified models that can predict the DIs, in terms of all statistically significant IMs.

For model building, attention is given to all regression properties, such as heteroscedasticity, autocorrelation, exogeneity of the regressors, etc. (Washington et al., 2011). As the dependent variables (the DIs) can only take positive values, an exponential relationship is assumed between the dependent variables and the regressors (the IMs). Note that in any other case, negative values for the dependent variables (the DIs) could also –theoretically– be predicted, which would be invalid. Regardless, the exponential transformation further allowed us to have models with better overall statistical fit and improved forecasting accuracy as compared to the linear regression model alternatives (where the relationship between the damage indices and the intensity measures are strictly linear). To that end, nonlinear regression models are estimated for each DI, and all IMs are tested for inclusion in the model. The nonlinear regression models are of the form:

$$Y_i = EXP[\beta_0 + \beta_1 * X_{1\iota} + \varepsilon_i] \tag{1}$$

where, Y_i is the dependent variable (i.e., the damage indices) which is a function of a constant term β_0 and a constant β_1 times the value X_1 of independent variable X (i.e., the IMs) for observation i (i = 1, 2, …, n) plus a disturbance term ε.

Furthermore, all explanatory parameters included in the models are statistically significant at 0.90 level of confidence (with most of them being statistically significant at 0.99 level of confidence). Finally, the effect of an IM on the DI may not be of a linear form. Hence, several transformations (power forms, logarithmic relationships, etc.) were tested, with the ones presented below, providing the best statistical fit and forecasting accuracy potential. The resulting linear regression model equation indicatively for μ_d/μ_c is as follows:

$$\frac{\mu_d}{\mu_c} = \text{EXP}\begin{bmatrix} 3.49*\sqrt{\text{PGA}} + 7.76*\frac{1}{\text{PGV}} - 2.69*\frac{1}{\text{PGD}} - 10.19*{A_{RMS}}^2 + 1.07*\frac{1}{\sqrt{D_{RMS}}} + 2.34*\sqrt{\text{I}_c} - 30.07*\frac{1}{{S_E}^2} + \\ 7037.15*\frac{1}{\text{CAV}^2} - 38.86*\frac{1}{\sqrt{\text{VSI}}} + 78.65*\frac{1}{I_H} - 0.00024*\frac{1}{\text{SMA}^2} + 0.0001*\text{SMV}^2 - 0.88*{A_{95}}^2 - 1.52*\frac{1}{\sqrt{T_{mean}}} \end{bmatrix} \tag{2}$$

The models' overall statistical fit can be assessed through the Adjusted R-squared, as follows:

$$R^2_{adjusted} = 1 - [(n-1)/(n-p)] * \left[\left(\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2\right)/\left(\sum_{i=1}^{n}(Y_i - \bar{Y})^2\right)\right] \tag{3}$$

where Y and $\hat{Y}$ are the observed and predicted values, respectively, of the dependent variable (i.e., DI) for observation i (i = 1, 2, …, n), $\bar{Y}$ is the observed mean value of the dependent variable, and p is the number of explanatory model parameters.

Efficiency of the Nonlinear Model Equations

The efficiency of the developed nonlinear regression model equations is examined comparing the predicted structural damage of the SDOF system by using the corresponding equation to the observed one, as obtained from the numerical analysis. Figure 4 presents the observed and the predicted structural damage for μ_d/μ_c. as well as the average deviations and the mean absolute percentage error (MAPE). The latter can be estimated as follows:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}|PE_i| \tag{4}$$

where $PE_i = 100\% \left(Y_i - \widehat{Y_\iota}\right)/\, Y_i$ is the percentage error for observation i of the actual damage index value Y, and the model-estimated damage index value $\widehat{Y_\iota}$, for observation i.

The resulting MAPE values give the percentage that the predictors under- or over-estimate the observed values, on average. From these results (R^2 = 0.96, MAPE = 29%) it can be concluded that the nonlinear regression model equations for predicting structural damage reduce significantly the deviations between the predicted results and the observed ones from the numerical analysis. These deviations are considered acceptable for the purposes of a Rapid Response System.

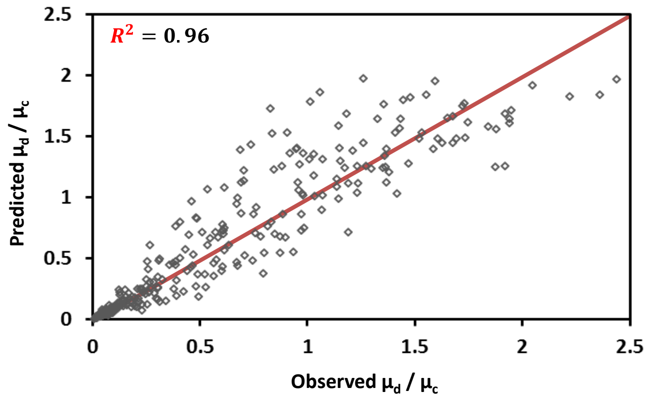

Figure 4. Observed (FE analysis) vs. predicted using the proposed nonlinear regression model equation for ductility demand over ductility capacity μ_d / μ_c.

The following step is to examine the efficiency of the developed nonlinear regression model equations on out-of-sample earthquake records. To that end, a set of 15 different historic records is used to perform a new series of nonlinear time history analyses in order to obtain the DIs and compare them to the relevant results of the equations. In Figure 5 the observed damage states with reference to Response Limit States (Priestley et al., 1996) of the numerical analysis are compared to the predicted ones using the nonlinear regression model equation for μ_d/μ_c. In general terms it is observed that the nonlinear regression model equations constitute a satisfactory way to estimate the structural damage of SDOF systems.

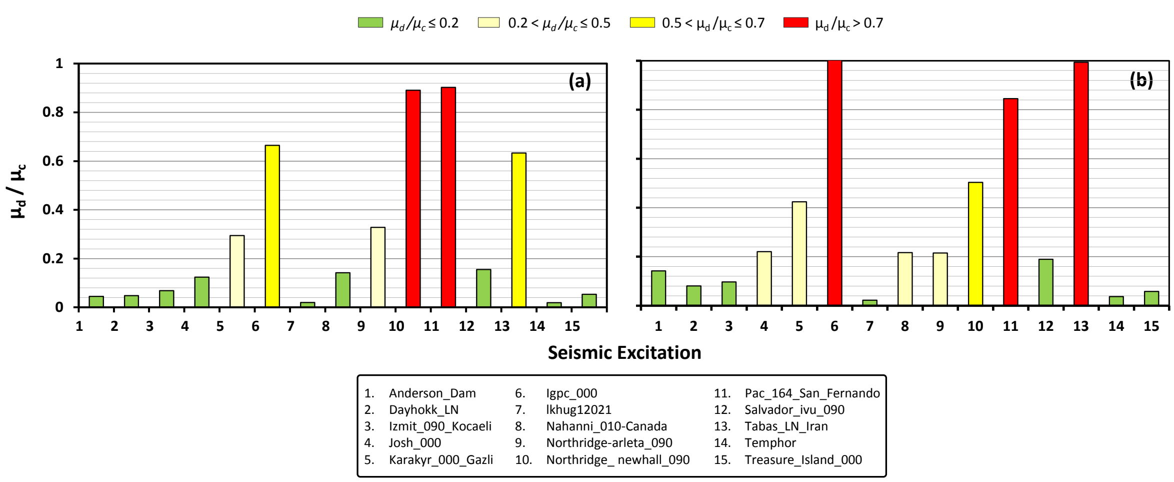

Figure 5. Comparison of (a) observed damage states based on ductility demand over ductility capacity μ_d / μ_c of the FE analysis with (b) predicted ones based on the proposed nonlinear regression model equation for 15 historic out-of-sample records, and differences between them.

Conclusions

The paper introduced a simple method to estimate the seismic damage of motorway bridges in real time, immediately after the occurrence of a seismic event. The work presented herein is part of an ongoing research effort aiming towards the development of a RApid REsponse (RARE) system for motorway networks. An inter-disciplinary approach has been applied, combining FE simulations with advanced econometric modeling. For each class of structures, the proposed method requires nonlinear dynamic time history analysis using multiple seismic records as seismic excitation. Based on the results of the FE analyses, advanced econometric modeling is applied to develop multivariate equations, expressing seismic damage, using three damage indices (DI's) as a function of statistically significant intensity measures (IMs). The multivariate 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 the motorway structures, employing the developed multivariate equations.

The efficiency of the proposed method has been demonstrated using a single bridge pier as an illustrative example. The seismic performance of the bridge pier has been simulated through nonlinear dynamic time history analysis using 30 real records, scaled to PGA ranging from 0.1 g to 1 g, and yielding a dataset of 300 seismic excitations. Based on the FE analysis results, three nonlinear regression models were estimated correlating each DI with the statistically significantly IMs. For this purpose, 19 IMs were identified. It is emphasized that the same procedure can be conducted using more sophisticated FE models or a different set of IMs. Moreover, the same procedure can be applied to other types of motorway structures.

The effectiveness of each IM to estimate the structural damage of the system was first examined, showing that multiple IMs should be considered simultaneously in order to accurately and unbiasedly forecast the structural damage the structure. The results identified a number of statistically significant IMs affecting each DI in a nonlinear fashion. The developed equations were evaluated in terms of various goodness-of-fit and forecasting accuracy measures, and with out-of-sample observations. Even though the study is exploratory in nature, the evaluation illustrates the potential that the estimated nonlinear regression model equations have in predicting damage indices, for future earthquakes, within the framework of a RARE System.

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