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SEISMIC RESPONSE ANALYSIS OF A COUPLED VEHICLE- BRIDGE SYSTEM

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Abstract. *Traditionally, the traffic and the seismic dynamics have been considered independently when analyzing the seismic response of bridges. Given the ever increasing traffic volume though, vehicles are more likely to encounter an earthquake while crossing a bridge. Hence, there is a growing need to examine the dynamic vehicle-bridge interaction (VBI) under the simultaneous action of seismic ground motions. This study presents an original framework to analyze the seismic response of a coupled vehicle-bridge system during earthquake excitation. The examined dynamical system consists of the vehicle subsystem and the bridge subsystem. The two subsystems are coupled through the contact forces between the vehicle wheels and the bridge. The bridge subsystem is simulated with the finite element method, while the truck vehicles are modelled as rigid body assemblies. The proposed approach relies on the calculation of the coupling contact forces, and results in a system of global equations which provides the response of both the bridge and the vehicle simultaneously. A pilot application of the proposed scheme to a realistic case of (highway) bridge – (truck) vehicles interaction is presented. In this context, the study brings forward new problems encountered when analyzing the seismic response of interacting vehicle-bridge systems. Specifically, the paper underlines the need to consider different positions of the vehicle/s (on the bridge) during earthquake shaking, and highlights the importance of selecting representative parameters for the speed, the number and type of vehicles, which should reflect the site-specific traffic characteristics.*

1 INTRODUCTION

The accumulative experience of past earthquakes (e.g., the 1989 Loma Prieta, the 1994 Northridge and 1995 Kobe earthquakes) unveils the devastating consequences of vehicle accidents due to (any type of) bridge failure [1, 2]. With bridges covering a significant percentage of the existing road network, in many earthquake-prone regions, and with the ever increasing traffic volume, the possibility of vehicles encountering an earthquake while crossing a bridge is also increasing. This observation underlines the growing need to investigate the seismic response of the interacting vehicle- bridge systems instead of focusing solely on the seismic analysis and/or assessment of bridges.

However, the dynamics of traffic and earthquake shaking have been traditionally considered independently when analyzing the response of the bridge. The existing codes and guidelines worldwide [3-5] account for the traffic load solely as an additional live load on the bridge. Research on vehicle - bridge dynamic interaction has shown [6-8] that it is not realistic to treat the vehicle as additional stationary mass; the seismic response of the bridge is reduced when the dynamics of the vehicles are properly simulated and it is amplified when the vehicles are treated as additional vertical masses.

There is a vast body of research on the seismic response of bridges detached from the running vehicles [9, 10], as well as, on the dynamic vehicle bridge interaction (VBI) without considering earthquake shaking (e.g. [11] and references therein). On the other hand, a limited amount of research focuses on the simulation of the effects of earthquakes on the interacting vehicle - bridge system. More specifically, Yang and Wu [12] investigated the stability of train vehicles, stationary or moving, on bridges shaken by earthquakes, and they stressed the importance of the vertical ground motion component on the stability of the vehicle. Tanabe et al. [13-15] studied numerically the behavior of the Shinkansen trains and railway bridges during earthquakes, and verified part of their results experimentally. Matsumoto et al.[16] examined the running safety of railway vehicles on bridges subjected to earthquakes using an inhouse computer simulation software. Xia et al.[17] and Du et al. [18] concluded that the vehicle running safety during earthquakes is overestimated when not considering the seismic wave propagation effect.

Another group of studies focuses on the vehicle performance on bridges in windy environments [19-21]. Chen and Cai [22, 23] deployed a framework for the analysis of vehicle accidents on long-span bridges under strong winds. They conducted dynamic interaction analyses of the coupled vehicle-bridge-wind system to predict both the bridge and vehicle response. Zhang and Cai [24], presented an approach for fatigue reliability assessment of existing bridges also considering an interacting vehicle-bridge system. They examined the effects of the road surface condition, vehicle speed and annual traffic increase rate on the fatigue reliability index, using 3D bridge-truck interaction simulations.

The present research is motivated by the need to elucidate the VBI dynamics between vehicles and highway bridges, during seismic excitation. Recently, the authors proposed [11, 25] an analysis approach of the VBI problem for curved (or straight) bridges and different types of vehicles, without considering seismic excitations. Herein the analysis examines a realistic bridge model, and a truck vehicle model under the influence of seismic ground motion excitations. In this context, the study brings forward various new problems which arise when the traffic and seismic loading are accounted for simultaneously.

2 SEISMIC RESPONSE OF THE INTERACTING VEHICLE-BRIDGE SYSTEM: THE PROPOSED METHODOLOGY

The present paper proposes a new approach for the dynamic analysis of the vehicle-bridge interacting (VBI) systems under earthquake ground motions. The examined dynamical system consists of the vehicle subsystem and the bridge subsystem. The two subsystems are coupled through the contact forces between the vehicle wheels and the deck of the bridge. The study simulates the bridge with the finite element method and models the vehicle as a multibody assembly. The proposed approach derives from a previous work of Dimitrakopoulos and Zeng, on vehicle-bridge interaction between trains and straight, or curved in-plan, bridges [11]. The present study adjusts this approach for truck vehicles travelling along the bridge, and adds the simultaneous action of earthquakes.

The VBI problem can be divided into four parts: the simulation of (i) the bridge, (ii) the vehicle model, (iii) the interacting vehicle-bridge system and (iv) the earthquake ground motion shaking. As a first approach, the present study adopts a two-dimensional (2D) vehicle-bridge model. This simplifies the analysis procedure and makes it more economic in terms of computational cost. For brevity we keep the presentation of the VBI analysis short, as it is described in detail in [11, 25].

The finite element model of the bridge is built with the commercial software program, ANSYS [26]. The bridge is modeled with Euler-Bernoulli beam elements [27]. The stiffness matrix $\mathbf{K}^B$, the mass matrix $\mathbf{M}^B$ and the Rayleigh damping matrix $\mathbf{C}^B$ are then exported to an in-house MATLAB[28] algorithm, developed and verified, previously [11]. The equations of motion for the bridge can be written in a general form as:

$$\mathbf{M}^B(t)\ddot{\mathbf{u}}^B+\mathbf{C}^B\dot{\mathbf{u}}^B+\mathbf{K}^B\mathbf{u}^B+\mathbf{W}^B\boldsymbol{\lambda}=\mathbf{F}^B \tag{1}$$

where superscript $(\ )^B$ denotes the bridge subsystem; $\mathbf{u}^B$ is the bridge displacement vector; $\mathbf{F}^B$ is the vector of forces acting on the bridge, in this case the earthquake ground motion; $\mathbf{W}^B$ is the direction matrix of the contact forces for the bridge subsystem and $\boldsymbol{\lambda}\,\boldsymbol{\lambda}_{\mathbf{N}}$is the vector of the coupling contact forces. Since the analysis herein is 2D, three DOFs are considered per node: two displacements and one rotation with respect to the X-longitudinal and Z-vertical axis, respectively.

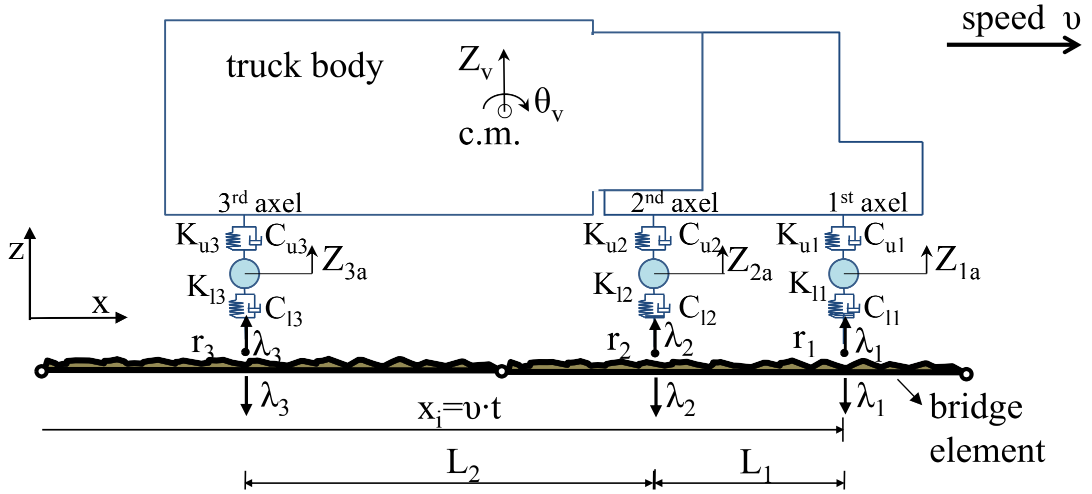

Figure 1: The adopted 3-axle 2D vehicle model.

The truck vehicles are modeled as assemblies of rigid-bodies (representing the car body and the wheel sets) connected with springs and dashpots [11, 23]. Figure 1 presents the *2D* vehicle model utilized in the present study (see for details in Section 3.2). The Newton- Euler equation of motion can describe the motion of the vehicle model in terms of generalized coordinates, as

$$\mathbf{M}^{\mathrm{V}}\ddot{\mathbf{u}}^{\mathrm{V}}+\mathbf{C}^{\mathrm{V}}\dot{\mathbf{u}}^{\mathrm{V}}+\mathbf{K}^{\mathrm{V}}\mathbf{u}^{\mathrm{V}}-\mathbf{W}^{\mathrm{V}}\boldsymbol{\lambda}=\mathbf{F}^{\mathrm{V}} \tag{2}$$

where: superscript $(\ )^{\mathrm{V}}$ denotes the vehicle subsystem; $\ddot{\mathbf{u}}^{\mathrm{V}}$ is the acceleration vector; $\mathbf{M}^{\mathrm{V}}$, $\mathbf{C}^{\mathrm{V}}$ and $\mathbf{K}^{\mathrm{V}}$ are the mass matrix, the damping matrix and the stiffness matrix of the vehicle, respectively; $\mathbf{F}^{\mathrm{V}}$ is the force vector, containing the gravity forces and the earthquake ground motion forces; and $\mathbf{W}^{\mathrm{V}}$ is the direction matrix of the contact forces.

The two sets of equations describing the motion of the bridge (Eq. 1) and the motion of the vehicle (Eq. 2) are coupled by the time-dependent contact forces $\boldsymbol{\lambda}$. Considering one single wheel at contact point j, the coupling contact force can be expressed as:

$$\lambda_{\mathrm{j}}=\mathrm{K}_{\mathrm{lj}}\left((\mathbf{W}^{\mathrm{Bj}})^{\mathrm{T}}\ \mathbf{u}^{\mathrm{B}}-\mathrm{Z}_{\mathrm{ja}}+\mathrm{r}_{\mathrm{j}}\right)+\mathrm{C}_{\mathrm{lj}}\left((\mathbf{W}^{\mathrm{Bj}})^{\mathrm{T}}\ \dot{\mathbf{u}}^{\mathrm{B}}-\dot{\mathrm{Z}}_{\mathrm{ja}}\right) \tag{3}$$

where: K_{lj} and C_{lj} are the stiffness and damping coefficients of the wheel at contact point j; r_{j} is the road roughness at that point; Z_{ja} and $\dot{\mathrm{Z}}_{\mathrm{ja}}$ are the displacement and velocity of the wheel at j, respectively (Figure 1). The superscript $(\ )^{\mathrm{T}}$ denotes the transpose of a matrix.

The final form of the equation of motion of the coupled vehicle-bridge system is:

$$\mathbf{M}\ddot{\mathbf{u}}+\mathbf{C}^{*}\dot{\mathbf{u}}+\mathbf{K}^{*}\mathbf{u}=\mathbf{F}^{*} \tag{4}$$

The global stiffness matrix $\mathbf{K}^{*}$, the global damping matrix $\mathbf{C}^{*}$ and the force vector $\mathbf{F}^{*}$ are defined as:

$$\begin{aligned}\mathbf{K}^{*}&=\mathbf{K}+\mathbf{W}\mathbf{K}_{c}\mathbf{W}^{\mathrm{T}}\\ \mathbf{C}^{*}&=\mathbf{C}+\mathbf{W}\mathbf{C}_{c}\mathbf{W}^{\mathrm{T}}\\ \mathbf{F}^{*}&=\mathbf{F}+\mathbf{W}\mathbf{K}_{c}\mathbf{r}_{c}\end{aligned} \tag{5}$$

where, $\mathbf{r}_c$ is the road roughness vector [24] which is given as an expression of irregularities of the road surface [29]; $\mathbf{K}_c$ and $\mathbf{C}_c$ are the *diagonal* matrices of the stiffness and damping of the wheels (Figure 1), given as:

$$\mathbf{K}_{c}=diag[K_{l1}\quad K_{l2}\quad K_{l3}],\ \mathbf{C}_{c}=diag[C_{l1}\quad C_{l2}\quad C_{l3}] \tag{6}$$

The global mass matrix $\mathbf{M}$ (of Eq. (4)), the global stiffness matrix $\mathbf{K}$ and the global damping matrix $\mathbf{C}$ (of Eq. (5)) are created by gathering the pertinent matrices of the two individual subsystems together as:

$$\mathbf{M}=\begin{bmatrix}\mathbf{M}^{V} & \\ & \mathbf{M}^{B}\end{bmatrix},\quad \mathbf{K}=\begin{bmatrix}\mathbf{K}^{V} & \\ & \mathbf{K}^{B}\end{bmatrix},\quad \mathbf{C}=\begin{bmatrix}\mathbf{C}^{V} & \\ & \mathbf{C}^{B}\end{bmatrix} \tag{7}$$

Accordingly, the displacement vector $\mathbf{u}$, the force vector $\mathbf{F}$ and the direction matrix $\mathbf{W}$ are:

$$\mathbf{u}=\begin{bmatrix}\mathbf{u}^{\mathrm{V}}\\ \mathbf{u}^{\mathrm{B}}\end{bmatrix},\ \mathbf{F}=\begin{bmatrix}\mathbf{F}^{\mathrm{V}}\\ \mathbf{F}^{\mathrm{B}}\end{bmatrix},\ \mathbf{W}=\begin{bmatrix}\mathbf{W}^{\mathrm{V}}\\ -\mathbf{W}^{\mathrm{B}}\end{bmatrix} \tag{8}$$

Further, this study assumes that the bridge elements and the wheels of the vehicle remain in contact without separation during the analysis.

The equations of motion of the interacting vehicle-bridge system (4) and (5) are numerically solved with MATLAB [28]

3 CASE STUDY: MODELLING, ASSUMPTIONS AND OBTAINED RESULTS

This paper presents a method for estimating the dynamic response of the interacting vehicle-bridge system under seismic excitation. The inelastic response of a bridge under strong ground motions is a topic that has been extensively covered in the literature, but it is not of interest for this study as it corresponds to strong ground motions. On the other hand, the lack of simultaneous consideration of earthquake and traffic loads is the primary motivation for the present analysis. In this study the focus is on R/C bridges that remain elastic during frequently occurring earthquakes.

3.1 Modelling of the adopted bridge

The bridge model adopted herein is based on an actual bridge configuration. The selected R/C highway bridge is a 3-span structure of 246.20m total length (Figure 2), constructed with the cantilever method. The deck consists of a 14.00m wide prestressed concrete box girder section. The spans of the deck have different lengths (63.80m+118.60m+63.80m). The height of the deck varies from 7.00m above the piers up to 3.00m at the midpoint of the middle span and to 2.50m above the abutments. The structure is supported on two single column piers (P1 and P2) of heights 36.00 m and 46.00 m. The deck is monolithically connected to the piers. Piers have a full height hollow rectangular cross section of 3.50m x 7.30m, with 0.74m wall thickness.

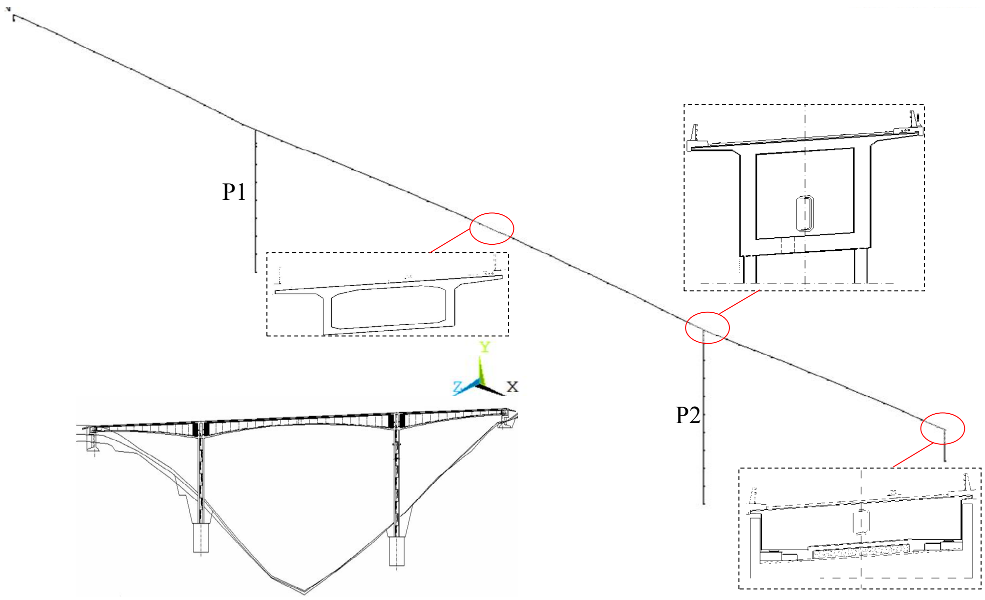

Figure 2: Layout of the bridge configuration and finite element model; inserts in Figure are the deck section (a) in the middle of each span, (b) on top of the piers and (c) on the top of the abutments.

The deck movement at the abutments is free in the longitudinal direction; in the transverse direction, the displacements are restrained by stoppers. The shear keys (Figure 2) at the specific part of the bridge, result in the restraint of the transverse displacements, as well as, the displacement along and the rotation about the vertical axis. The bridge is assumed to be founded on very stiff soil therefore the boundary condition at the base of the piers is taken as a fully fixed support. Both the deck and the piers are designed to remain into the elastic range during the earthquake excitations.

3.2 Modeling the vehicle

The vehicle model should be representative of the actual traffic load anticipated. In order to define a representative vehicle type and its distribution, the traffic flow information is required. Under real-life conditions, multiple types of vehicles with different distribution patterns may occupy different lanes at the same time randomly. It is still technically difficult to conduct a coupled analysis using all possible vehicles together, based on simulated real traffic flow through current computer techniques. The common practice in analyzing the interaction between vehicles and bridges is to use only one type of vehicle alone or a series of identical vehicles in one line [22, 23, 30]. Therefore, in the present study, it is assumed that vehicles have the same truck geometry, number of axles, axle spacing and gross vehicle weight. The differentiation of the vehicle characteristics and their impacts on the bridge response are not investigated herein. In addition, the traffic loading is based on the assumption that the traffic flow is free-flowing and that traffic is only in a single lane of the bridge.

Parameter	*Description*	Value
Mass	Truck body	30.000 kg
	First axle suspension	490 kg
	Second axle suspension	808 kg
	Third axle suspension	653 kg
Spring stiffness	Upper, 1st axle (K_{u1})	242.604 N/m
	Lower, 1st axle (K_{l1})	875.082 N/m
	Upper, 2nd axle (K_{u2})	1903.172 N/m
	Lower, 2nd axle (K_{l2})	3503.307 N/m
	Upper, 3rd axle (K_{u3})	1969.034 N/m
	Lower, 3rd axle (K_{l3})	3507.429 N/m
Damping coefficient	Upper, 1st axle (C_{u1})	2.190 N.s/m
	Lower, 1st axle (C_{l1})	2.000 N.s/m
	Upper, 2nd axle (C_{u2})	7.882 N.s/m
	Lower, 2nd axle (C_{l2})	2.000 N.s/m
	Upper, 3rd axle (C_{u3})	7.182 N.s/m
	Lower, 3rd axle (C_{l3})	2.000 N.s/m
Length	L_1	2.90 m
	L_2	5.00 m
Total length of the truck	L	13.40 m

Table1: Parameters of the vehicle model (see Figure 1) [24].

The simulated vehicle model used herein is a three-axle truck with gross vehicle weight equal to 30t, which corresponds to a fully loaded truck [31], as shown in Figure 1. The truck body is assigned 2 DOFs: the vertical displacement of the center of mass of the rigid body expressed as Z_v, and the pitching displacement in x-z plane, θ_v. For each wheelset, only 1 DOF is designated: the vertical displacement in the central line of the j axle, Z_{ja}. The displacement vector $\mathbf{u}^V$ for each vehicle is:

$$\mathbf{u}^{V} = \begin{bmatrix} Z_v & \theta_v & Z_{1a} & Z_{2a} & Z_{3a} \end{bmatrix}^T \tag{9}$$

Table 1 lists the main parameters [24] of the vehicle model used in this study.

Different numbers of vehicles during the earthquake excitation, as well as, different relative distance between them may have important impact on the dynamic response of the bridge. The present study, assumes a series of up to two vehicles moving along the side lane. The typical length of the selected truck is 13.40m. Therefore, a 2m full-stop bumber-to-bumber minimum gap [32] gives 15.40m required length for each truck on the deck. Based on this, we investigate the impact of three different values of relevant distances between the moving vehicles: (i) a distance of 5m, (ii) a distance of 20m and (iii) a distance of 50m, in order to ensure a variety of distances between the moving vehicles. In order to investigate the influence of the speed of the vehicles on the dynamic response of the bridge, we examine three vehicle speeds: (i) 90km/h (25.0 m/s), (ii) 70km/h (19.4 m/s) and (iii) 50km/h (13.8 m/s). In all cases, analyses are conducted with and without considering earthquake excitations.

3.3 Selection of the earthquake records

The aim of the present study is to explore the seismic response of interacting vehicle-bridge systems and not just to assess the seismic response of a bridge. The focus is on frequently occurring earthquake excitations, as they are more likely to happen. Therefore, we adopt a ground motion recorded (CDMG, station 1117) during the historic San Francisco earthquake (22/3/1957) with magnitude 5.28 (PEER) [33]. Specifically, both the east-west (E-W) and the upper-down (U-D) components are considered simultaneously along the longitudinal direction of the bridge, and the vertical axis of the system, respectively. The peak ground accelerations (PGA) are 0.1073g (or 1.053 m/s^2) in the X (longitudinal) direction, and 0.047g (or 0.46 m/s^2) in the Z (vertical) direction.

4 SEISMIC RESPONSE OF THE INTERACTING VEHICLE- BRIDGE SYSTEM

This study examines the following three scenarios: (i) the seismic response of the bridge neglecting the dynamics of the vehicles; (ii) the dynamic interaction between the moving truck vehicles and the bridge, not considering earthquake excitations; and (iii) the seismic response of the interacting vehicle-bridge system. First, a conventional time history response analysis of the bridge model is performed for the earthquake excitation of Section 3.3, without considering the influence of the traffic. Figure 3, illustrates the results in terms of vertical displacements of the midpoint of the bridge versus time. The results of the developed in-house MATLAB algorithm are identical with the pertinent results obtained from ANSYS [11].

Further, the present section examines the response of the interacting vehicle-bridge system considering (and not) the simultaneous action of earthquake ground motions. Interaction starts when the first vehicle enters the bridge and stops when the last vehicle leaves the bridge. Figure 4, illustrates the seismic response of the bridge in terms of vertical displacements of the midpoint of the deck, for three cases: (i) there is no vehicle moving on the bridge (standard approach); (ii) there is only one vehicle moving on the deck, and (iii) there are two vehicles, moving in line, with a relevant distance of 5m between them. For cases (ii) and (iii) it is assumed that vehicles move with a constant speed of 90km/h (or 25m/s). In addition, all the results assuming the earthquake occurs when the first truck enders the bridge. For the first four seconds of the analysis, the response of the midpoint of the bridge is the same for all cases independently of the presence of the moving vehicles. The influence of the trucks on the response of the particular node of the deck can be seen when the first vehicle is at a distance of 23.11m from the observed point. The presence of one vehicle (continuous black line) causes an increase (from 0.2mm to 1.0mm) of the vertical displacements of the observed point, compared to the seismic response without considering the interacting vehicle-bridge system (black dashed line). Higher vertical displacements (up to 1.5mm) can be observed when two vehicles move along the deck (continuous grey line). The influence of the traffic on the response of the bridge stops when the last vehicle leaves the bridge, at 9.85s. As will be seen later, both the vehicle speed and the distance between the moving vehicles have important effect on the response of the bridge.

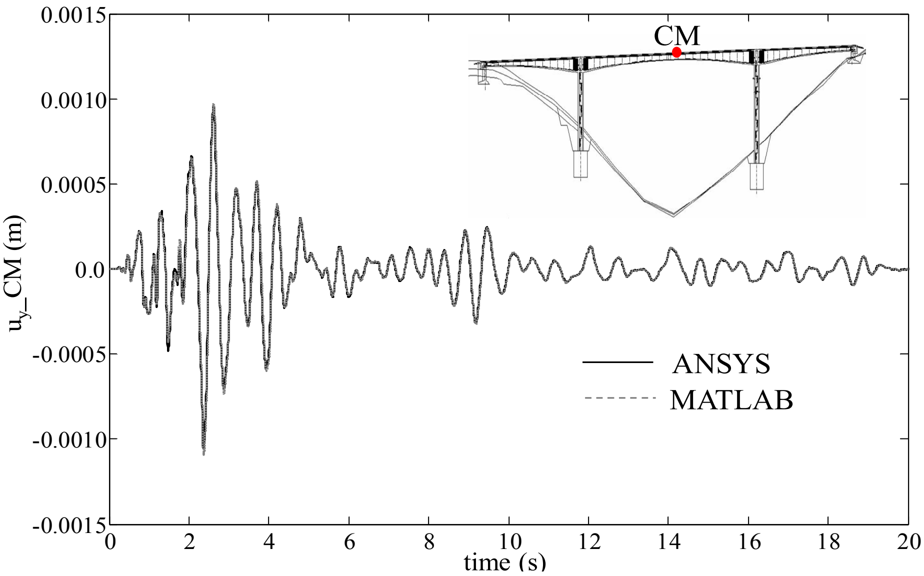

Figure 3: The vertical displacement time history of the midpoint of the bridge.

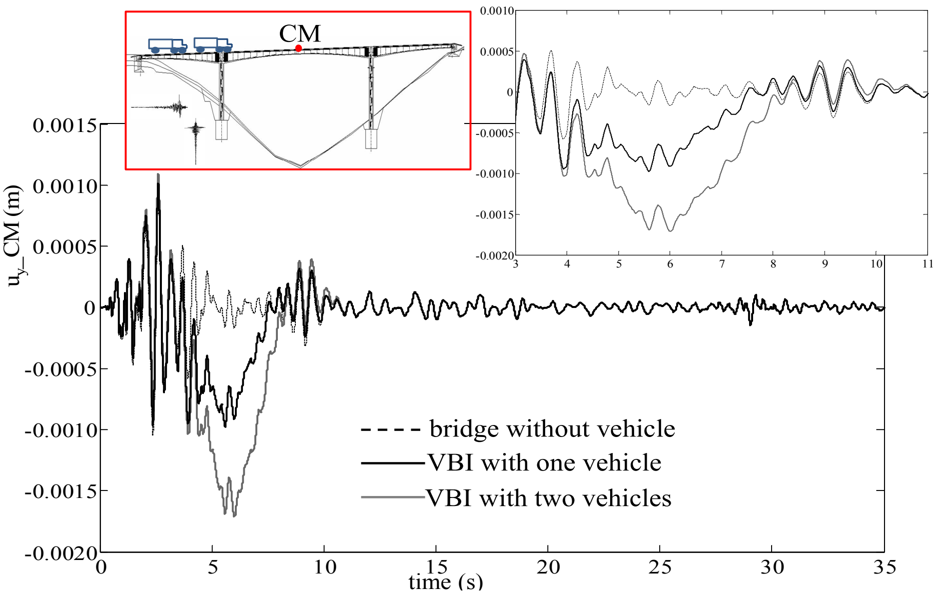

Figure 4: Seismic response of the bridge for the cases: (i) bridge without vehicles; (ii)VBI with one truck, and (iii)VBI with two trucks in line with a relevant distance equal to 5m. The speed of the vehicles 90km/h (25m/s).

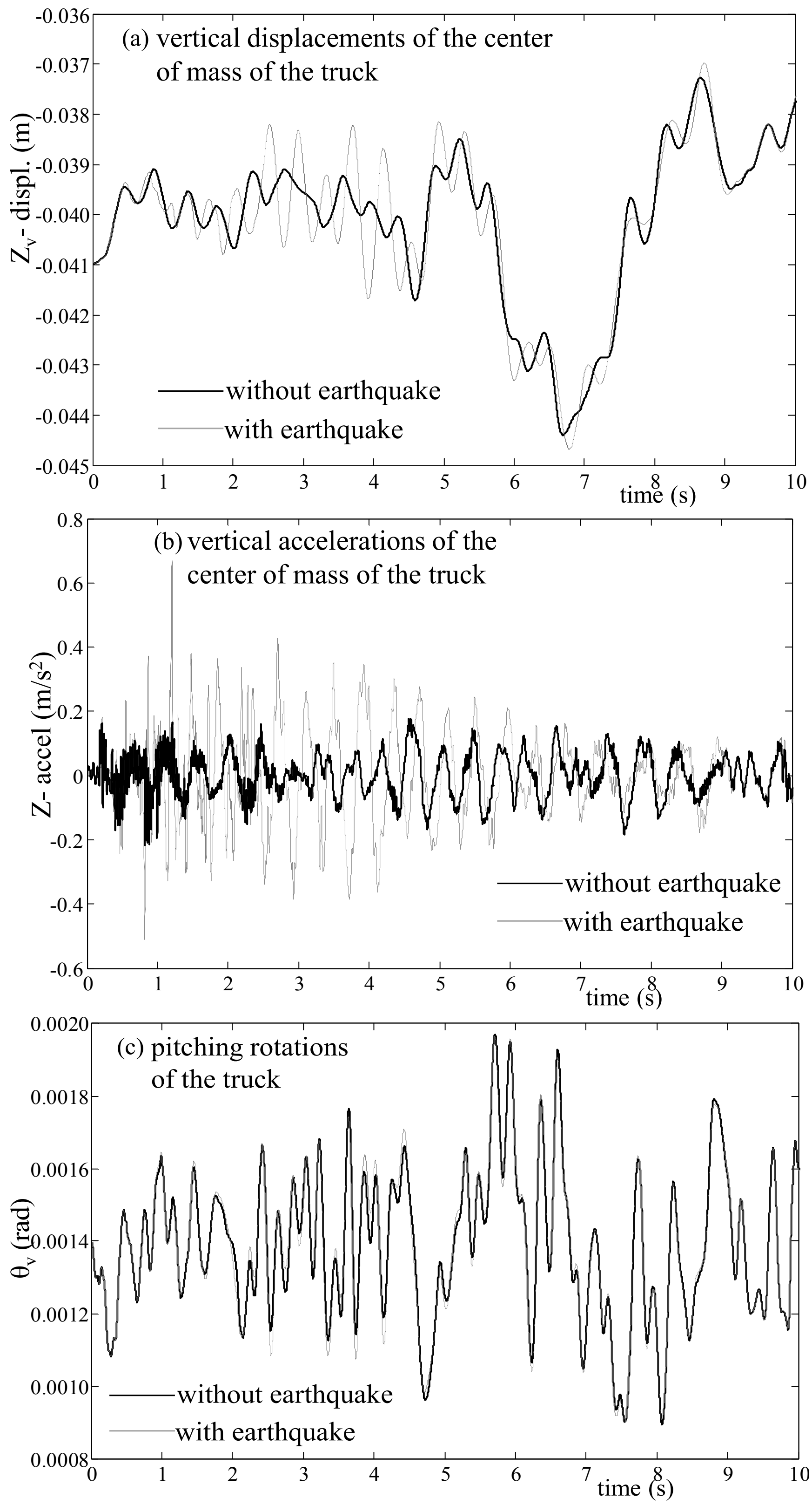

Figure 5: The response of the vehicle in terms of (a) vertical displacements of the rigid body; (b) vertical accelerations and (c) pitching rotations.

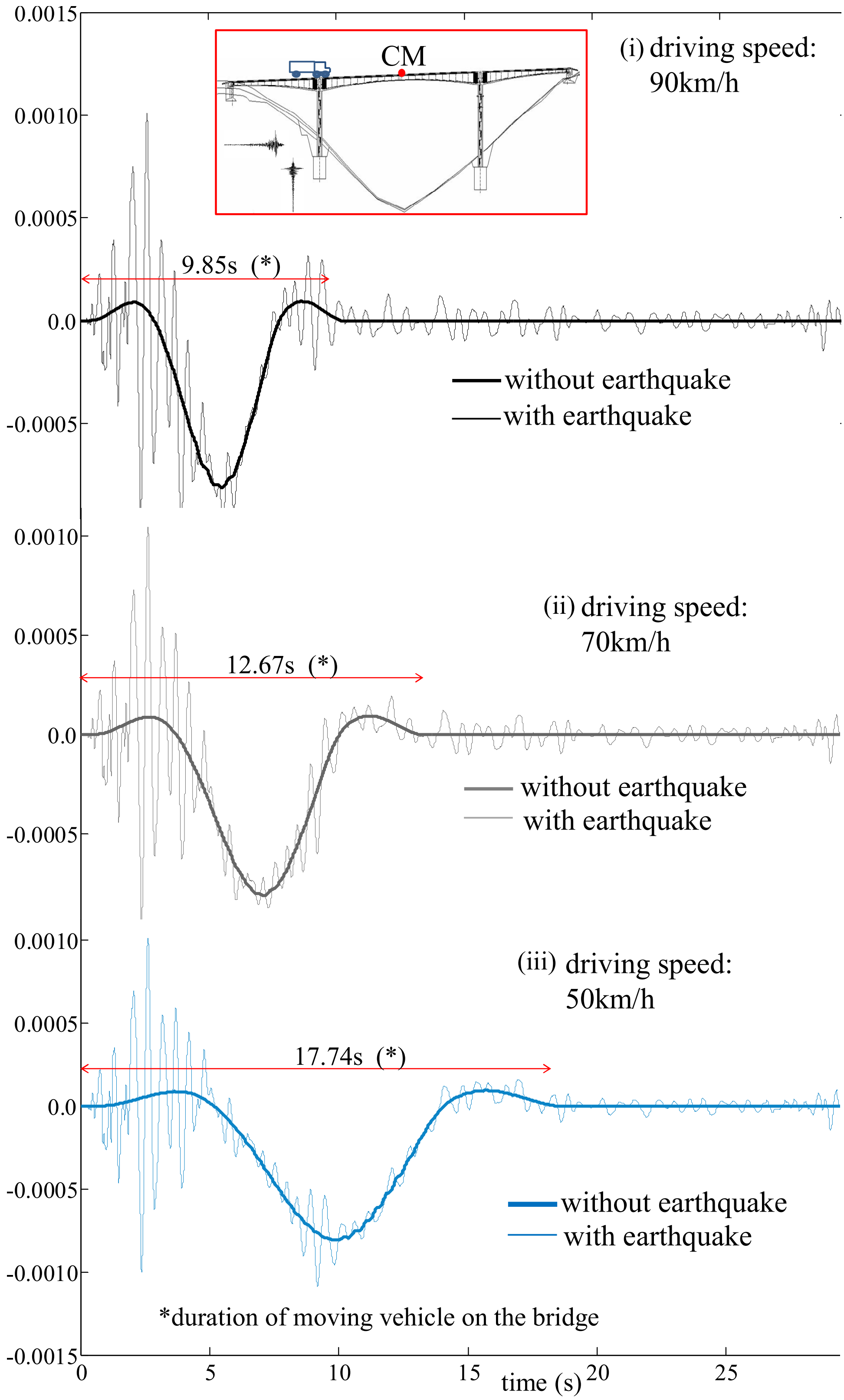

Figure 6: Vertical displacement time histories of the midpoint of the deck considering for vehicle speeds: (i) 90km/h, (ii) 70km/h and (iii) 50km/h.

Figure **5** plots: (a) the vertical displacements Z_v; (b) the vertical accelerations, and (c) the pitching rotations θ_v, versus the time of the center of mass of the truck (see Figure 1), of the first vehicle that moves on the bridge with speed 90km/h. The total duration of the moving vehicle on the bridge is 9.85s. Results are obtained for the interacting vehicle-bridge system with and without the simultaneous action of the earthquake ground motions. When the vehicle enters the bridge (time=0.0s), the study accounts for the non-zero starting values of the vertical displacements and the pitching rotations, due to the steady-state vibration of the moving vehicle. Figure **5**(a) shows significant differences between the vertical displacements of the truck (from the second up to the fifth second of the vehicle response) when the seismic excitation is considered. In Figure **5**(b) the ground motion amplifies the accelerations by a factor of 3. On the contrary, the effect of the earthquake shaking on pitching rotations (Figure **5**(c)) is hardly noticeable.

Figure 6 presents the effect of vehicle speed on the response of the bridge with and without considering the earthquake excitation. In all cases, only one vehicle is accounted for, while all other analysis parameters are as in Figure 5. Different vehicle speeds have significant impact on the peak value of the vertical displacements of the midpoint of the bridge. On the contrary, the VBI last longer, and the amplification of the bridge response increases as the vehicle speed decreases. However, it seems that at a specific time of the response, a higher speed can result in either higher (i.e., at t=5s) or lower (i.e. at t=12s) vertical displacement of the deck. This observation underlines the time-dependency of the problem and the additional complications which emerge from the time superposition of the seismic and the traffic loading.

In order to investigate the influence of the distance between the moving vehicles on the bridge response, the analysis of Figure 6 is repeated for 70km/h considering two moving vehicles with (i) a 5m relative distance between them, (ii) a 20m relative distance and (iii) a 50m relative distance. Figure 7 gives the vertical displacements of the observed point (deck of the midpoint of the deck), during the earthquake excitation, for the aforementioned cases. The maximum response of the bridge appears for the shorter relative distance of the two vehicles. As the distance between the vehicles increases, the influence of the vehicles on the seismic response of the bridge in terms of maximum vertical displacements decreases. This is in agreement with the expected trend based on influence lines.

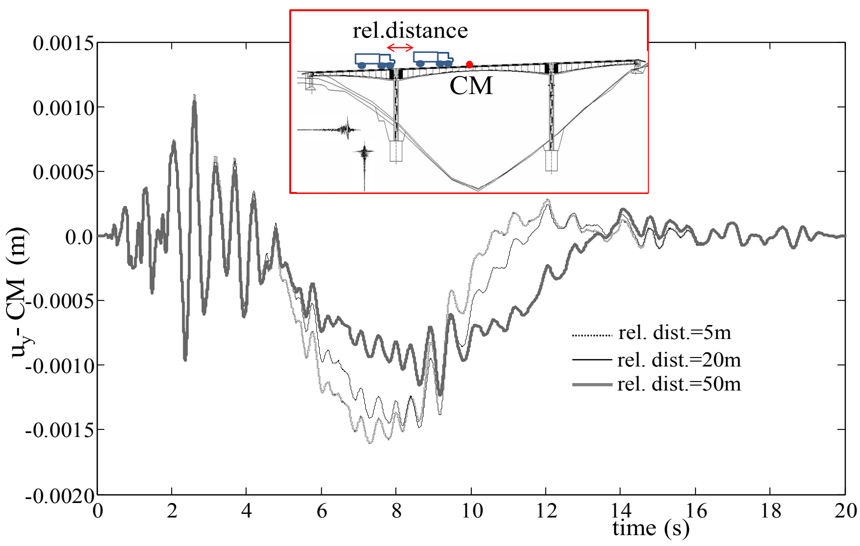

Figure 7: The vertical displacements of the midpoint of the bridge for three different relative distances between the moving vehicles: (i) a 5m relative distance, (ii) a 20m relative distance and (iii) a 50m relative distance.

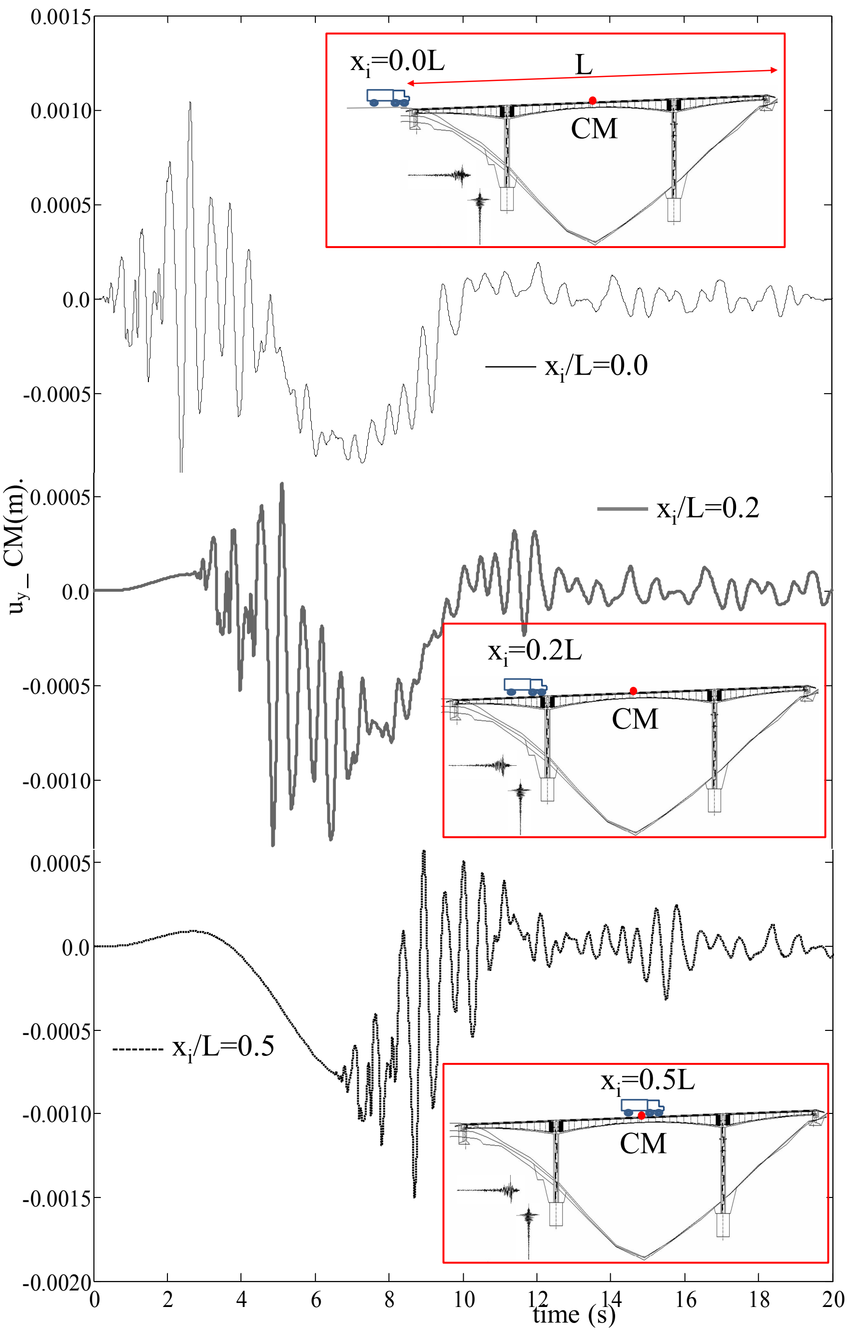

Figure 8: Vertical displacement time histories of the midpoint of the deck for different positions of the vehicle on the deck when the earthquake strikes. The vehicle speed is 70km/h.

Figures 8 and 9 show the seismic response of the bridge for different locations (x_i) of the vehicle, on the deck, when the earthquake excitation occurs. In particular, Figure 8 illustrates the time histories of the vertical displacements of the deck considering three different locations of the truck on the deck: in the first plot, it is assumed that the earthquake occurs when the truck enters the bridge (x_i/L=0.0); in the second plot the vehicle is located at x_i=0.2L(=49m) when the earthquake excitation starts; and in the third plot the earthquake occurs when the vehicle is at the middle of the deck, x_i=0.5L. L is the total length of the bridge. For the adopted earthquake excitation, the seismic response is accentuated the closer to the midpoint of the deck the vehicle is at the time the earthquake occurs. When the vehicle is passing over the midpoint of the bridge, it maximizes the vertical displacement of the observed point. Therefore, when the earthquake acts at that time, the seismic effects are added on the response of the deck and as a result the deck vertical displacements are maximized.

Figure 9, extends the results of Figure 8 considering ten different positions of the vehicle on the deck when the earthquake excitation occurs. The first set of analyses (the black column in Figure 9) accounts for only one moving vehicle. The second (the grey column in Figure 9) and the third set (the stripes) of analyses assume two moving vehicles with a relative distance between them equal to 5m and 20m, respectively. In all cases, vehicles are crossing the bridge with a constant speed of 70km/h (or 19.4m/s). The stronger influence is observed when the first vehicle is at the middle of the bridge and specifically when it is at position x_i=0.4L (= 98m) at the time the earthquake starts. In most cases, the moving vehicles with a relative distance of 5m, have higher impact on the deck compared to those with a relative distance of 20m. When the first vehicle is at positions x_i equal to 0.7L up to 0.9L, the peak vertical displacements of the midpoint of the bridge are governed by the contribution of the seismic excitation (for the adopted ground motions), and not by the impact of the presence of the vehicles on the bridge. For these cases, the impact of vehicles is not crucial to the peak values of the seismic response of the bridge. In general, and as expected, the presence of two vehicles on the bridge, instead of a single vehicle, induces higher deck vertical displacements.

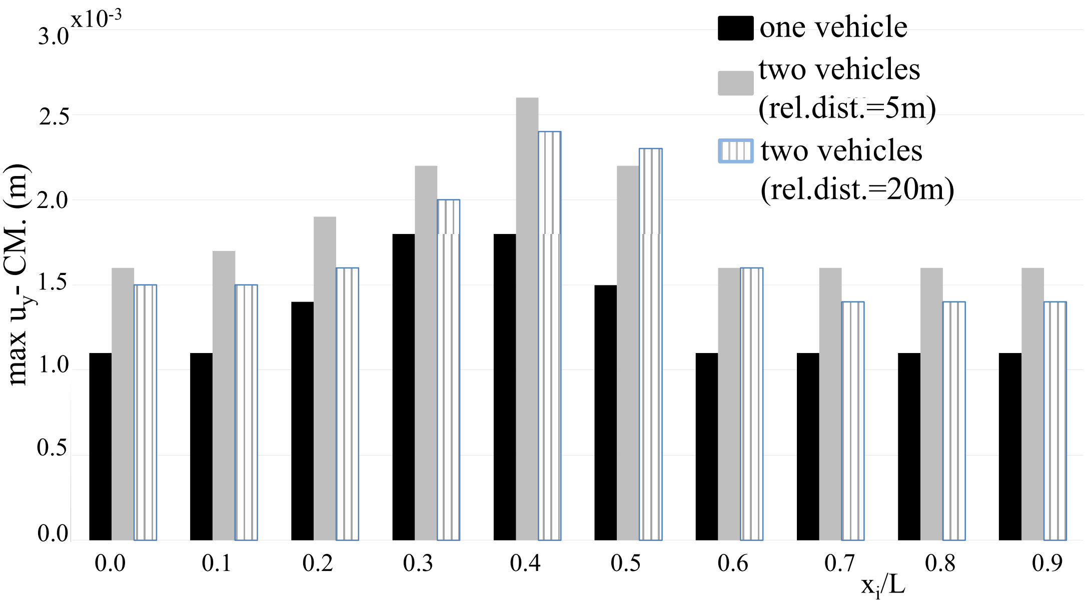

Figure 9: Peak values of the midpoint vertical displacements of the deck for (i) one vehicle; (ii) two vehicles with a 5m relative distance, and (iii) two vehicles with a 20m relative distance. All vehicles have a speed of 70km/h.

5 NEW PROBLEMS ENCOUNTERED DURING THE SEISMIC RESPONSE ANALYSIS OF INTERACTING VEHICLE- BRIDGE SYSTEMS.

In developing the proposed approach of estimating the seismic response of interacting vehicle –bridge systems two new significant problems are encountered. First, given the probabilistic nature of earthquakes, it is practically impossible to predict the position of the moving vehicles on the bridge at the time the earthquake occurs. Each vehicle can be located at any position on the deck when the earthquake strikes. Therefore, different positions of the vehicle on the deck are equally probable events that should be examined. However, the different positions of the vehicles on the deck may alter substantially the seismic response of the vehicle-bridge system. For instance, when a vehicle enters a bridge ($x_i/L=0.0$) and at the same time an earthquake occurs, the interacting vehicle-bridge system response is different than when the vehicle is in the middle of the deck ($x_i/L=0.5$) at the time the earthquake strikes (Figure 8).

The second very important issue that needs to be addressed, in future studies, is the definition of an accurate interacting traffic vehicle model. The selection of a representative type of vehicle, the number of crossing vehicles, as well as, the distance between them as they move on the deck during the earthquake excitation, are some of the parameters that have to be estimated for an accurate seismic VBI analysis. These parameters are dependent on the site-specific traffic density. The traffic density can be defined as the ratio of the truck flow rate to a constant speed for the traffic stream [31]. Again, when considering the uncertain nature of earthquakes, this problem is far too complicated to be defined deterministically. The study, offers a first insight on the influence of these parameters to the seismic response of the interacting vehicle-bridge system, in order to bring forward these problems.

6 CONCLUSIONS

The present study proposes a framework for the seismic response analysis of interacting vehicle-bridge systems during earthquake excitation. To demonstrate the proposed methodology a numerical example of a realistic case of three–axle trucks on a straight R/C bridge is presented. The particular goal of the work is to unveil new problems encountered when analyzing the seismic response of interacting vehicle-bridge systems.

The study shows that several additional variables may influence the response of the interacting vehicle-bridge system. Thus, for a given ground motion, both the number of moving vehicles and the relative distance between them, influence substantially the seismic response of the vehicle-bridge. As expected, more vehicles induce larger vertical displacements of the deck, whereas different relative distances of the vehicles cause different response of the bridge. The vehicle speed affects significantly the displacement time history of the bridge response. Different vehicle speeds have significant impact on the duration of the VBI, as well as, the amplification of the response of the bridge: it increases as the driving speed decreases. However, for a specific time of the analysis, a higher speed can result in either a larger vertical displacement of the deck or in a lower deck displacement. In the process, the study shows that the position of the moving vehicles on the deck at the time the earthquake occurs, influence significantly the seismic response of the bridge. In this context, the VBI analysis reveals the need for further investigation of all the parameters that influence the seismic response of the interacting vehicle-bridge system under the simultaneous consideration of earthquakes.

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