IMPACT OF SPATIAL VARIABILITY OF EARTHQUAKE GROUND MOTION ON SEISMIC RESPONSE OF A RAILWAY BRIDGE

RACHID DERBAL[1,2], NASSIMA BENMANSOUR[2] & MUSTAPHA DJAFOUR[2]
[1]Department of Civil Engineering, University centre of Ain Temouchent, Algeria.
[2]Department of Civil Engineering, University of Tlemcen, Tlemcen, Algeria.

ABSTRACT
This paper studies the impact of spatially varying ground motions on the responses of a railway bridge. The evaluation of the seismic hazard for a given site is to estimate the seismic ground motion at the surface. This is the result of the combination of the action of the seismic source, which generates seismic waves, the propagation of these waves between the source and the site, and the local conditions of the site. Firstly, the seismic ground motions are modelled by assuming the base rock motions of the same intensity and modelling them with a filtered Tajimi-Kanai power spectral density function and a spatial ground motion coherency loss function. Then, the power spectral density function of ground motion on surface is derived by considering the site amplification effect based on the one-dimensional seismic wave propagation theory. A comparison between the bridge responses to uniform ground motion, to spatial ground motions with and without considering local site effects is established. Discussions on the seismic ground motion spatial variability and local site conditions effects on structural responses of railway bridge are made.
Keywords: bridge responses, coherency loss, site effects, spatially varying ground motions, Tajimi-Kanai power spectral

1 INTRODUCTION

The seismic analysis of the structures requires a good understanding of the seismic loading. For extended structures, such as bridges, there is the appearance of a phenomenon called spatial variability of ground motions. A good representation of the seismic input must take into account this phenomenon. The sources of this variation have been described [1, 2] as: wave passage effect, wave coherency loss, and site effects.

Many studies have investigated the spatial variability of ground motion and assume that the site is uniform and homogeneous. The only variations are loss of coherency and a phase delay. This hypothesis can not be retained because the soil is heterogeneous. Therefore, the seismic wave propagation is affected in terms of intensity and frequency content.

For this purpose, a good representation of the seismic loading must take into account all the factors of the spatial variability of the ground motion, namely the loss of coherency loss effect, the waves passage effect and, in particular, local site effect.

Some researchers have tried to model the effect of local site conditions on earthquake ground motion spatial variations.

Kaiming *et al.* [3] have proposed an approach where the spatial ground motions are modelled in two steps. Firstly, the base rock motions are assumed to have the same intensity and are modelled with a filtered Tajimi-Kanai power spectral density function and an empirical spatial ground motion coherency loss function. Then, power spectral density function of ground motion on surface of the canyon site is derived by considering the site amplification effect based on the one dimensional seismic wave propagation theory. A discussion on the ground motion spatial variation and local soil site amplification effects on structural responses

ISSN: 2046-0546 (paper format), ISSN: 2046-0554 (online), http://www.witpress.com/journals
DOI: 10.2495/CMEM-V6-N5-910-920

are made. They conclude that the effects of neglecting the site amplifications in the analysis as adopted in most studies of spatial ground motion effect on structural responses are highlighted.

Konakli and Der Kiureghian [4, 5] presented a simulation of the seismic ground motions by two approaches: The conditional approach where the simulated motion is conditioned by an observed acceleration at a site and the unconditional approach where the ground motion is compatible with an estimated spectral density function

The work of Benmansour *et al.* [6–8] evaluated the method proposed by the RPOA (the Algerian bridge seismic regulation code) and compared it with more refined approaches and with the provisions of EC8. They have developed a method of generating of asynchronous seismic ground motion in the sense that the displacement signals can be obtained directly without going through the double integration. Based on the study of several bridges, the results obtained of this work show that the simplified RPOA method overestimates the seismic demand. They proposed to modify some provisions, and the new approach gives results which are in better

Kaiming and Hao [9] developed a method for generating asynchronous seismic ground motions that takes account of local site effects. This method is based on the theory of wave propagation presented by WOLF 1985. As a hypothesis, the motion at the rock base is composed of SH wave (off-plan) or the combination of P and SV waves with an incident angle given. The simulated movements are compatible with the spectral density function of the target response spectrum. They concluded that the proposed method leads to a more realistic modeling of the asynchronous seismic ground motions in sites with different characteristics compared to the hypothesis of identical intensity of the movements.

In this study, the generation model of seismic ground motions described by Benmansour *et al.* [8, 10–13] is developed to take account local site effect. Several recent studies have shown that the local conditions of the site should not be neglected when interpreting the spatial variability of the seismic ground motions. Consequently, the model proposed in this study takes into account all the effects of the spatial variability of the spatially varying ground motion, in particular the site effect. The aim of this work is to evaluate the influence of the site effect on the dynamic response of bridges. The generation of asynchronous seismic ground motion is made for all supports of bridge. Structural responses to uniform ground motion and to spatial ground motion with considering the site effect are calculated and compared. Discussions on the ground motion spatial variation and site effect in terms of the site properties on structural responses are made.

2 BRIDGE AND SPATIAL GROUND MOTION MODEL

2.1 Railway bridge model

Figure 1 illustrates the bridge model on the site, in which CA, P1, P2, P3 and CB are the supports on ground surface. The corresponding points at the base rock are CA', P1', P2', P3'and CB', respectively.

ρ_i, v_i, ξ_i and h_i are the density, shear wave velocity, damping ratio and depth of the soil under support, respectively, where i represents CA, P1, P2, P3, CB, respectively. The corresponding parameters on the base rock are ρ_R, v_R and ξ_R Table 1 gives the values of these parameters.

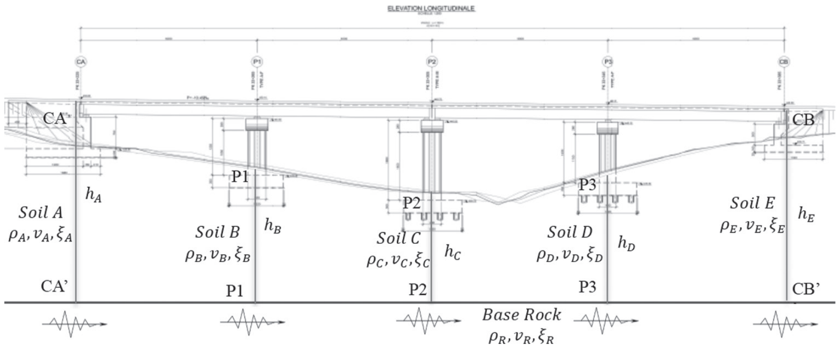

Figure 1: Longitudinal view of a bridge crossing a canyon site.

Table 1: Parameters of soil foundation.

Soil A		**Soil B**		**Soil C**		**Soil D**		**Soil E**	
ρ_A	v_A	ρ_B	v_B	ρ_C	v_C	ρ_D	v_D	ρ_E	v_E
2500	800	1500	300	1500	200	1800	400	2000	500
ξ_A	h_A	ξ_B	h_B	ξ_C	h_C	ξ_D	h_D	ξ_E	h_E
5%	59.6	5%	40.5	5%	45.6	5%	50.6	5%	57.9

2.2 Base rock model

Assume the amplitudes of the power spectral densities at different locations on the base rock are the same and in the form of the filtered Tajimi-Kanai power spectral density function [3, 9]:

$$S_g(\omega) = |H_P(\omega)|^2 S_0(\omega) = \frac{\omega^4}{(\omega_f^2-\omega^2)^2 + (2\omega_f\omega\xi_f)^2} \cdot \frac{\omega_g^4 + 4\xi_g^2\omega_g^2\omega^2}{(\omega_g^2-\omega^2)^2 + 4\xi_g^2\omega_g^2\omega^2} \tag{1}$$

in which $|H_P(\omega)|^2$ is a high pass filter [13, 15], ianai power spectral density function [8], ω_g ωg and ξ_g ξg are uency and damping ratio of the Tajimi-Kanai power spectral density function, Γ is a scaling factor depending on the ground motion intensity, and ω_f and ξ_f are the central frequency and damping ratio of the high pass filter.

I study, it is assumed that $\omega_f = 0.5\pi\, Hz$, $\xi_f = 0.6$, $\omega_g = 6\pi\, Hz$, $\xi_g = 0.6$ and $= 0.00565\ \mathrm{m}^2 / s^3$ (see Fig. 1). These values correspond to a peak ground acceleration (PGA) 0.2 g with duration $T = 20\ s$ (Der Kreiughian 1980) [3]. Figure 2 shows the power spectral density of the base rock motion.

2.3 Coherency model

The complex coherency function describes the correlation between the amplitudes and phase angles of two ground motion time histories in the frequency domain. This function is defined as (Der Kiureghian, 1996) [3, 14, 15]:

$$\gamma_{jk}(\omega) = \frac{S_{jk}(\omega)}{\sqrt{S_j(\omega S_k(\omega))}} \tag{2}$$

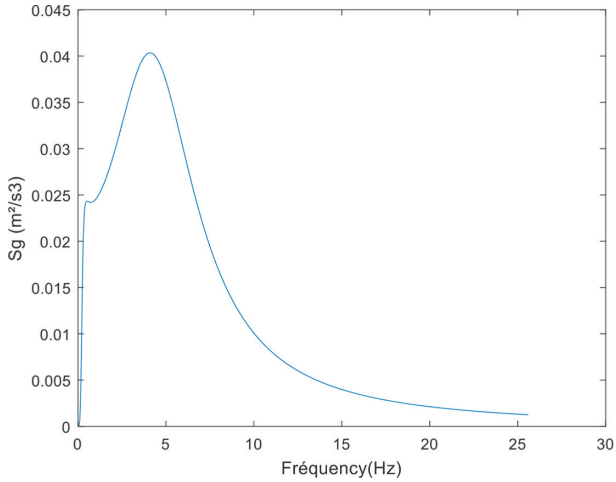

Figure 2: Filtered ground motion power spectral densfution on the base rock.

where ω is the circular frequency; $S_j(\omega)$, Sk(ω) $S_k(\omega)$ are the power spectral density functions of the time histories $g_j(t)$ and $g_k(t)$, respectively; and $S_{jk}(\omega)$ is the cross-power spectral density of the considered time histories.

The coherency function can be written as (Der Kiureghian, 1996) [7]:

$$\gamma_{jk}(\omega) = \left|\gamma_{jk}(\omega)\right| exp\left(i - \frac{\omega d_{jk}}{v}\right) \tag{3}$$

where d_{jk} is the projected horizontal distance along the direction of propagation of the waves, which is from station j to station k, and v ishe surface apparent velocity of waves, considered as constant over the frequency range of the wave.

The Hindy and Novak coherency loss model is used to model the seismic ground motion at the base rock:

$$\left|\gamma(f,\lambda)\right| = exp\left(-\alpha(2\pi f \lambda)^{\beta}\right) \tag{4}$$

The evolution of the loss coherency as a function of the frequency is described in Fig. 3. The parameters of this model are: α =3,007 10^{-4} and β =0.9 [16].

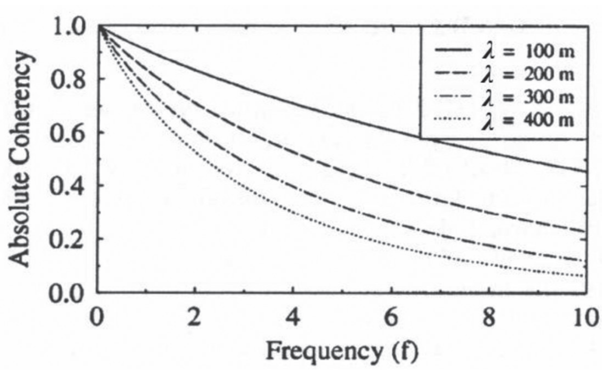

Figure 3: Hindy and Novak coherency loss model [16].

3 SPATIAL GROUND MOTION MODEL

The stationary time series are simulated using the method described by Deotatis (1997) [14], which is as follows.

From eqn (2), the cross-spectral density matrix $S_0(\omega)$ for the stationary process $g_j(t)$; j = 1,2,...,n. is given by [3, 9, 16]:

$$S_{jk}(\omega)=\left[S_j(\omega)S_k(\omega)\gamma_{jk}(\omega)\right] ; j,k=1,2,\ldots,n. \tag{5}$$

In order to simulate samples of the n-variant stationary stochastic process $g_j(t)$; $j,k=1,2,\ldots,n.$ Its cross-spectral density matrix $S_0(\omega)$ given in eqn (5) is factorized into the following product using Cholesky's decomposition method:

$$S_0(\omega)=H_0(\omega)H^{T*}(\omega) \tag{6}$$

The elements of $H_0(\omega)$ can be written in polar form as:

$$H_0(\omega)=\left|H_{jk}(\omega)\right|exp\left(i\theta_{jk}(\omega)\right) ; j>k. \tag{7}$$

where:

$$\theta_{jk}(\omega)=tan^{-1}\left(\frac{Im\left[H_{jk}(\omega)\right]}{Re\left[H_{jk}(\omega)\right]}\right) \tag{8}$$

Using eqns (6) and (7) the stationary stochastic vector process $g_j(t)$; $j,k=1,2,\ldots,n$, can be simulated by the following series as $N\rightarrow\infty$ [6, 8]

$$g_j(t)=2\sum_{m=1}^{n}\sum_{l=1}^{N}\left|H_{jm}(\omega)\right|\sqrt{\Delta\omega}cos\left(\omega_l-\theta_{jm}(\omega_l)+\phi_{ml}\right) \tag{9}$$

where:

$$\omega_l=l\Delta\omega ; l=1,2,\ldots,N \tag{10}$$

$$\Delta\omega=\frac{\omega_u}{N} \tag{11}$$

N represents the number of the frequency step $\Delta\omega$ needed to reach the upper cut-off frequency ω_u.

The $\{\phi_{ml}\}$; $m=1,2,\ldots,n$; $l=1,2,\ldots,N$ appearing in eqn (9) are n sequences of independent random phase angles distributed uniformly over the interval $[0,2\pi]$.

4 NUMERICAL RESULTS AND DISCUSSION

4.1 Finite element model of railway bridge

In this paper, we considered a linear dynamic analysis. A finite element model in 3D was created using a finite element code (see Fig. 4). The bridge, composed of four equal spans, has a total length of 160m. The pile heights are 11.9 m, 17.4 m and 12.9 m respectively. The superstructure of the bridge is connected to the piers by rigid elements (rigid link elements). The deck is supported by four beams of metal frame PRS2300. The deck and the piers are

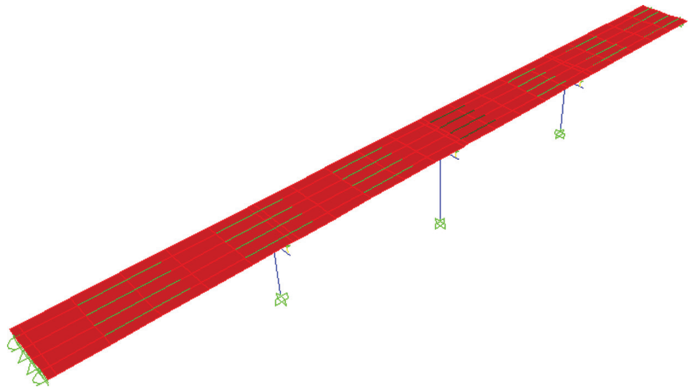

Figure 4: Finite element model of bridge.

assumed to have elastic behavior. The bridge piers are modelled by beam elements at two nodes (Beam element). The bearing devices are modelled in link elements. The conditions of support of the two ends of the bridge are modelled according to the details of fixing the beams provided by the execution plans. The damping ratio of the structure is assumed to be 5%.

4.2 Modal analysis

The first three periods and frequency of the railway bridge are given in Table 2. Figures 5–7 show the shape of the Eigen modes of vibration.

Table 2: Parameters of the three first Eigen modes of vibration.

	Mode 1	Mode 2	Mode 3
Period (s)	0.90561	0.89320	0.73683
Frequency (Hz)	1.10423	1.11957	1.35716

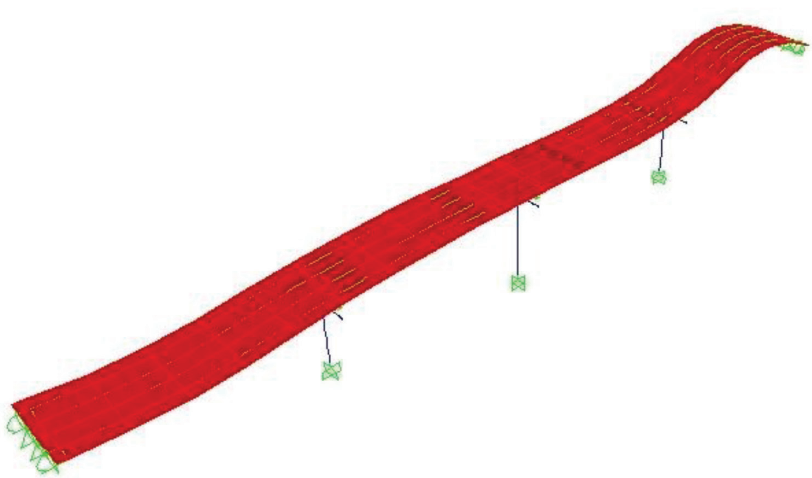

Figure 5: Mode 1: T = 0.90561 s.

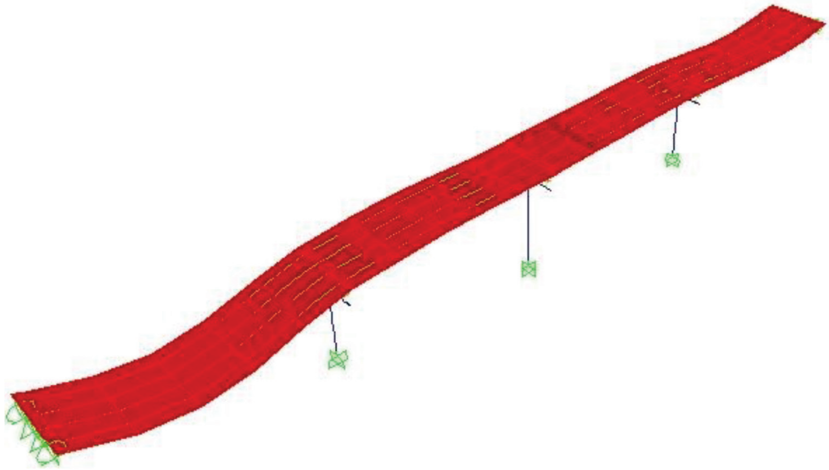

Figure 6: Mode 2: T = 0.89320 s.

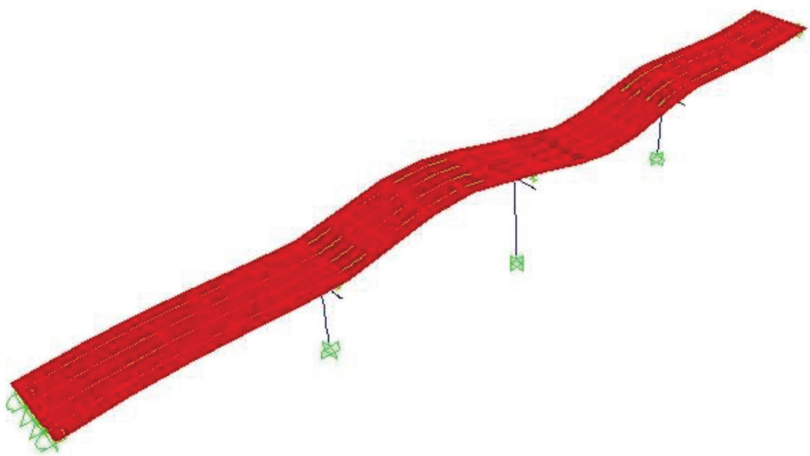

Figure 7: Mode 3: T = 0.73683 s.

4.3 Seismic loads generated

Note that the seismic loads are applied as time history of displacements at the bottom of piers. These displacements were generated using the simulation model described above (see Figs 8 and 9).

4.4 Dynamic analysis

To show the impact of the spatial variability of ground motions, taking into account local site conditions, four analyses were performed. The first analysis considers that load is uniform, i.e. that the seismic loading generated for the first bridge support (using the simulation approach described above) is applied to all of the bridge supports by taking into account local

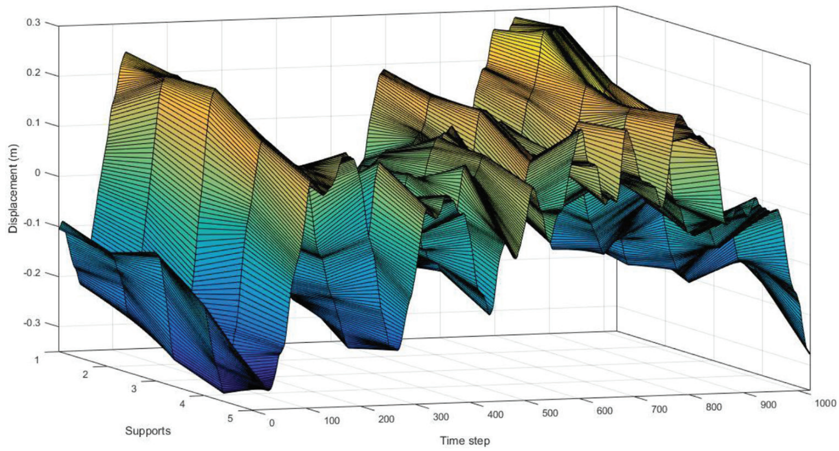

Figure 8: Displacements generated by considering local site effects.

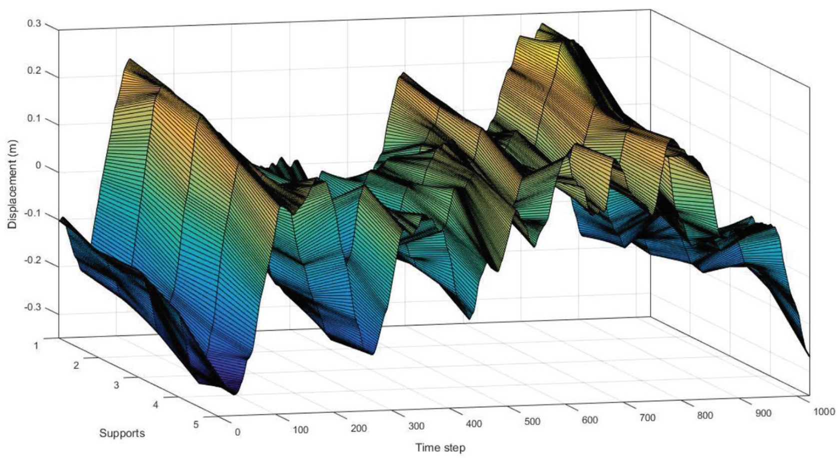

Figure 9: Displacements generated without considering local site effects.

site effects (denoted UNIF-WSE). The second analysis is performed in the same way of the first but neglecting local site effects (denoted UNIF-WOSE).

In the third analysis, each support has its own seismic loading (using the simulation approach) by considering local site effects (denoted SVGM-WSE). The last analysis is carried out in the same way as the third but neglecting local site effects (denoted SVGM-WOSE). The generated seismic loads are defined as time history displacements applied at the piers bottoms.

The results of the structural dynamic analysis, subjected to the four cases of excitations, are compared in terms of bending moment and shear force in piers. The maximum values of the bending moments and shear force obtained at each pier are illustrated in Figs 8 and 9.

We observe that the SVGM-WSE analysis provides higher internal forces than those produced by UNIF-WSE analysis and this is for the entire piers (see Fig. 10).

For these two analyses which take into account site effect, the decrease of bending moments vary between 4% for the pier P1 and 22% for the pier P3.

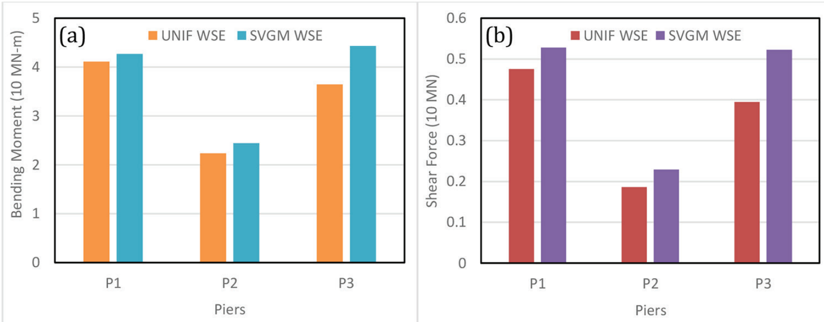

Figure 10: Dynamic analysis considering local site effects (a) Maximum bending moment. (b) Maximum shear force.

Figure 11 shows that bending moments outcome from SVGM-WOSE analyses are higher than those of UNIF-WOSE analysis with 3% for pier 1 and 17% for pier 3. Whereas for pier P2, there is a decrease of 6% in the bending moment. Noting that these analyses neglect the site effect. It is important to note that SVGM-WSE and SVGM-WOSE analyses caused seismic demand increase. These observations are consistent with previous studies results (Monti *et al*., 1996) [8].

Results of seismic analysis of a bridge under variable seismic load, which take into account the site effect (SVGM-WSE), are higher than those produced from the analysis neglecting the site effect (SVGM-WOSE). Bending moments increase with 4% for pier P1 and 20% for pier P2. Shear forces values show an increase which vary between 4% for pier P1 and 18% for the pier P2 (see Fig. 12).

Note that site local condition variation leads to an increase in seismic loading especially for the piers, whereas the coherence model gives rise to pseudo-static displacements.

A seismic loading realistic representation must take into account these two parameters; coherency loss and site effect. Neglecting the site effect, case of several studies, can leads to an under estimation of internal forces.

The results presented in the case of variable seismic loading taking into account site effect correspond to foundation soil parameters (fixed above). In the case where soil parameters are divergent between bridge supports, an increase in the amplification factor is possible. Hence, the local site effect can lead to an important seismic demand.

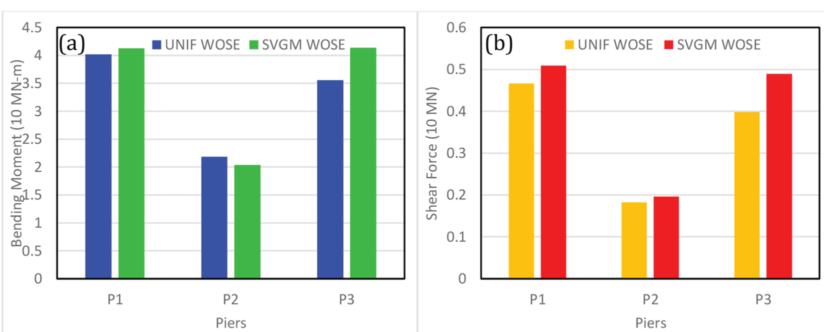

Figure 11: Dynamic analysis neglecting local site effects. (a) Maximum bending moment. (b) Maximum shear force.

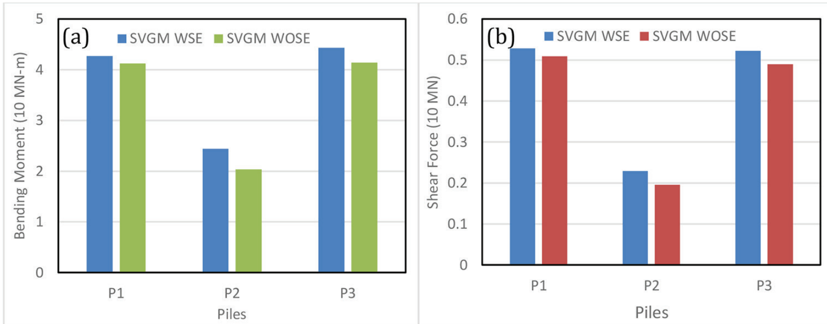

Figure 12: Comparison between the internal forces resulting from SVGM-WSE and SVGM-WOSE. (a) Maximum bending moment. (b) Maximum shear force.

5 CONCLUSION

A study was carried out to evaluate the impact of a spatial variability of earthquake ground motions, taking into account the local conditions of the soil foundation on the dynamic behavior of a railway bridge. A seismic simulation model has been developed to take account of local site effect.

Four loading cases are considered in this study. Two cases of spatial variability of ground motions, the first considers a coherency loss model the site effect. The second assumes that the spatial variability ground motion is defined only by a coherency loss function. Two other analyses under uniform seismic loading are carried out. The seismic loading was applied in the form of time history of displacements imposed on the base of each pier.

Results of this work show that the dynamic analysis under spatial variable seismic loading taking into account the site effect leads to an increase of the seismic demand. A dynamic analysis under spatial variability ground motions neglecting the site effect may lead to an underestimation of the seismic demand of the bridge.

The soil parameters of the site can generate an amplification of the seismic excitation while the coherency loss model leads to pseudo-static motions. Thus, a realistic representation of seismic loading must take into account these two effects.

REFERENCES

[1] Deodatis, G., Non-stationary stochastic vector processes: seismic ground motion applications. *Probabilistic Engineering Mechanics*, **11**, pp. 149–168, 1996. https://doi.org/10.1016/0266-8920(96)00007-0

[2] Der Kiureghian A., A coherency model for spatially varying ground motions. *Earthquake Engineering and Structural Dynamics*, **25**(1), pp. 99–111, 1996. https://doi.org/10.1002/(sici)1096-9845(199601)25:1<99::aid-eqe540>3.3.co;2-3

[3] Kaiming, B., *Effects of ground motion spatial variations* (*PHD thesis*). University of western Australia, Crawley, 2011.

[4] Konakli, K. & Der Kiureghian, A., Simulation of spatially varying ground motions including incoherence, wave, passage and differential site response effects. *Earthquake Engineering & Structural Dynamics*, **41**(3), pp. 495–513, 2012. https://doi.org/10.1002/eqe.1141

[5] Zerva, A., *Spatial Variation of Seismic Ground Motions: Modeling and Engineering Applications*, CRC Press, Group, Taylor & Francis, 2009.

[6] Benmansour, N., Djafour, M., Bekkouche, A., Zendagui, D. & Benyacoub, A., Seismic response evaluation of bridges under differential ground motion: a comparison with the new Algerian provisions. *European Journal of Environmental and Civil Engineering*, **16**(7), pp. 863–881, 2012.
https://doi.org/10.1080/19648189.2012.681951

[7] Benmansour, N., *Étude du comportement dynamique des barrages voûtes face au mouvement sismique différentiel* (Master Thesis). University of Tlemcen, Algeria, 2004.

[8] Benmansour, N., *Effet de la variabilite spatiale du mouvement sismique sur le comportement dynamique des ponts* (Doctoral Thesis). University of Tlemcen, Algeria, 2013.

[9] Kaiming, B. & Hong, H., Modelling and simulation of spatially varying earthquake ground motions at sites with varying conditions. *Probabilistic Engineering Mechanics*, **29**, pp. 92–104, 2012.
https://doi.org/10.1016/j.probengmech.2011.09.002

[10] Djafour, M., Meddane, N., Derbal, R., Megnounif, A., Zendagui, D. & Bekkouche, A., *Response of a gravity arch dam to spatially varying earthquake ground motion.* 8th National Conference on Earthquake Engineering, California, 2006.

[11] Derbal, R., *Analyse dynamique de barrages poids - voûtes sous chargement sismique différentiel* (Master thesis). University Abou Bakr Belkaid, Tlemcen, Algeria, 2005.

[12] Djafour, M., Meddane, N., Derbal, R., Zendagui, D. & Bekkouche, A., Étude du comportement dynamique d'un barrage poids-voûte face au mouvement sismique différentiel. 18ème Congrès Français de Mécanique, 27–31 août 2007.

[13] Zendagui, D., Berrah, M.K. & Kasusel, E., Stochastic deamplification of spatially varying seismic. *Soil Dynamics and Earthquake Engineering*, **1**, pp. 409–421, 1999.
https://doi.org/10.1016/s0267-7261(99)00015-9

[14] Dumanoglu, A.A. & Soyluk, K.A., Stochastic analysis of long span structures subjected to spatially varying ground motions including the site-response effect. *Engineering Structures*, **25**(10), pp. 1301–1310, 2003.
https://doi.org/10.1016/s0141-0296(03)00080-4

[15] Harichandran, R. & Vanmarcke, E., Stochastic variation of earthquake ground motion in space and time. *Journal of Engineering Mechanics*, *ASCE*, **112**, pp. 154–174, 1986.
https://doi.org/10.1061/(asce)0733-9399(1986)112:2(154)

[16] Chen, M.T. & Harichandran, R.S., Response of an earth dam to spatially varying earthquake ground motion. *Journal of Engineering Mechanics ASCE*, **127**, pp. 932–939, 2001
https://doi.org/10.1061/(asce)0733-9399(2001)127:9(932)