

## SIMPLIFIED METHOD TO ESTIMATE THE SEISMIC VULNERABILITY OF BRIDGES CONSIDERING SOIL-STRUCTURE INTERACTION

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**Abstract:** The indirect consequences of a strong seismic event in a metropolitan motorway (such as the deterioration of its serviceability) can be effectively mitigated through timely development and implementation of a rapid response system. The development of such a system requires knowledge of the seismic vulnerability of critical infrastructures, such as bridges. However, a typical motorway network is composed of a multitude of bridges, making it practically impossible to analyse each case in full detail as the amount of computational effort would be overly excessive. Hence, there is a need to develop adequately simplified but realistic models, which is the scope of the present paper. In order to develop such models, the effect of each structural component is examined, with emphasis on soil-structure interaction (SSI). For this purpose a detailed three-dimensional numerical model is developed, utilizing an overpass bridge from the Attica Motorway in Athens (Greece) as an illustrative example. The seismic performance of the bridge is studied applying 29 real seismic records of different intensities and kinematic characteristics in the transverse and the longitudinal direction. A simplified model is developed, consisting of a single pier carrying an appropriate mass, and connected with a series of springs and dashpots representing the deck and the seismic isolation system. SSI is taken into account in a similar manner, replacing the foundation and the soil with equivalent springs and dashpots.

### Introduction

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 an action 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 will be 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 bridges in real time.

Bridges tend to be most vulnerable during strong seismic shaking. This paper contributes towards such a direction by introducing a simple method to estimate the seismic vulnerability of motorway bridges. The large number and complexity of bridges encountered along motorways in operation worldwide, present a particular challenge to engineers. The development of detailed 3D models of the bridge–foundation–abutment–soil system is the most comprehensive way to simulate their seismic performance. However, in order to cover a wide range of strong motion characteristics, a large number of seismic excitations are necessary. Conducting such analysis with full 3D models of the bridge–foundation–abutment–soil system would require quite a substantial computational effort, rendering the use of simplified models a practical necessity.

To this end, a simplified method for seismic vulnerability assessment of typical motorway bridges is introduced herein using as an illustrative example a characteristic bridge of Attiki Odos, in the Athens metropolitan area.

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### Problem definition, analysis methodology

A common case of bridge (A01-TE20) encountered in the Attiki Odos Motorway is examined herein as an illustrative example. The selected bridge system is representative of about 30% of the bridges of the specific motorway, and is also considered quite common for other metropolitan motorways in the world. As shown in Figure 1, the selected system is a symmetric 3-span bridge with a continuous pre-stressed concrete box-girder deck, supported on two reinforced concrete (RC) cylindrical piers of diameter  $d = 2$  m and height  $h = 8.8$  m.

The piers are monolithically connected to the deck, which is supported by 4 elastomeric bearings at each abutment. Each bearing is  $0.3$  m x  $0.5$  m (longitudinal x transverse) in plan and has an elastomer height  $t_b = 63$  mm. The piers are founded on  $B = 8$  m square footings, while the abutments consist of retaining walls of  $9$  m height and  $1.5$  m thickness. The latter are connected to two side walls of  $0.6$  m thickness and founded on a rectangular  $7$  m x  $10.4$  m rectangular footing.

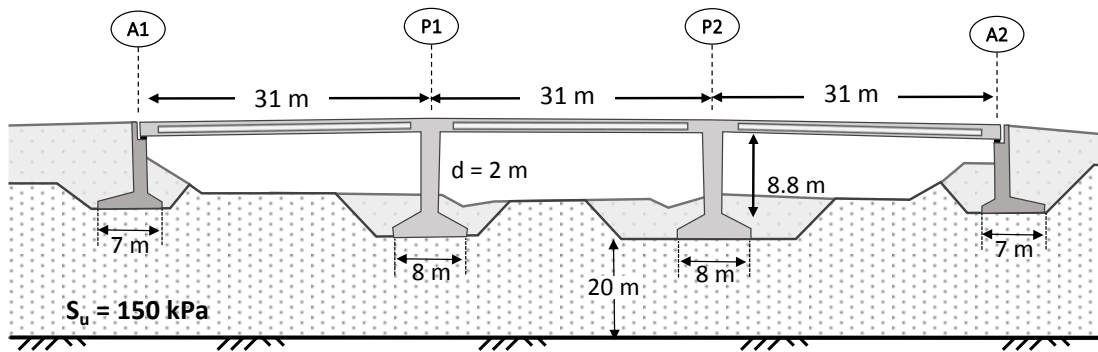


Figure 1. Key attributes of the examined A01/TE20 bridge of Attiki Odos motorway network.

The seismic performance of the bridge is analysed employing the FE method. The deck and the piers are modeled with elastic and inelastic beam elements, respectively. The reinforcement of the  $d = 2$  m RC piers has been computed according to the provisions of the Greek Code for Reinforced Concrete (ΕΚΩΣ, 2000) for columns with large ductility demands. The inelastic behavior of the piers is simulated with a nonlinear model, calibrated against the results of RC section analysis using the USC-RC software [2001]. Linear elastic springs and dashpots are used to model the compression ( $K_{c,b}$ ) and shear stiffness ( $K_{s,b}$ ) and damping ( $C_{c,b}$ ,  $C_{s,b}$ ) of the bearings.

The footings and the abutments are modelled with elastic hexahedral continuum elements, assuming the properties of RC ( $E = 30$  GPa). An idealised  $20$  m deep substratum of homogeneous stiff clay is considered, having an undrained shear strength  $S_u = 150$  kPa (Figure 2). The latter is also modeled with hexahedral continuum elements. Nonlinear soil behaviour is modelled with a kinematic hardening model, having a Von Mises failure criterion and an associated flow rule [Anastasopoulos et al., 2011].

Appropriate “free-field” boundaries are used at the lateral boundaries of the model, while dashpots are installed at the base of the model to simulate the half-space underneath the  $20$  m of the soil that is included in the 3D model. Special contact elements are introduced at the soil-footing interfaces to model possible separation (uplifting) and sliding. A friction coefficient  $\mu = 0.7$  is assumed, which is considered realistic for the soil conditions investigated herein. The same applies to the interfaces between the abutment and the embankment soil. A reinforced soil embankment is considered, which is quite common in such motorway bridges (due to space limitations). The latter is modeled in a simple manner, by “installing” appropriate kinematic constraints in the transverse direction.

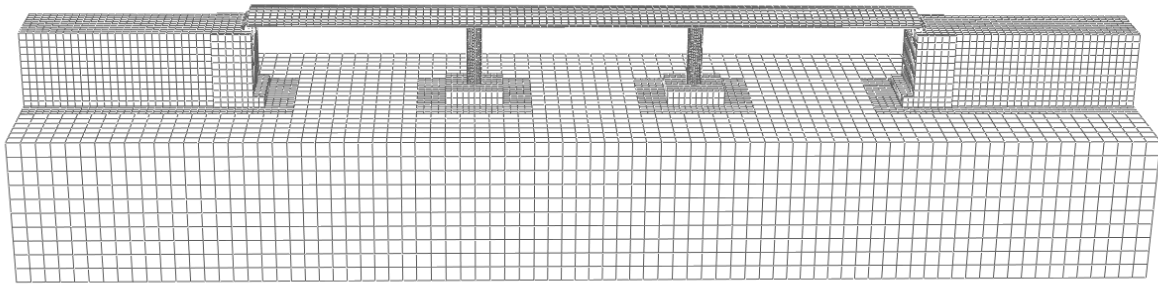


Figure 2. Detailed 3D model of the bridge, including the foundations, the abutments, and the subsoil.

### Simplified method

A simplified model is developed for the selected bridge in both directions, accounting for the main resistance mechanisms of the bridge system when subjected to dynamic loading (Figure 3). The 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.

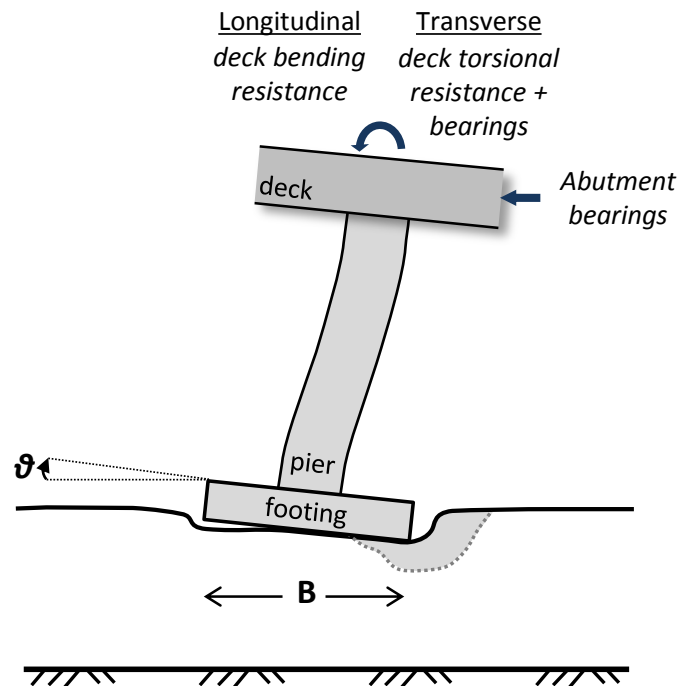


Figure 3. Main resistance mechanisms of the bridge system in both directions, when subjected to dynamic loading.

The nonlinear soil–structure interaction is also considered 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 proposed models in both directions are presented in Figure 4.

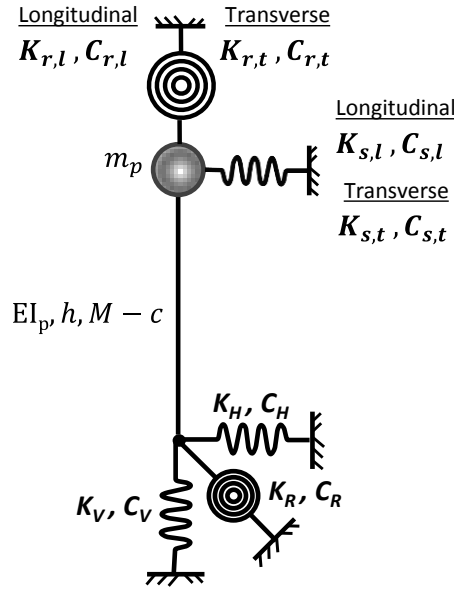


Figure 4. Proposed simplified model in both directions, accounting for the contribution of key structural components and nonlinear SSI.

The performance of the simplified models in both directions is assessed using as a benchmark the detailed 3D model of the bridge–abutment–foundation–soil system. The latter requires substantial computational effort, calling for careful selection of the seismic excitations. Hence, three characteristic records are selected: (a) Aegion, which is considered representative of moderate intensity shaking; (b) Lefkada-2003, which contains multiple strong motion cycles and can be considered representative of medium intensity shaking; and (c) the notorious Rinaldi-228 record (Northridge 1994), containing a very strong forward rupture directivity pulse, and being representative of very strong seismic shaking (Figure 5).

The seismic performance of both examined models (detailed 3D and simplified) in terms of time histories of deck drift  $\delta$  of pier P1 (left column) is shown in Figure 6, indicatively for Lefkada/2003 record. The comparison is equally successful when considering the longitudinal and transverse direction, as the time histories of  $\delta$  are practically identical. Moreover, the comparison is excellent in terms of the maximum value.

Figure 7 also shows the comparison of the simplified model to the full 3D detailed model in terms of moment–curvature response, using as seismic excitation the Lefkada/2003 record. The comparison is quite acceptable also in terms of M–c loops. The above conclusions apply also for the Aegion and Rinaldi records, covering different excitation levels. The simplified model compares well with the full 3D model in both directions of seismic loading and therefore can be considered a reasonable approximation of the seismic response of the bridge.

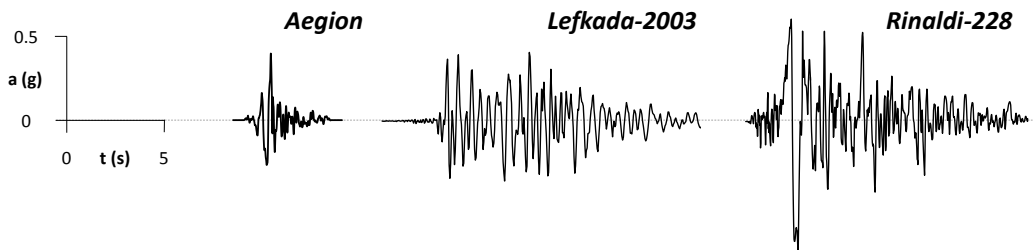


Figure 5. 3 real records used for nonlinear dynamic time history analysis.

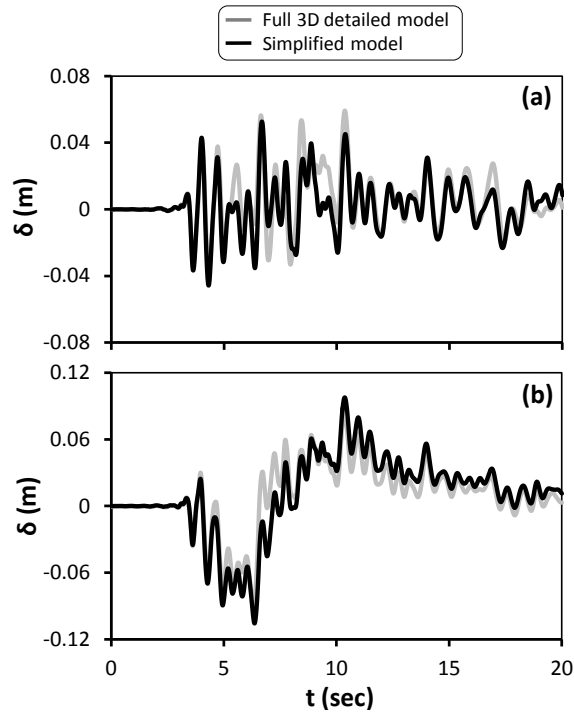


Figure 6. Comparison of the simplified model to the full 3D detailed model in terms of time histories of deck drift  $\delta$ , in (a) the transverse and (b) the longitudinal direction, using as seismic excitation the Lefkada/2003 record.

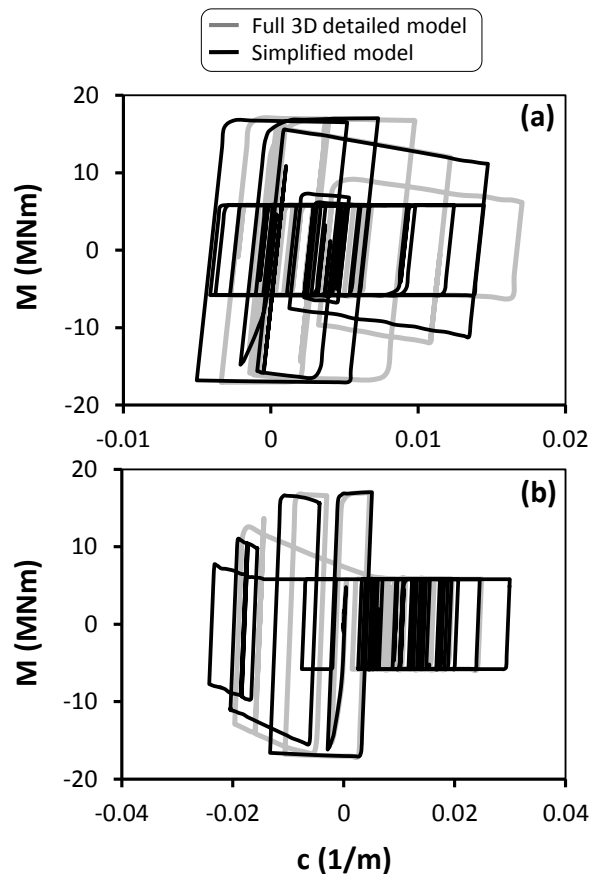


Figure 7. Comparison of the simplified model to the full 3D detailed model in terms of moment–curvature response, in (a) the transverse and (b) the longitudinal direction, using as seismic excitation the Lefkada/2003 record.

## Conclusions

Conducting dynamic analyses using detailed 3D models of bridge–abutment–foundation–soil systems requires substantial computational effort, rendering the use of simplified models indispensable. The present study introduced such a simplified method for seismic analysis of typical motorway bridges, accounting for the key structural components and the nonlinear soil–structure interaction (SSI).

For this purpose a typical overpass bridge of the Attiki Odos Motorway in Athens (Greece) is used as an illustrative example. A detailed 3D model of the bridge is developed to assess the effectiveness of the simplified method. The proposed model comprises an equivalent SDOF system of a single bridge pier, with lateral and rotational springs and dashpots connected at the top, representing the deck and the abutment bearings. The definition of the model requires cross-sectional analysis of the most vulnerable pier, and computation of spring and dashpot coefficients using simple formulas. The simplified models also account for nonlinear SSI.

Although the proposed models are based on a number of simplifying approximations, they have been found reasonably accurate, as was highlighted in the paper. Despite our focusing on a representative but specific bridge system, the results could perhaps be of more general validity.

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