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Effects of soil heterogeneity on the nonlinear response of highway bridges and conditionally simulated spatial variable movements

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Abstract

This paper investigates the effects of soil lateral heterogeneity on conditionally simulated spatially variable ground motions and the nonlinear dynamic behavior of highway bridges, particularly focusing on the loss of coherence induced by this heterogeneity as excitation frequencies increase past the mean dominant frequency of the soil profile. Spatially variable seismic ground motions are conditionally generated according to a coherency model that takes into account this heterogeneity, implemented through a simulation algorithm with linear prediction estimators. The simulated time histories are then used to analyses the nonlinear dynamic behavior of a three spans continuous deck concrete bridge subjected to differential and identical support seismic ground motions. The results indicate as the coefficient of variation (CV) increases, the power spectral density of simulated time histories increases too. The comparison of the pseudo-acceleration response spectra of target acceleration and that of simulated ones reveals that spectral values of simulated motions are 1.6 times greater than those of the reference motion in the vicinity of the mean predominant soil frequency because they are influenced by the site effects. This influence is obvious in the pseudo-velocity response spectra where the pseudo-velocity values are 2 times greater than those of reference motion in the vicinity of the mean resonant soil frequency for a relatively low value in CV (10%). The analysis of the bridge's response indicates that the loss of coherence induced soil lateral heterogeneity effects as the frequencies increase beyond the mean predominant frequency of the site has a great influence on the dynamic response of the studied bridge and cannot be neglected, despite the relatively short length of the studied bridge and its foundation on firm soil. It is found that soil heterogeneity induces an increase of 50% in the relative displacements of pier 2 of the bridge studied. This influence can be more significant for long bridges founded on soft soil type.

Keywords

Spatial variability, Soil heterogeneity, Coherency, Conditional simulation, Nonlinear analysis, Bridge response

1. Introduction

For extended structures such as bridges, local site conditions can be significantly different at the supports. This variation can substantially contribute to global seismic effects on multi-supported structures by generating different excitations at the foundations. During an earthquake, bridges subjected to spatially variable ground motions can be solicited essentially beyond the elastic domain. The assessment of the nonlinear response of bridges requires dynamic time-history analysis. This analysis requires, in its turn, seismic records to be applied as input excitations at the bridges' supports. However, it is rare to find spatially variable seismic records corresponding to the bridge studied. So, we have recourse to synthetic ground motions using the Monte Carlo simulation framework for predicting the configuration of spatially variable seismic excitation.

Conditional simulation of random fields allows to generate spatially variable ground motions compatible with predefined time histories and the adopted spatial variability coherency model (Zerva, A 2009). The advantage of this approach is that the generated time series inherits the physical characteristics of the predefined ground motions. Using conditionally simulated spatial variable motions, structural analyzes have been performed on several highway bridges (Derbal et al. 2019; Efthymiou and Camara 2022; Fontara, IK et al. 2017; Mariano and Estores 2022; Savor Novak et al. 2019). Many of these structural analyzes consider uniform soil conditions underneath the highway bridges. However, it has been recognized that lateral heterogeneity affects the incident seismic ground motion and contributes to the spatial variation of the surface motion due to the scattering of the incident waves at the irregular local topography. (Shinozuka,M et al. 2000) carried out nonlinear analyses of some RC bridges to explore the effect of the spatial variability of the seismic excitation on their responses. The bridges were assumed to be found either on uniform or variable site conditions. Their results indicated that the peak ductility demand at the piers increased significantly when variable site conditions were considered for the bridge support, and, also, the effects of wave passage and loss of coherency are generally less significant compared to the effect of variable site conditions. Additional studies on highway bridges have been carried out to investigate the effect of variable site conditions on both the linear and nonlinear response of these structures using different coherency models (Belkheiri and Tilioune 2023; Guajardo et al. 2024; Li et al. 2018; Ozsarac et al. 2023; Papadopoulos and Sextos 2018; Rodríguez et al. 2022; Yan et al. 2024; Zhao et al. 2024).

(Zerva and Harada 1997) investigated the effects of the local site on the coherency function and indicated that the effect of stochastic variations in the site's characteristics on the overall pattern of spatial variation in ground surface motion is limited to the vicinity of the mean resonant frequency of the site, where a drop in coherence is observed. The same observation has been made by (Liao and Li 2002) in their analysis of the uncertainty in soil properties. Thereafter, (Laib et al. 2015) conducted an analytical study on soil lateral heterogeneity effects on spatial coherency and demonstrated that the shape of the spatial variation of the motions on the ground surface can be influenced significantly by side effects. This influence is not limited to the vicinity of the mean resonant frequency of the layer but reaches considerably high frequencies. The present work seeks to evaluate the impact of high-frequency phenomena on the dynamic response of the structures considered.

The aim of this paper is to an analysis of spatial variability of seismic ground motion effects, especially the loss of the coherence induced by soil lateral heterogeneity effects as the excitation frequencies increase past the mean dominant frequency of the soil profile, on the nonlinear dynamic behavior of highway bridges. Spatially variable seismic ground motions are conditionally simulated to be compatible with the coherency model of (Laib et al. 2015) using the simulation algorithm of (Vanmarcke et al. 1993). Simulated time histories are then subjected to appropriate processing to return realistic acceleration, velocity and displacement time histories. A sensitivity analysis is performed to determine the influence of the coefficient of variation (CV) of the site's resonant frequencies and the loss of coherence of the incident motions at the bedrock-layer interface on the simulated time histories. The simulated time histories are then used for the analysis of the nonlinear dynamic behavior of a three-span continuous deck concrete bridge subjected to differential and identical support seismic ground motions. Results are presented in terms of normalized values of displacements, shear forces and flexion moments in the piers of the studied bridge.

2. Conditional simulation of spatially variable ground motions

The conditional simulation method of (Vanmarcke et al. 1993) for the spatially variable ground motions generation using linear prediction estimators is used in the following analysis. The basic idea underlying this method is to find the unknown Fourier coefficients of the simulated time histories at the unknown point set conditioned by the Fourier coefficients of the known time histories, and then the generation of the conditionally simulated time histories using the inverse Fourier Transform (Liao S 2006). A Fortran computer program (SIMQE II) has been written by (Vanmarcke et al. 1993) to perform this approach of conditional simulation. The basic inputs to the program are the locations of the points, the known time histories and their power spectral density functions (PSD) and the model of the spatial variability coherency.

2.1 Coherency model

The model of frequency-dependent spatial correlation function proposed by (Laib et al. 2015) is used in this work to characterize the coherence of the surface motions (Eq. 1). This model was selected because it takes into account the soil's lateral heterogeneity effect. In this model, the total spatial variability of seismic ground motion $\gamma_{tot}(u,\omega)$ is attributed to the loss of coherence in the bedrock motion $\gamma_{i\,coh}(u,\omega)$, wave passage effects $\gamma_{i\,prop}(u,\omega)$ and site response effects $\gamma_{site}(u,\omega)$:

$$\gamma_{tot}(u,\omega) = \gamma_{site}(u,\omega)\cdot\gamma_{i\,coh}(u,\omega)\cdot\gamma_{i\,prop}(u,\omega) \qquad (1)$$

With is the loss of coherence of the incident motions at the bedrock-layer interface estimated by the model of (Luco and Wong 1986) as:

$$\gamma_{i\,coh}(u,\omega) = exp\left(-\bar{\alpha}^2\,\omega^2\,u^2\right) \qquad (2)$$

Where the coherency drop parameter that controls the exponential decay ratio of the function is assumed to be equal to a median value as proposed by (Luco and Wong 1986). u and ω represent the separation distance between two stations and the angular frequency of the seismic motion, respectively.

The wave passage effect is out of the scope of the present study.

is coherency function of local site response estimated for vertically propagating shear-waves through a horizontal layer with stochastic properties:

$$\gamma_{site}(\omega,u) = \frac{H_1(\omega)+C_{\omega\omega}(u)H_2(\omega)}{H_1(\omega)+\sigma^2_{\omega\omega}H_2(\omega)} \qquad (3)$$

In which:

$$H_1(\omega) = p(\omega)\times f(\omega) \qquad (3a)$$

$$H_2(\omega) = g(\omega)\times\{j(\omega)+k(\omega)+l(\omega)+m(\omega)+n(\omega)\} \qquad (3b)$$

$$p(\omega) = 2(1-\xi^2)\left[{\omega_0}^2+\omega^2-2\omega_0\omega\sqrt{1-\xi^2}\right]^2\times\left[{\omega_0}^2+\omega^2+2\omega_0\omega\sqrt{1-\xi^2}\right]^2 \qquad (3c)$$

$$f(\omega) = \left[{\omega_0}^2+\omega^2\right]\cdot\left[{\omega_0}^2+\xi{\omega_0}^2\,sin(2\varphi+\varphi_1+\pi)\right]+{\omega_0}^2\sqrt{1-\xi^2}\left[{\omega_0}^2-\omega^2\right]cos(2\varphi+\varphi_1+\pi) \qquad (3d)$$

$$g(\omega) = 2(1-\xi^2)\times\left[{\omega_0}^4+\omega^4-2{\omega_0}^2\omega^2(1-2\xi^2)\right] \qquad (3e)$$

$$j(\omega) = {\omega_0}^2\omega^2\left[4{\omega_0}^2\omega^2(1-\xi^2)+({\omega_0}^2+\omega^2)^2\right] \qquad (3f)$$

$$k(\omega) = {\omega_0}^4\left[-2\xi^2({\omega_0}^4+\omega^4)+({\omega_0}^2-\omega^2)^2\right]cos(2\varphi) \qquad (3g)$$

$$k(\omega) = {\omega_0}^4\left[-2\xi^2({\omega_0}^4+\omega^4)+({\omega_0}^2-\omega^2)^2\right]cos(2\varphi) \qquad (3h)$$

$$m(\omega) = \xi{\omega_0}^2\,sin(2\varphi+\varphi_1+\pi)\times\left[{\omega_0}^6+\omega^6+{\omega_0}^2\omega^2(4\xi^2-1)({\omega_0}^2+\omega^2)\right] \qquad (3i)$$

$$n(\omega) = {\omega_0}^2\sqrt{1-\xi^2}\,cos(2\varphi+\varphi_1+\pi)\times\left[{\omega_0}^6-\omega^6+{\omega_0}^2\omega^2(4\xi^2-3)({\omega_0}^2-\omega^2)\right] \qquad (3j)$$

The parameters of the coherency model depend on the soil characteristics. ξ and ω_0 are the damping coefficient and mean resonant frequency of the soil profile, respectively. $\sigma_{\omega\omega}$ is the standard deviation, which represents the degree of scatter of fluctuations about the mean resonant frequency. $C_{\omega\omega}(u)$ is the spatial autocorrelation function of soil predominant frequencies and represents the fluctuation of the soil predominant frequency around its mean value.

(Zerva and Harada 1997) proposed a soil profile consisting of six sublayers, with thicknesses that vary along the horizontal direction, and soil properties that are constant within each sublayer (Fig. 1). The spatial variability of soil characteristics arises from variations in the depths of the six sublayers. The soil profile is subdivided into 60 vertical subsections, each measuring 20m × 70m. The dominant frequencies of each vertical subsection have been evaluated by the authors (Zerva and Harada 1997) using equation 4:

$$\omega^*(x_n) = \frac{\pi}{2}\frac{1}{\sum_{i=1}^{60} H_i(x_n)/V_{S_i}(x_n)} \qquad (4)$$

Where and are the thickness and shear wave velocity of the sublayer at the vertical subsection, respectively.

The mean dominant frequency and the standard deviation can be calculated from the frequencies of the 60 vertical subsections using standard techniques.

The mean dominant frequency and the damping coefficient adopted in this study are those proposed by (Kiureghian and Neuenhofer 1992): and for soft, medium and firm soil conditions, respectively. The standard deviation is assumed to have the value of 0.5 for estimating coherency functions, i.e., the coefficient of variation (CV= / ×100) is assumed to be equal to 10% for the soft soil profile. The spatial autocorrelation function $C_{\omega\omega}(u)$ proposed by (Zerva and Harada 1997) for the example soil profile is adopted for characterizing the behavior of the spatial variability of soil predominant frequencies (Eq. 5):

$$C_{\omega\omega}(u_k) = \frac{1}{N-k}\times\sum_{n=1}^{N-k}\left[\frac{\omega^*(x_n+u_k)-\omega_0}{\omega_0}\right]\cdot\left[\frac{\omega^*(x_n)-\omega_0}{\omega_0}\right] \qquad (5)$$

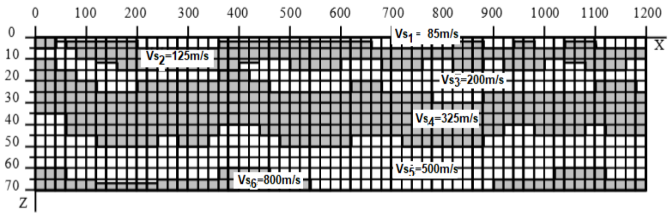


Fig. 1 An example of a soil profile consisting of six sublayers proposed (Zerva and Harada 1997)

2.2 Generation of ground motions

For analyzing site effects on the simulated seismic motion on the ground surface, we considered a conditional simulation where four points are located 100 m from each other on a straight line, and the recording point is the first one (Fig. 2). The north-south component of the natural ground motion recorded at Manisa station (rocky site) during the 1999 earthquake in Kocaeli, Turkey, is chosen as the reference acceleration. The three other stations are assumed to be found on the same laterally heterogeneous soil profile (firm soil,).

Conditionally simulated ground accelerations need special processing to produce realistic velocity and displacement via direct integration. They were processed with a high-pass Butterworth filter to get zero residual displacement. The reference acceleration and an example of conditionally simulated accelerations on the soil ground surface at the three stations with the corresponding velocities and displacements obtained via direct numerical integration are illustrated in Fig. 3. The site effects are clearly illustrated in the three motion parameters. Table 1 presents a comparison of the peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) of the reference motion and the mean of 25 values of simulated motions at the three other stations. It is observed that these parameters of simulated motions are greater than those of reference motion because they are influenced by side effects.

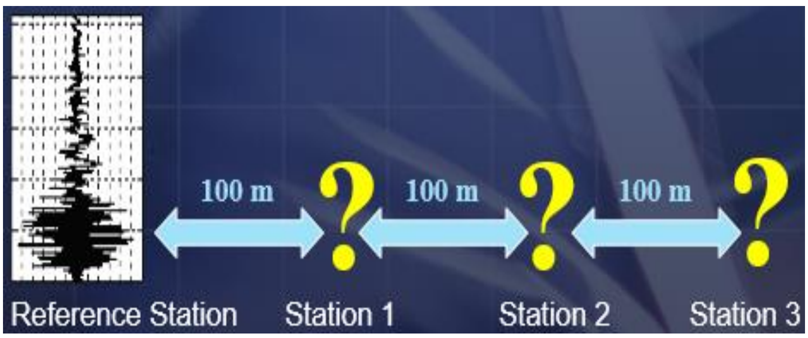
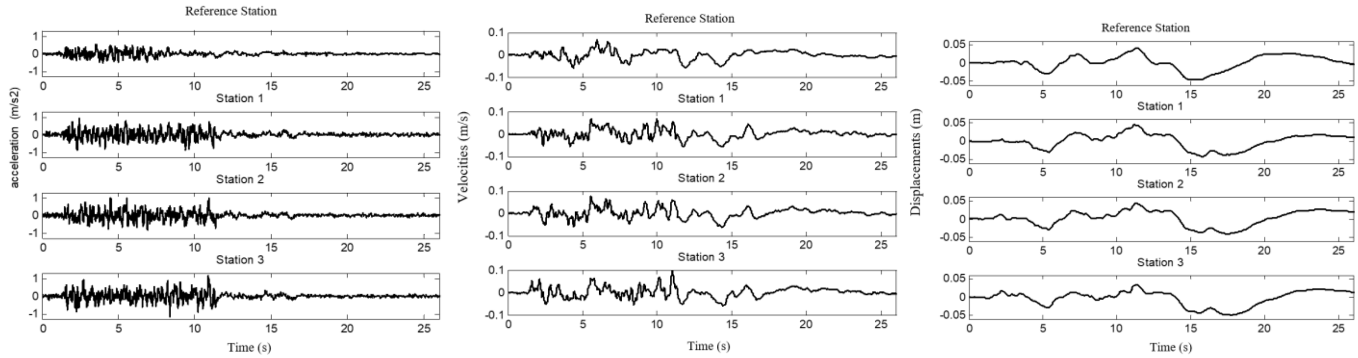


Fig. 2 A Schematic of Conditional Simulation with Four Points Aligned at 100 m Intervals, Starting from reference station

Table 1. Values of PGA, PGV and PGD are estimated from 25 simulated motions at the three stations and the reference station.

Station	PGA (m/s2)	PGV (m/s)	PGD (m)
Reference	0.54	0.06	0.054
Station 1	0.99	0.08	0.054
Station 2	1.04	0.08	0.054
Station 3	0.99	0.08	0.054



(a) (b) (c)

Fig. 3 An example of' (a) simulated accelerations, (b) velocities and (c) displacements evaluated by integration for the three stations

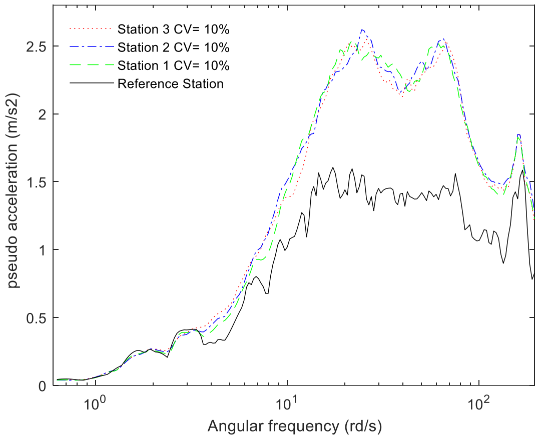


Fig. 4. The mean of 25 pseudo-acceleration response spectra of conditionally simulated accelerations and that of reference station.

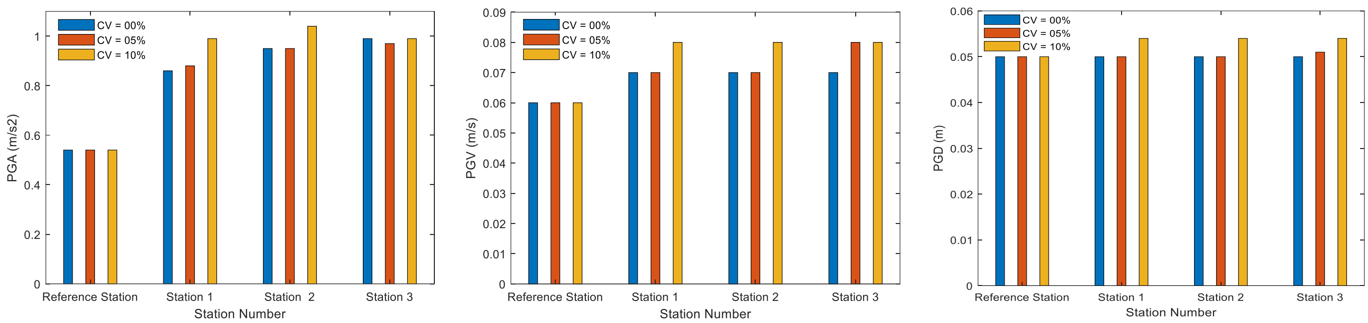


Fig. 5. The mean values of PGA, PGV and PGD obtained from 25 simulated motions at the three stations and those of reference motion for different values of CV

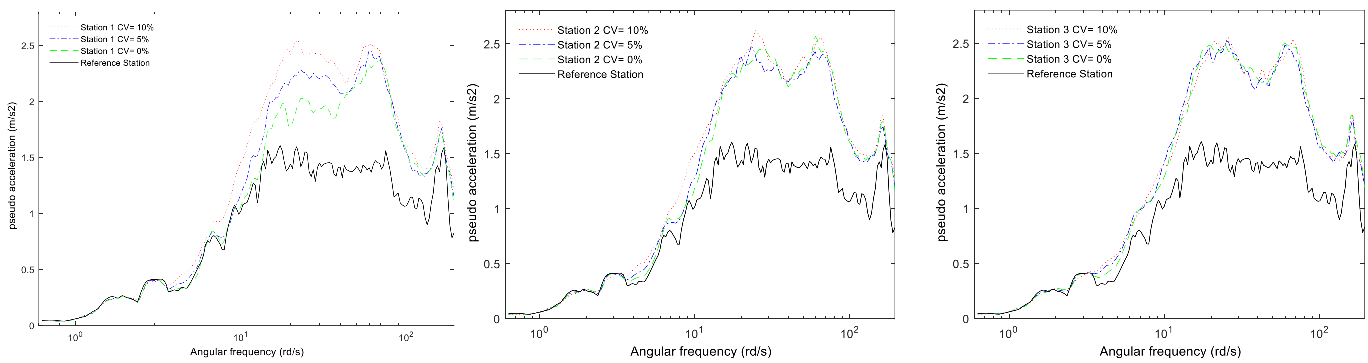


Fig. 6. The mean of 25 pseudo-acceleration response spectra of conditionally simulated accelerations and those of reference station for different values of CV.

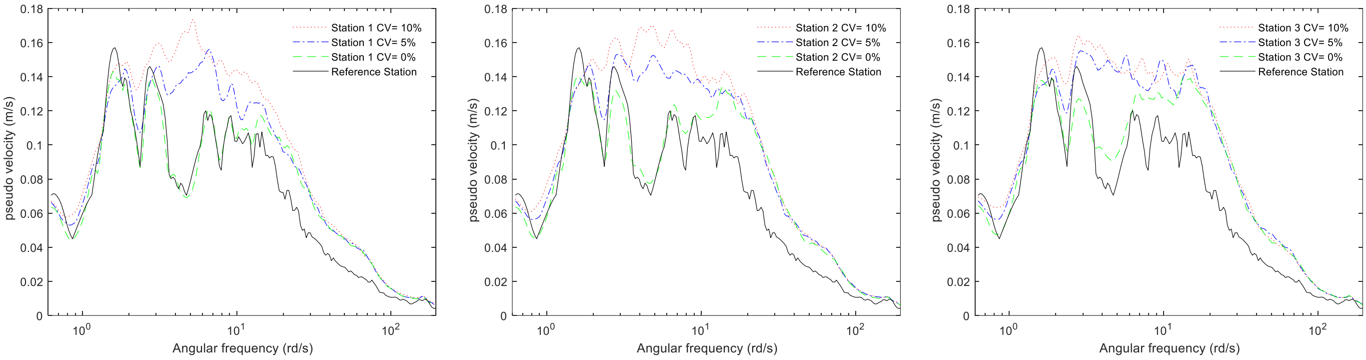


Fig. 7. The 25 pseudo-velocity response spectra of conditionally simulated accelerations and those of reference station for different values of CV.

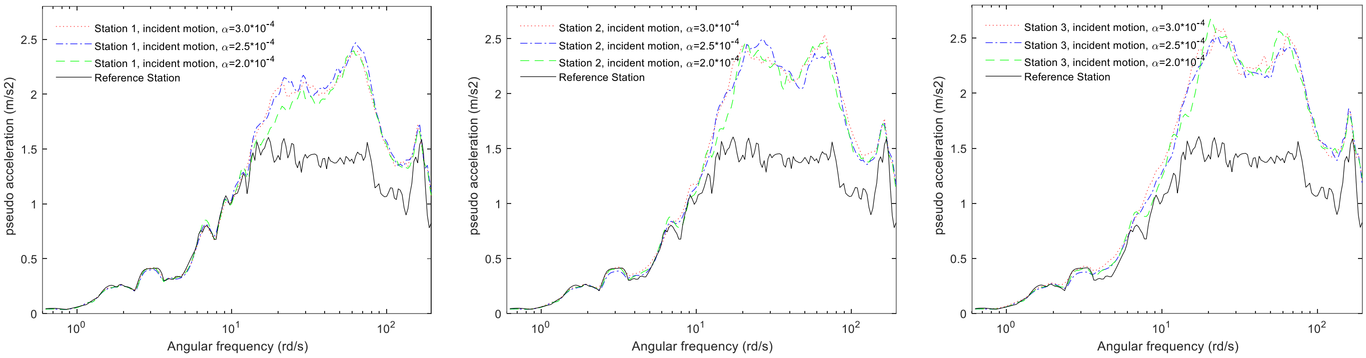


Fig. 8. The mean of 25 pseudo-acceleration response spectra of conditionally simulated accelerations and those of reference station for different values of incoherence parameter α

Fig. 4 represents the pseudo-acceleration response spectra of the reference motion and the mean of 25 pseudo-acceleration response spectra of simulated motions at the three stations located on the firm soil. The obtained results show that the spectral values of simulated motions are 1.6 times greater than those of the reference motion in the vicinity of the mean resonant soil frequency.

Soil lateral heterogeneity effects on the PGAs, PGVs and PGDs of 25 simulated motions on the ground surface of the soft soil for different values of CV are shown in Fig. 5. Results indicate that as the heterogeneity of the soil profile increases, the maximum values of simulated motions (PGA, PGV, PGD) increase.

It is shown in Fig. 6 that the soil lateral heterogeneity effects on the pseudo-acceleration response spectra of 25 simulated motions at the three stations founded on the firm soil for different values of CV. The obtained results indicate that as the heterogeneity level increases, the Pseudo Spectral Acceleration values (Psa) increase. The influence of the CV is pronounced in the vicinity of the mean resonant soil frequency of the soil layer. This influence is obvious in the pseudo-spectral velocity (Psv) response spectra shown in Fig. 7, where the values of the pseudo-velocity are 2 times greater than those of the reference motion in the vicinity of the mean resonant soil frequency for 10% of CV.

For soil profile with deterministic characteristics, the variability of motion at the ground surface is identical to that of the incident motion (Laib et al. 2015). Fig. 8 illustrates the effects of the incident motion variability on the pseudo-acceleration response spectra of 25 simulated motions at the three stations. Contrary to the soil heterogeneity effects, which appear at frequencies higher than 3 rd/s, the effects of the incident motion variability start to appear around 10 rd/s. Furthermore, the results of Psa of simulated motions don't indicate any clear tendency with the increase of the loss of coherence of incident motion.

The results obtained in this section will be exploited in the next section for the analysis of bridge response under differential excitation.

3. Nonlinear response of highway bridge to multi-support excitation

Both long and short span bridge behavior may be significantly affected by the spatial heterogeneity of earthquake ground motions. The critical seismic demand for structural components cannot always be predicted by uniform excitation at the supports of the structures (Lou and Zerva 2005). This section studies how the nonlinear dynamic response of highway bridges is affected by the spatial variation of seismic ground motion caused by soil lateral heterogeneity.

3.1 The bridge model

The example bridge chosen for this analysis is a reinforced concrete bridge that has three spans of 50 m, 70 m and 50 m. The elevation and transversal of the bridge are presented in Fig. 9 (a and b). Its superstructure is a prestressed reinforced concrete box girder which is connected to two piers of rectangular hollow shape and unequal heights. The transversal section of piers is shown in Fig. 9(c). The abutment bearings are considered to be free to slide in the longitudinal direction and fixed in the transverse direction. The abutments and the two piers are assumed to be pinned to the ground. A finite element model of this bridge is established in SeismoStruct (SeismoStruct" 2016) using a 3D inelastic beam-column element for piers (Fig. 10). The superstructure is modeled by 3D elastic beam elements. A symmetric élasto-plastic behavior is attributed to the contact between the abutments and the two ends of the box girder according to the bilinear force-displacement law with an initial rigidity of K0=1.00 ×106 N/m. The unconfined and confined concrete of the pier-columns is based on the model developed by (Mander et al. 1988) and the cyclic rules suggested by (Martínez-Rueda and Elnashai 1997).

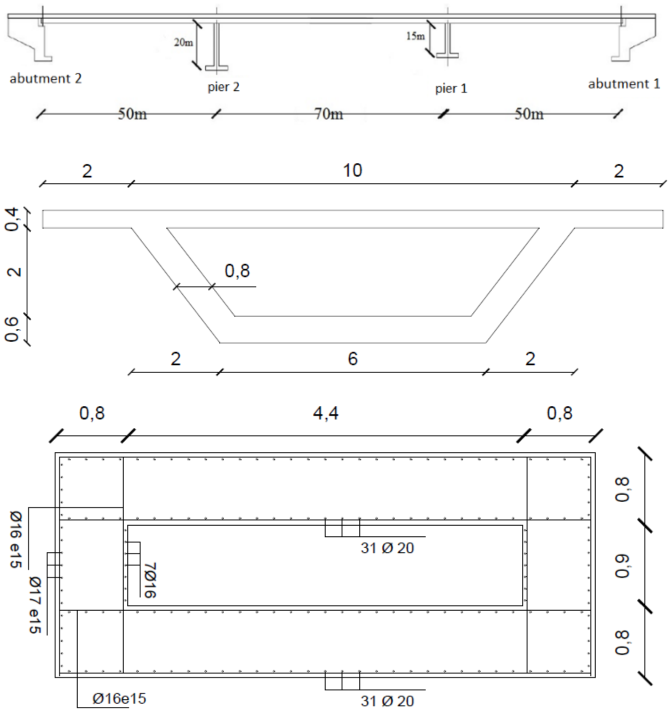


Fig 9. The elevation (a) and transversal (b) of the bridge, the transversal section of the two piers (c).

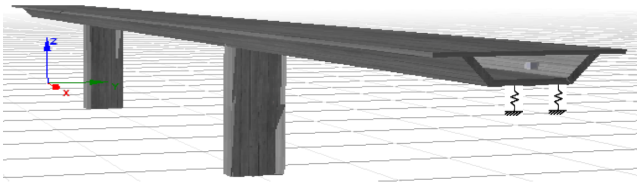


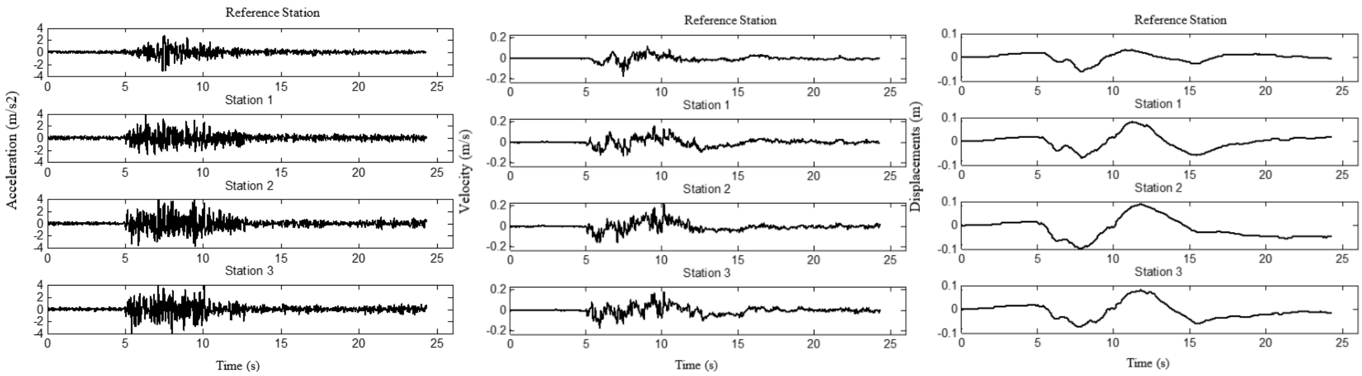
Fig 10. A finite element model of the studied bridge.

3.2 Ground motion modeling

The east-west component of the natural ground motion recorded at Keddara 1 station during the 2003 earthquake in Boumerdes, Algeria, is chosen as the reference acceleration for conditionally simulating spatially variable ground motion according to the methodology of (Vanmarcke et al. 1993) and using the coherency model of (Laib et al. 2015). Abutment 1 is considered to be founded on the reference station. The two piers and the second abutment are supposed to be installed on the heterogeneous firm soil cited in section 2.1; and the standard deviation is assumed to have the value of 1.5 for estimating coherency functions, i.e., the CV is assumed to be equal to 10% for the firm soil profile. The input excitations are applied in the transversal direction of the bridge. The reference acceleration recorded at Keddara 1 station and an example of conditionally simulated accelerations on the soil ground surface at the three stations using the coherency model of (Laib et al. 2015) are illustrated in Fig. 11. The corresponding velocities and displacements obtained via direct numerical integration are also shown on Fig. 11.

For analyzing the effect of the loss of coherence as the excitation frequencies increase past the mean dominant frequency of the soil profile on the highway bridge, the coherency model of (Zerva and Harada 1997) is also used for conditional simulation of spatially variable ground motions.

It is worth noting that there is a good agreement between the coherency model of (Laib et al. 2015) and that of (Zerva and Harada 1997) for the quantification of the loss of coherency at the mean predominant soil frequency. However, as the excitation frequencies increase beyond the mean predominant frequency of the site, the site contribution to the coherency of the model of Zerva and Harada vanishes Harada vanishes (Fig. 12). These generated differential motions will be used as input excitations at the bridge's supports.



(a) (b) (c)

Fig 11. An example of' (a) simulated accelerations, (b) velocities and (c) displacements evaluated by integration for the three stations.

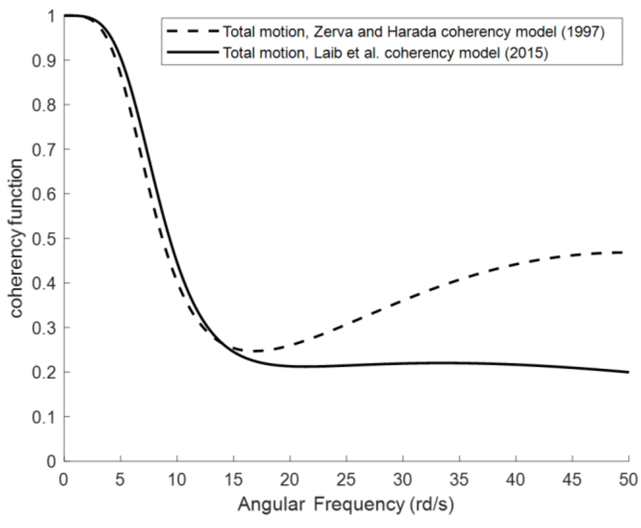


Fig 12. Coherency models used for conditionally simulating spatially variable ground motion

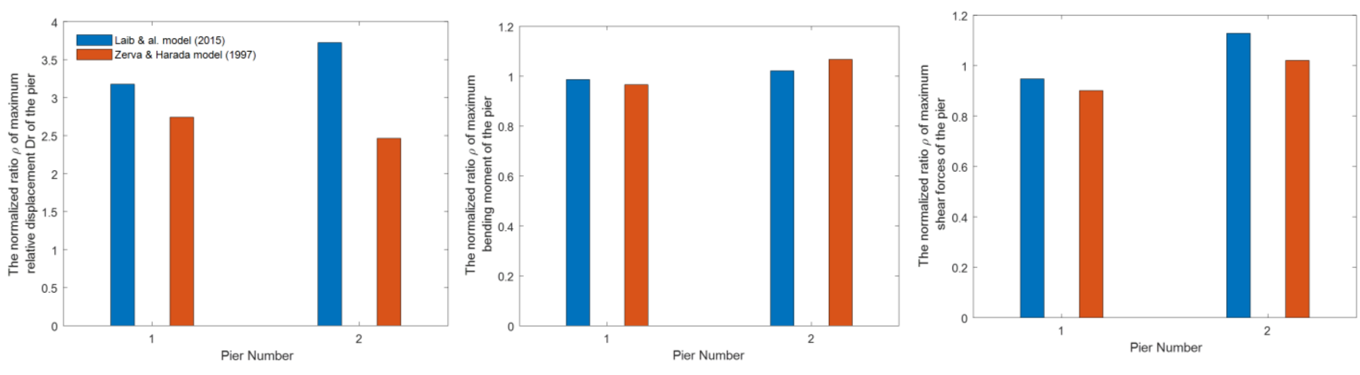


Fig 13. The values of the ρ of cases 2 and 3 normalized with respect to case 1 (a) displacements, (b) moments et (c) shear force.

3.3 Soil lateral heterogeneity effects on the bridge response

For determining the relative importance of the soil lateral heterogeneity effects on the nonlinear dynamic structural response, the following three cases of spatially varying ground motions by taking into account the incoherence of incident motion and soil lateral heterogeneity effects, were considered for the bridge supports:

Case 1: uniform; reference acceleration is applied as input at each support (uniform firm soil).

Case 2: Spatially variable; conditionally simulated ground motions using the coherency model of (Laib et al. 2015) are used as input excitations.

Case 3: Spatially variable; conditionally simulated ground motions using the coherency model of (Zerva and Harada 1997) are used as input excitations.

The difference between case 2 and case 3 is that case 2 takes into account the loss of coherence induced by the soil lateral heterogeneity effects as the frequencies increase beyond the mean predominant frequency of the site. For the evaluation of the spatial variation of ground motion effects, normalized response values with respect to uniform ones are used. The normalized ratio ρ is obtained as:

ρ =|the mean of the maximum responses for spatially variable excitations| / |the mean of the maximum responses for uniform excitations.

For Monte Carlo simulation needs, the process of bridge analysis is repeated 10 times to get a stable mean of the bridge response (displacement, moment and shear force in the piers).

Fig. 13 presents the normalized values of cases 2 and 3 in relation to case 1. The values of the normalized bridge responses are greater than 1 which indicates that the response of the studied bridge, in terms of displacements, bending moments and shear forces at the piers, is greater under variable excitations compared to uniform excitation, despite the relatively short length of the bridge (170 m with three spans) and its foundation on firm soil. The effect is more pronounced for the displacement of piers. This is due to the fact that spatially variable excitations induce the anti-symmetric modes of the bridge and excite its higher modes more significantly than uniform motions.

The comparison of the normalized responses using the two coherency models shows that maximum displacements of pier 2 (taller than pier 1, see Fig. 9), using the coherency model of Laib et al., present an increase of 50% compared to those using the coherency model of Zerva and Harada. This indicates that the loss of coherence as the frequencies increase beyond the mean predominant frequency of the site has a great influence on the dynamic response of the studied bridge and cannot be neglected, despite the relatively short length of the bridge (170 m with three spans) and its foundation on firm soil. This influence can be more significant for long bridges founded on soft soil type. It's also observed that this effect is not so pronounced for the bending moment and shear forces in the pier 1. Also, soil lateral heterogeneity has a favorable effect on the bending moment and shear forces in the pier 1 (ρ less than one).

4. Conclusion

In this paper, the spatial variation of seismic ground motion effects, particularly those due to soil lateral heterogeneity, on the conditionally simulated ground motions and the nonlinear response of the highway bridges is analyzed. Spatially variable seismic ground motions are conditionally simulated to be compatible with the coherency model of Laib and al. This model was selected because it takes into account the soil lateral heterogeneity effect on the coherency of the seismic motions as the excitation frequencies increase past the mean dominant frequency of the soil profile.

Obtained results indicate that spectral values of simulated motions are 1.6 times greater than those of the reference motion in the vicinity of the mean predominant soil frequency because they are influenced by site effects. This influence is obvious in the pseudo-velocity response spectra, where the values of the pseudo-velocity are 2 times greater than those of the reference motion in the vicinity of the mean resonant soil frequency for a relatively low value in the coefficient of variation (10%). Contrary to the soil heterogeneity effects, the effects of the motion variability on the simulated motions don't indicate any clear tendency with the increase of the loss of coherence of incident motion.

The analysis of the spatial variation of seismic ground motion due to soil lateral heterogeneity effects on the nonlinear dynamic response of highway bridge indicates that the response of the studied bridge, in terms of displacements, bending moments and shear forces at the piers, is greater under variable excitations compared to uniform excitation.

The results indicate that the loss of coherence as the frequencies increase beyond the mean predominant frequency of the site has a great influence on the dynamic response of the studied bridge and cannot be neglected, despite the relatively short length of the bridge (170 m with three spans) and its foundation on firm soil. It is found that soil heterogeneity induces an increase of 50% in the relative displacements of pier 2 of the bridge studied. This influence can be more significant for long bridges founded on soft soil type. It is worth noting that the soil heterogeneity effect on the loss of coherence as the excitation frequencies increase beyond the mean resonant frequency of the site can have a favorable influence, as is the case of pier 1.

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