International Journal of Steel Structures 17(2): 501-513 (2017)
DOI 10.1007/s13296-017-6010-z
ISSN 1598-2351 (Print)
ISSN 2093-6311 (Online)

International Journal of
STEEL
STRUCTURES
www.springer.com/journal/13296

Wave-Passage Effect on the Seismic Response of Suspension Bridges Considering Local Soil Conditions

Süleyman Adanur[1], Ahmet Can Altunışık[1,*], Hasan Basri Başağa[1], Kurtuluş Soyluk[2], and A. Aydın Dumanoğlu[3]

[1]*Department of Civil Engineering, Karadeniz Technical University, Trabzon, Turkey*
[2]*Department of Civil Engineering, Gazi University, Ankara, Turkey*
[3]*Emiretus Prof., Department of Civil Engineering, Canik Baþarý University, Samsun, Turkey*

Abstract

In this study, a comprehensive investigation of the stochastic analysis of a suspension bridge subjected to spatially varying ground motions is carried out for variable local soil cases and wave velocities. Bosphorus Suspension Bridge built in Turkey and connects Europe to Asia in Istanbul is selected as a numerical example. The spatial variability of the ground motion is considered with the incoherence, wave-passage and site-response effects. The incoherence effect is examined by taking into account Harichandran and Vanmarcke model, the site-response effect is outlined by using firm, medium and soft soil types, and the wave-passage effect is investigated by using 1000-2000, 500-1000, and 300-500 m/s wave velocities for the firm, medium and soft soils, respectively. Mean of maximum response values obtained from the spatially varying ground motions are compared with those of the specialized cases of the ground motion model. At the end of the study, it is seen that total displacements are dominated by dynamic component. The response values obtained for SMFF soil condition are generally the largest. When the varying local soil condition is considered, the variation of relative contributions of response components to the total response values for varying wave velocity cases is insignificant. Also, the variation of the wave velocity has important effect on the deck and towers total response values as compared with those of the constantly travelling wave velocity case. It is concluded that the site-response effect of ground motion on the response of suspension bridges is more important than that of the wave-passage, and the variation of the wave velocities depending on the local soil conditions, has important effects on the dynamic behavior of suspension bridge.

Keywords: suspension bridge, stochastic response, spatially varying ground motion, incoherence effect, wave-passage effect, site-response effect

1. Introduction

The significance of the spatial variation effects of earthquake ground motions on the dynamic response of both long and short span bridges and bridge type structures have been recognized by many researches. Abdel-Ghaffar and Rubin (1983) investigated the effects of the multiple-support seismic excitations on suspension bridges. Abdel-Ghaffar and Stringfellow (1984) performed the effect of the wave propagation on the seismic response of suspension bridges. Dumanoglu and Severn (1989) carried out the seismic response of modern suspension bridges to asynchronous ground motions in the vertical, longitudinal and lateral directions. Hyun *et al.* (1992) studied the nonstationary response analysis of suspension bridges for multiple support excitations. Der Kiureghian and Neuenhofer (1991) performed the simplified bridge models and a suspension bridge model subjected to the spatially varying earthquake motions. Rassem *et al.* (1996) investigated the response of a long span suspension bridge to spatially varying ground motion due to the topographic effects. Zembaty and Rutenberg (1998) investigated on the sensitivity of bridge seismic response with local soil amplification. Wang *et al.* (1999) performed the geological variability effect and spatial variation produced by propagation and coherence loss of seismic ground motion on the response of long span suspension bridges. Allam and Datta (2000) studied seismic behaviour of cable-stayed bridges under multi-component random ground motion. Dumanoglu and Soyluk (2003) performed the stochastic response analyses of cable-stayed bridges subjected to spatially varying ground motions. Lin *et al.*

Received February 19, 2016; accepted October 18, 2016;

---

*Corresponding author
E-mail: ahmetcan8284@hotmail.com

(2004) studied the seismic spatial effects for long-span bridges using the pseudo excitation method. Lupoi *et al.* (2005) carried out the seismic design of bridges accounting for spatial variability of ground motion. Lou and Zerva (2005) performed the effects of spatially variable ground motions on the seismic response of a skewed, multi-span, RC highway bridge. Zhang *et al.* (2005) studied the wave passage effect of seismic ground motions on the response of multiply supported structures. Ates *et al.* (2005) investigated the stochastic response of seismically isolated highway bridges with friction pendulum systems to spatially varying earthquake ground motions. In these studies underlined the significance of the spatially varying ground motions between the support points. Zhang *et al.* (2009) presented a study about the random vibration analysis of long-span structures subjected to spatially varying ground motions. Kuyumcu and Ates (2012) determined the soil-structure-foundation effects on stochastic response analysis of cable-stayed bridges. Soyluk and Sıcacık (2012) carried out the soil-structure interaction analysis of cable-stayed bridges for spatially varying ground motion components. Falsone and Settineri (2013) presented the exact stochastic solution of beams subjected to delta correlated loads. Shrestha *et al.* (2014) investigated the effectiveness of using rubber bumper and restrainer on mitigating pounding and unseating damage of bridge structures subjected to spatially varying ground motions. Experimental investigation of inelastic bridge response under spatially varying excitations with pounding was evaluated by Li and Chouw (2014). Bai *et al.* (2015) attained the stochastic elastic wave behaviour of angled beams. Fang *et al.* (2015) conducted the time variant structural fuzzy reliability analysis under stochastic loads applied several times. Beside these studies, some up-to-date articles can be available from the literature about the stochastic analyses, spatially varying ground motion effect, local site effect, and wavelet-based evolutionary response of different type of structures (Basu and Gupta, 2000; Chakraborty and Basu, 2008; Dinh and Basu, 2012; Konakli and Der Kiureghian, 2012; Jia *et al.*, 2013; Dinh *et al.*, 2014; Adanur *et al.*, 2016a, 2016b; Hacıefendioğlu 2017).

This paper presents a study of the wave-passage effect on the stochastic response of suspension bridges subjected to spatially varying ground motions including the site-response effect. The main objective of this paper is to investigate the importance of the wave-passage effect as well as site-response effect. For this purpose the stochastic analysis of a suspension bridge subjected to spatially varying ground motion by the incoherency, wave-passage and site-response effects is investigated. The incoherence effect is examined by taking into account Harichandran and Vanmarcke (1986) model, the site-response effect is outlined by using firm, medium and soft soil types proposed by Der Kiureghian and Neuenhofer (1991) and the wave-passage effect is investigated by using 1000-2000, 500-1000, and 300-500 m/s wave velocities for the firm, medium and soft soil types, respectively. Mean of maximum response values obtained from the spatially varying ground motions are compared with those of the specialised cases of the ground motion model. Relative contributions of the pseudo-static, dynamic and covariance components to the total response are also presented.

2. Formulation

2.1. Random vibration theory for spatially varying ground motion

In the random vibration theory, the variance of the ith total response component is expressed as (Harichandran *et al.*, 1996)

$$\sigma_{z_i}^2 = \sigma_{z_i}^{2qs} + \sigma_{z_i}^{2d} + 2Cov(z_i^{qs}, z_i^d) \tag{1}$$

where, $\sigma_{z_i}^{2qs}$ and $\sigma_{z_i}^{2d}$ are the variances of pseudo-static and dynamic response components, respectively and $Cov(z_i^{qs}, z_i^d)$ is the covariance between the pseudo-static and dynamic components and can be written as

$$\sigma_{z_i}^{2qs} = \sum_{l=1}^{r}\sum_{m=1}^{r} A_{il}A_{im}\int_{-\infty}^{\infty}\frac{1}{\omega^4}S_{\ddot{v}_{gl}\ddot{v}_{gm}}(\omega)d\omega \tag{2}$$

$$\sigma_{z_i}^{2d} = \sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{r}\sum_{m=1}^{r} \psi_{ij}\psi_{ik}\Gamma_{lj}\Gamma_{mk}\int_{-\infty}^{\infty}H_j(-\omega)H_k(\omega)S_{\ddot{v}_{gl}\ddot{v}_{gm}}(\omega)d\omega \tag{3}$$

$$Cov(z_i^{qs}, z_i^d) = -\sum_{j=1}^{n}\sum_{l=1}^{r}\sum_{m=1}^{r} \psi_{ij}A_{il}\Gamma_{mj}\int_{-\infty}^{\infty}\frac{1}{\omega^2}H_j(\omega)S_{\ddot{v}_{gl}\ddot{v}_{gm}}(\omega)d\omega \tag{4}$$

where ω is the circular frequency, r is the number of support degrees of freedom where the ground motion is applied, n is the number of the modes used in the analysis, A_{il} and A_{im} are the static displacement components due to unit support motions, $S_{\ddot{v}_{gl}\ddot{v}_{gm}}(\omega)$ is the cross-power spectral density function of accelerations between supports l and m, G is the modal participation factor, y is the eigenvectors, $H(w)$ is the frequency response function.

2.2. Spatially varying ground motion model

The cross-power spectral density function of the accelerations $\ddot{v}_{g_l}$ and $\ddot{v}_{g_m}$ at the support points l and m is expressed as (Der Kiureghian 1996),

$$S_{\ddot{v}_{gl}\ddot{v}_{gm}}(\omega) = \gamma_{lm}(\omega)\sqrt{S_{\ddot{v}_{gl}\ddot{v}_{gl}}(\omega)S_{\ddot{v}_{gm}\ddot{v}_{gm}}(\omega)} \tag{5}$$

where $\gamma_{lm}(\omega)$ is the coherency function describing the variability of the ground acceleration processes for support degrees of freedom l and m, $S_{\ddot{v}_{gl}\ddot{v}_{gl}}(\omega)$ and $S_{\ddot{v}_{gm}\ddot{v}_{gm}}(\omega)$ are the auto-power spectral densities of the accelerations $\ddot{v}_{g_l}$ and $\ddot{v}_{g_m}$ at the support points l and m.

Spatial variability of the ground motion is characterised with the coherency function in frequency domain. This function is dimensionless and complex valued. For the coherency function, the following model proposed by Der Kiureghian (1996) is used

$$\begin{aligned}\gamma_{lm}(\omega) &= \gamma_{lm}(\omega)^{i}\gamma_{lm}(\omega)^{w}\gamma_{lm}(\omega)^{s}\\ &= \gamma_{lm}(\omega)^{i}\exp[i(\theta_{lm}(\omega)^{w}+\theta_{lm}(\omega)^{s})]\end{aligned} \tag{6}$$

where $\gamma_{lm}(\omega)^{i}$ characterises the real valued incoherence effect, $\gamma_{lm}(\omega)^{w}$ indicates the complex valued wave-passage effect and $\gamma_{lm}(\omega)^{s}$ defines the complex valued site-response effect.

For the incoherence effect, resulting from reflections and refractions of seismic waves through the soil during their propagation, the widely used model proposed by Harichandran and Vanmarcke (1986) is considered. This model is based on the analysis of recordings made by the SMART-1 seismograph array in Lotung, Taiwan and defined as

$$\begin{aligned}\gamma_{lm}(\omega)^{i} &= A\exp\left[-\frac{2d_{lm}}{\alpha\theta(\omega)}(1-A+\alpha A)\right]\\ &+(1-A)\exp\left[\left(-\frac{2d_{lm}}{\theta(\omega)}\right)(1-A+\alpha A)\right]\end{aligned} \tag{7}$$

$$\theta(\omega) = k\left[1+\left(\frac{\omega}{2\pi f_0}\right)^{b}\right]^{-\frac{1}{2}} \tag{8}$$

where d_{lm} is the distance between support points l and m. A, a, k, f_0 and b are model parameters and in this study the values obtained by Harichandran *et al.* (1996) are used (A=0.636, a=0.0186, k=31200, f_0=1.51 Hz and b=2.95).

The wave-passage effect resulting from the difference in the arrival times of waves at support points is defined as (Der Kiureghian 1996)

$$\theta_{lm}(\omega)^{w} = -\frac{w d^{L}_{lm}}{v_{app}} \tag{9}$$

where v_{app} is the apparent wave velocity and d^{L}_{lm} is the projection of d_{lm} on the ground surface along the direction of propagation of seismic waves. The apparent wave velocities employed in this study are v_{app}=300-500 m/s for soft soil, v_{app}=500-1000 m/s for medium soil and v_{app} =1000-2000 m/s for firm soil.

The site-response effect resulting from the differences in local soil conditions at the support points is obtained as (Der Kiureghian 1996)

$$\theta_{lm}(\omega)^{s} = \tan^{-1}\frac{Im[H_l(\omega)H_m(-\omega)]}{Re[H_l(\omega)H_m(-\omega)]} \tag{10}$$

where $H_l(\omega)$ is the local soil frequency response function representing the filtration through soil layers.

The auto-power spectral density function of the ground acceleration ($\ddot{v}_{g_l}$) characterising the earthquake process is assumed to be of the following form modified by Clough and Penzien (1983).

$$S_{\ddot{v}_{gl}\ddot{v}_{gl}}(\omega) = S_0\left[\frac{\omega_l^4+4\xi_l^2\omega_l^2\omega^2}{(\omega_l^2-\omega^2)^2+4\xi_l^2\omega_l^2\omega^2}\right]\left[\frac{\omega^4}{(\omega_f^2-\omega^2)^2+4\xi_f^2\omega_f^2\omega^2}\right] \tag{11}$$

where S_0 is the amplitude of the white-noise bedrock acceleration, w_l and x_l are the resonant frequency and damping ratio of the first filters, w_f and x_f are the resonant frequency and damping ratio of the second filters, respectively.

In this study, firm (F), medium (M) and soft (S) soil types proposed by Der Kiureghian and Neuenhofer (1991) are used. The filter parameters for these soil types are utilized as presented in Table 1. The amplitude of the

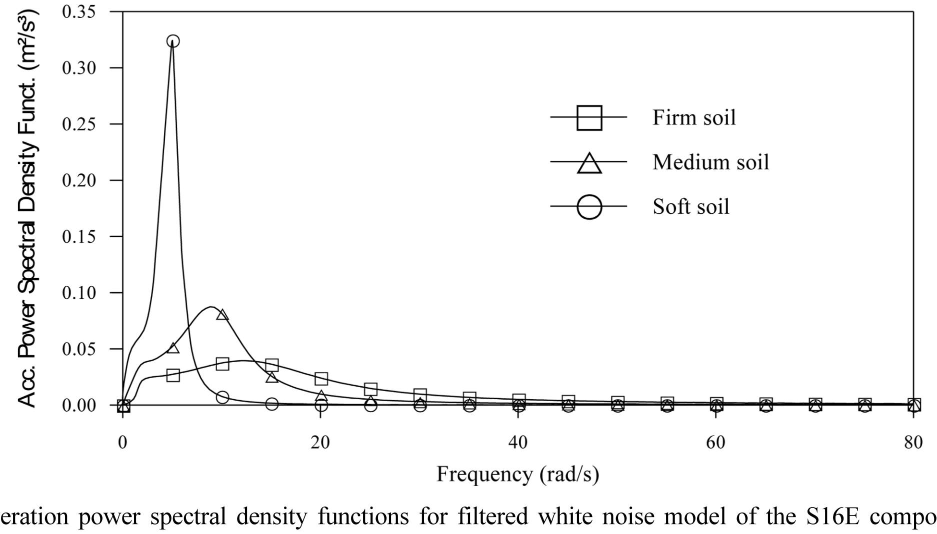


Figure 1. Acceleration power spectral density functions for filtered white noise model of the S16E component of Pacoima Dam record of 1971 San Fernando earthquake.

white-noise bedrock acceleration (S_0) is obtained for each soil type by equating the variance of the ground acceleration to the variance of S16E component of Pacoima Dam acceleration records of 1971 San Fernando earthquake. The calculated values of the intensity parameter for each soil type are S_0 (firm)=0.021338 m^2/s^3, S_0 (medium)= 0.031707 m^2/s^3, S_0 (soft)=0.044515 m^2/s^3. Acceleration power spectral density function for each soil type is presented in Fig. 1.

3. Application

In this study, as an example the Bosporus Suspension Bridge built in Turkey and connects Europe to Asia in Istanbul is selected. The bridge has flexible steel towers of 165 m high, inclined hangers and a steel box-deck of 1074 m main span, with side spans of 231 and 255 m on the European and Asian sides, respectively, supported on piers. The horizontal distance between the cables is 28 m and the roadway is 21 m wide, accommodating three lanes each way. The roadway at the mid-span of the bridge is approximately 64 m above the see level.

The finite element model of the suspension bridge is constituted in SVEM software (Dumanoğlu and Soyluk, 2002). This software can be used for stochastics dynamic analyses of engineering structures considering spatially spatially varying ground motions. Two-dimensional finite element model of Bosporus Suspension Bridge with 202 nodal points, 199 beam elements and 118 truss elements is considered for the analysis. While the deck, towers and cables are represented by beam elements, the hungers are represented by truss elements. The selected finite element model of the bridge is represented by 475 degrees of freedom. The spatially varying ground motion is applied

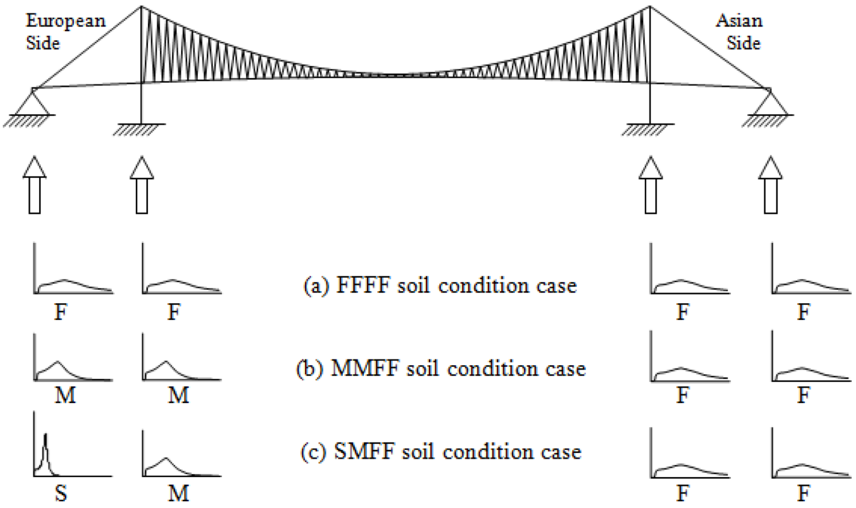
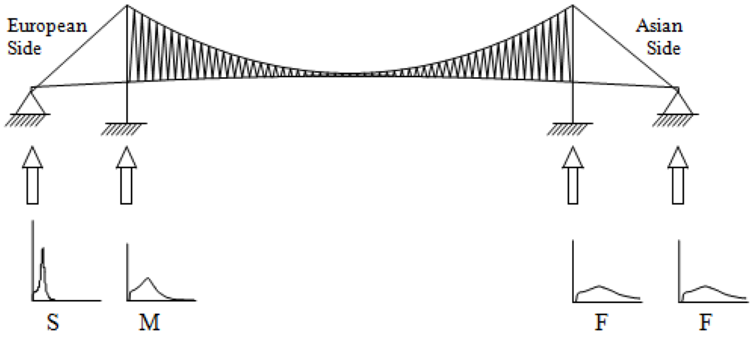
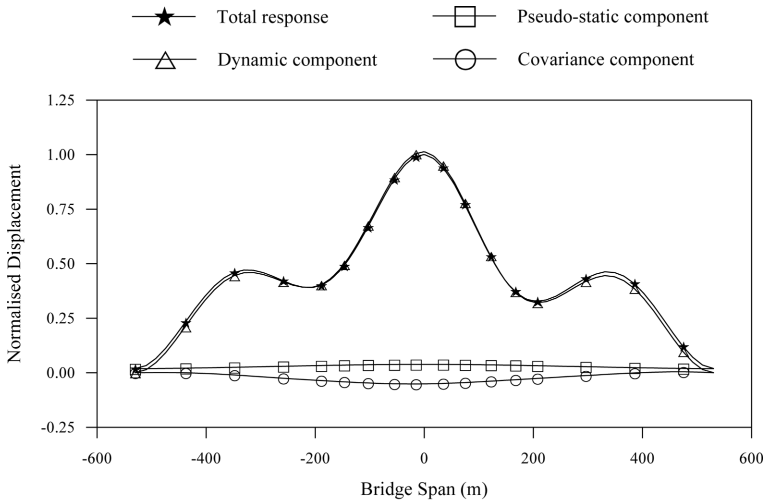


Figure 2. Suspension bridge subjected to spatially varying ground motions in the vertical direction for the various soil condition cases.

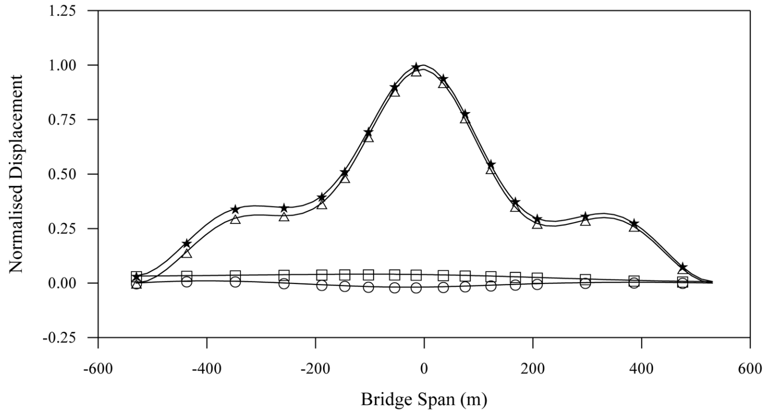


Case 1:	v_{app}=1000m/s	v_{app}=1000m/s	v_{app}=1000m/s	v_{app}=1000m/s
Case 2:	v_{app}=500m/s	v_{app}=1000m/s	v_{app}=2000m/s	v_{app}=2000m/s
Case 3:	v_{app}=400m/s	v_{app}=750m/s	v_{app}=1500m/s	v_{app}=1500m/s
Case 4:	v_{app}=300m/s	v_{app}=500m/s	v_{app}=1000m/s	v_{app}=1000m/s

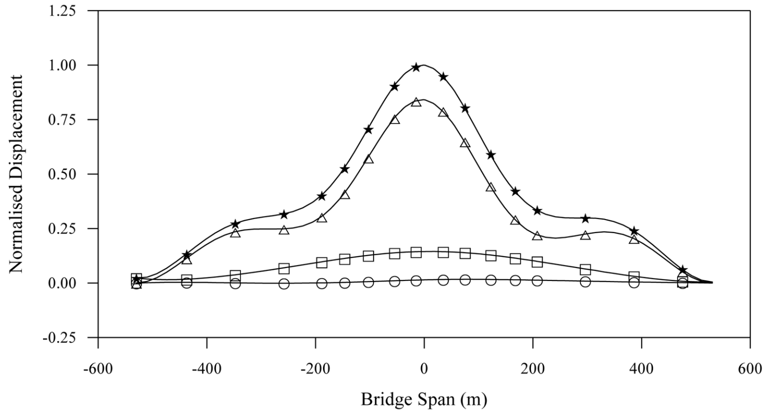
Figure 3. Suspension bridge subjected to spatially varying ground motions in the vertical direction for the various apparent wave velocities.



(a) FFFF soil condition case



(b) MMFF soil condition case

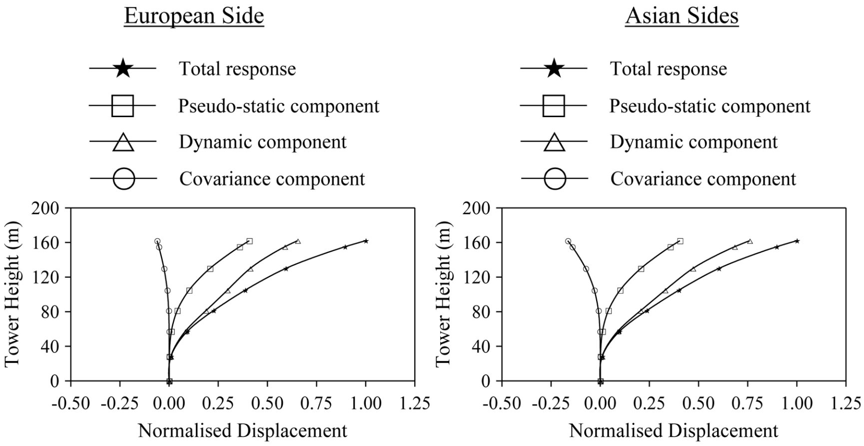


(c) SMFF soil condition case

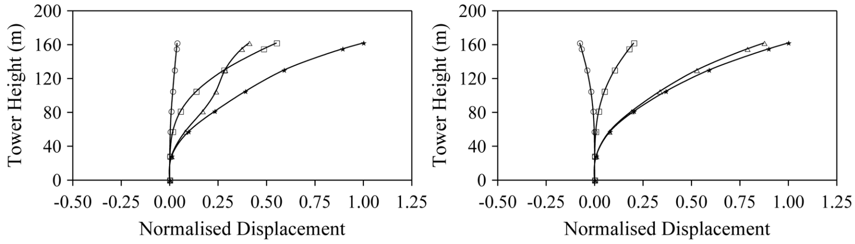
Figure 4. Normalised displacement variances of the deck for various soil condition cases.

to bridge supports in vertical direction.

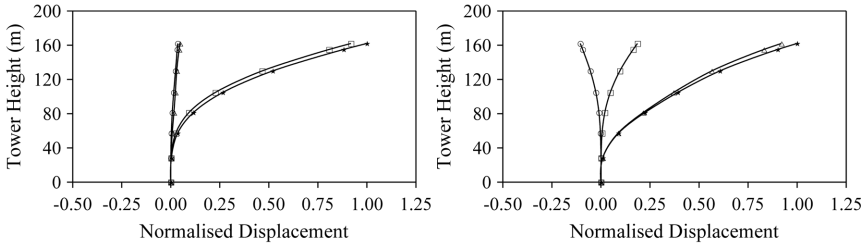
In this paper, stochastic analysis of a suspension bridge subjected to spatially varying ground motions by taking into account the incoherence, wave-passage and site-response effects is performed for variable local soil cases and wave velocities. For this purpose, the following three different soil condition cases are considered for the bridge supports and the four different apparent wave velocity cases are taken into account depending on the local soil condition cases. The suspension bridge subjected to spatially varying ground motions in the vertical direction for the various soil condition cases is shown Fig. 2 and for the various apparent wave velocities is shown in Fig. 3.



(a) FFFF soil condition case



(b) MMFF soil condition case



(c) SMFF soil condition case

Figure 5. Normalised displacement variances of the European and Asian sides tower for various soil condition cases.

Different soil condition cases:

Case A: All the supports are assumed to be founded on soils with firm soil type (FFFF).

Case B: While the supports at the European side are assumed to be founded on medium soil, the supports at the Asian side are assumed to be founded on firm soil type (MMFF).

Case C: The European side anchorage is founded on soft soil, the European side tower pier is founded on medium soil and the other supports of the bridge at the Asian side are founded on firm soil (SMFF).

Different apparent wave velocity cases:

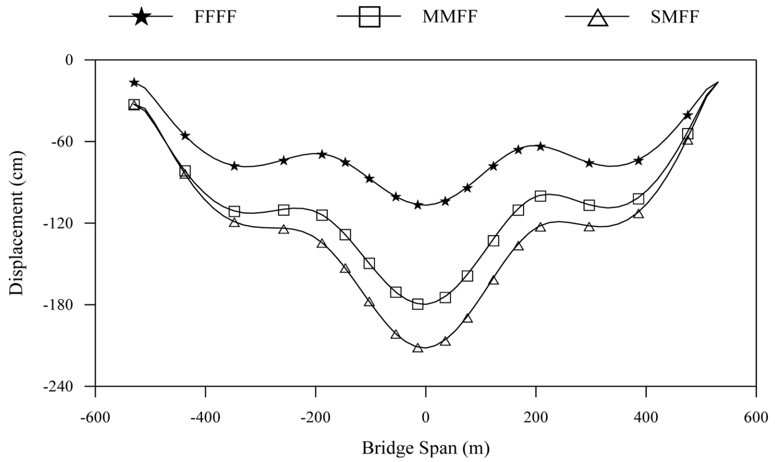
Case 1: v_{app}=1000 m/s for constant wave velocity case

Case 2: v_{app}=500 m/s for soft soil, v_{app}=1000 m/s for medium soil, v_{app}=2000m/s for firm soil

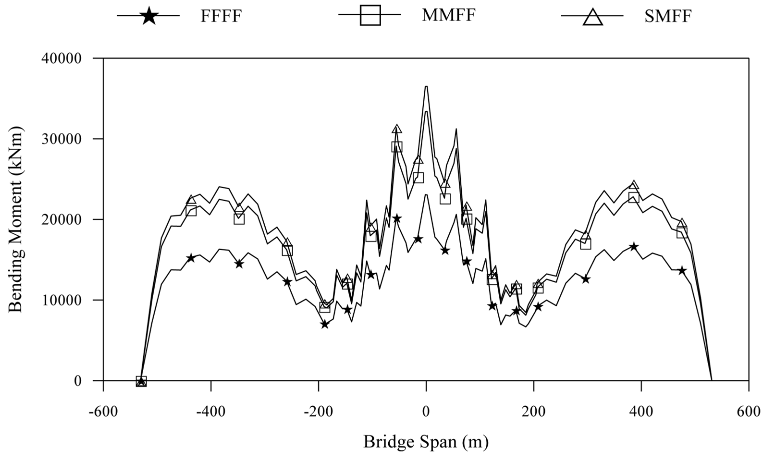
Case 3: v_{app}=400 m/s for soft soil, v_{app}=750 m/s for medium soil, v_{app}=1500m/s for firm soil

Case 4: v_{app}=300 m/s for soft soil, v_{app}=500 m/s for medium soil, v_{app}=1000m/s for firm soil

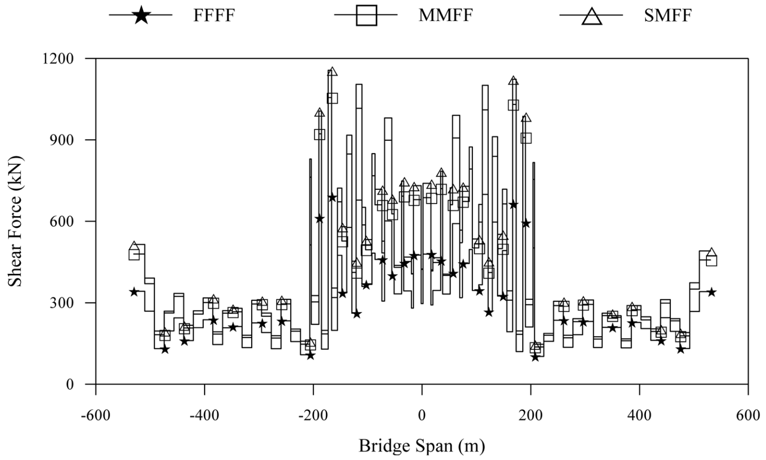
The analysis is obtained for 2.5% damping ratio and for the first 15 modes. The stiffening effects of the cables caused by the dead load are also accounted for in the analysis. The filtered white noise ground motion model modified by Clough and Penzien (1993) is used and applied in the vertical direction as a ground motion model where the spectral density function intensity parameter is determined according to the S16E component of the Pacoima Dam record of the San Fernando Earthquake in 1971. The filtered white noise ground motion model is widely used to stochastic analyses for facilitate the conducted analyses by convert the time domain data and graphics to frequency domain.



(a) Vertical displacements



(b) Bending moments



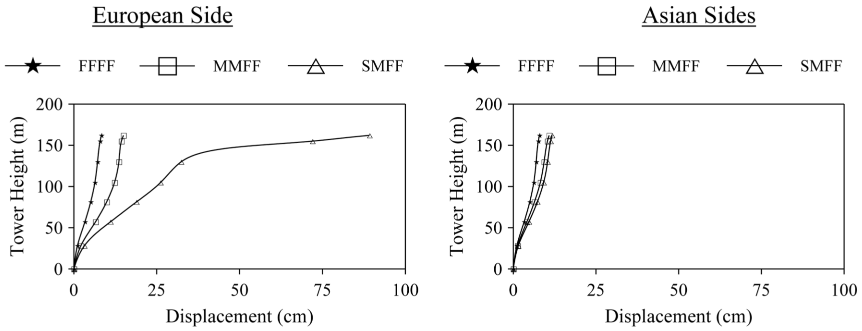
(c) Shear forces

Figure 6. Mean of maximum total response values of the deck for various soil condition cases.

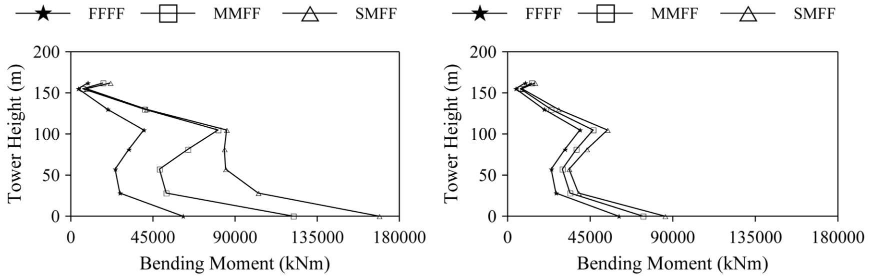
4. Numerical Results

4.1. Comparison of various soil condition cases

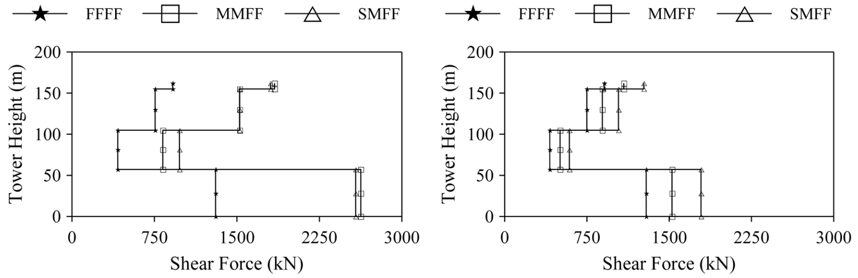
Variance of total response has three components; the pseudo-static component, the dynamic component and the covariance component between the pseudo-static and dynamic components. In this section, contribution of the each component to the total responses of the bridge is investigated. The process of normalisation is performed by dividing the variance values by the maximum total



(a) Horizontal displacements



(b) Bending moments



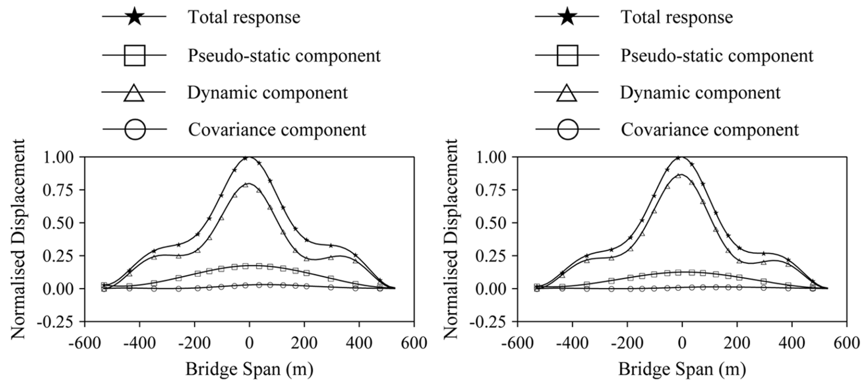
(c) Shear forces

Figure 7. Mean of maximum total response values of European side tower for various soil condition cases (a) Horizontal displacements, (b) Bending moments (c) Shear forces.

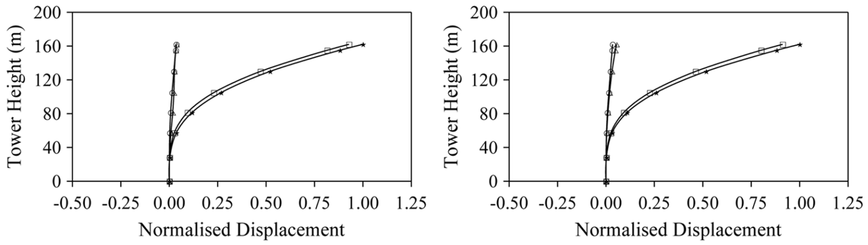
response. The relative contribution of each component to the total vertical displacement along the bridge deck for FFFF, MMFF and SMFF soil condition sets are presented in Fig. 4. It is shown that the total displacements are dominated by the dynamic component for the three soil condition sets. However, the contribution of the dynamic component to the total response decreases and the contribution of the pseudo-static and the covariance components increase while the soil condition changes from firm to soft.

The relative contributions of the response components to the total horizontal tower displacements at the European and Asian sides are shown in Fig. 5 for the three soil condition cases. While the variations obtained for the displacements at the Asian side tower for each soil condition case are similar, the variations obtained for the European side tower are somehow different. At the European side tower top point where maximum total horizontal displacement take place, it can be observed that the dynamic component contribute 65.35, 41.00, 4.66%; the pseudo-static component contribute 40,79, 55.19, 91.86% and the covariance component contribute −6.14, 3.81, 3.48% for FFFF, MMFF, SMFF soil condition cases, respectively. Similarly, at the Asian side tower top point the dynamic component contribute 76.01, 87.50, 92.00%; the pseudo-static component contribute 40.51, 20.23, 18.60% and the covariance component contribute −16.52, −7.73, −10.60% for FFFF, MMFF, SMFF soil condition cases, respectively. At the European side tower, the total displacements are dominated by the dynamic component for FFFF soil condition case whereas the total displacements are dominated by the pseudo-static component for MMFF and SMFF soil condition cases. This is because the European side support soil conditions range from firm to soft and amplify the pseudo-static components. The total response is dominated by the dynamic component at the Asian side tower for each soil condition case.

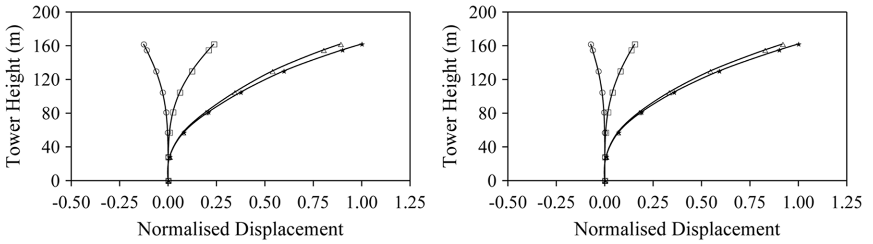
Mean of maximum total response values are carried out for the previously defined soil condition cases defined as



(a) Deck



(b) European side tower



(c) Asian side tower

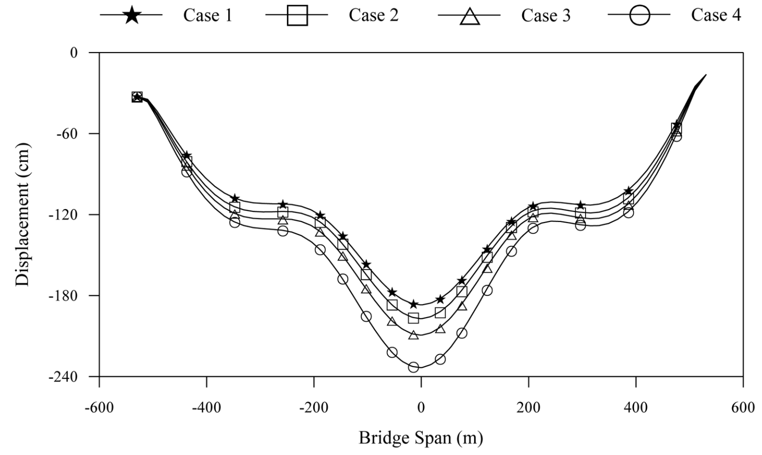
Figure 8. Normalised displacement variances for constant (Case 1) and varying wave velocity case (Case 4).

FFFF, MMFF and SMFF. Mean of maximum total deck vertical displacements, bending moments and shear forces calculated for various soil condition cases are compared in Fig. 6. As can be observed from the figures, while the response values obtained for FFFF soil condition case are the smallest, the response values for SMFF soil condition case are the largest. The total displacements and bending moments at the middle of the deck overestimates the responses by 68.39, 98.42%, and by 44.61, 58.15% for MMFF, SMFF soil condition cases, respectively when compared to the response due to the FFFF soil condition case. At the deck point where maximum shear forces take place it can be observed that the total shear forces overestimates the response by 52.94, 67.48% for MMFF, SMFF soil condition cases, respectively when compared to the response due to the FFFF soil condition case. While the total vertical displacements at the end of the Asian side for the three different soil condition sets are close to each other, the displacements at the end of the European side for the MMFF and SMFF soil condition sets are larger than those of the FFFF soil condition case. This is because of the pseudo-static displacements, depending on the variation of the soil conditions at the European side from firm to soft.

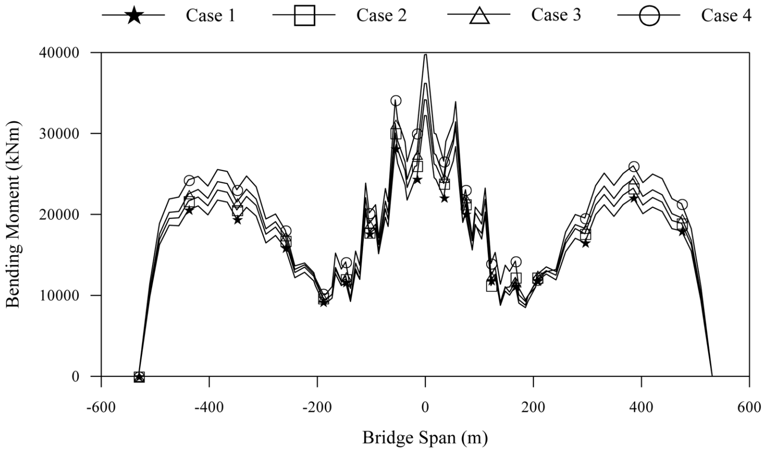
Mean of maximum total horizontal displacements, bending moments and shear forces of the European and Asian side towers obtained for the three different soil condition cases are presented in Fig. 7. It is shown that the response values obtained at the Asian side tower are very smaller than the response values calculated at the tower of the European side where the soil conditions change from firm to soft. It is also shown that the response values obtained for SMFF soil condition case are generally the largest and the more difference between the soil conditions, generally the more response values take place at both towers.

4.2. Comparison of various apparent wave velocity cases

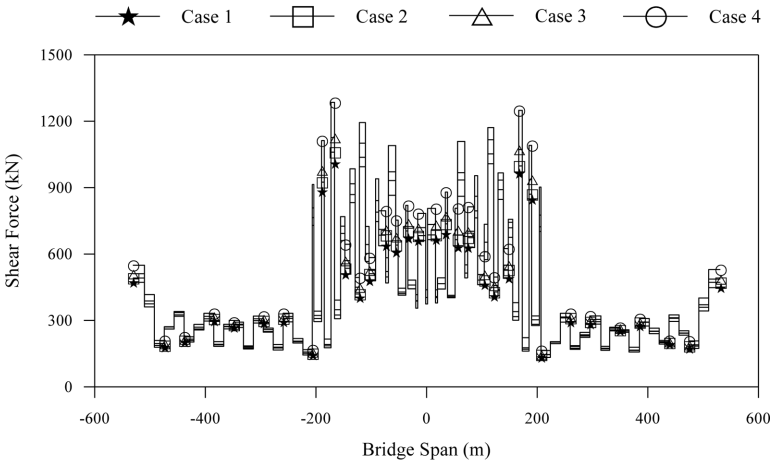
The relative contributions of the pseudo-static, dynamic and covariance components to the total displacement responses at the deck, at the European and Asian side



(a) Vertical displacements



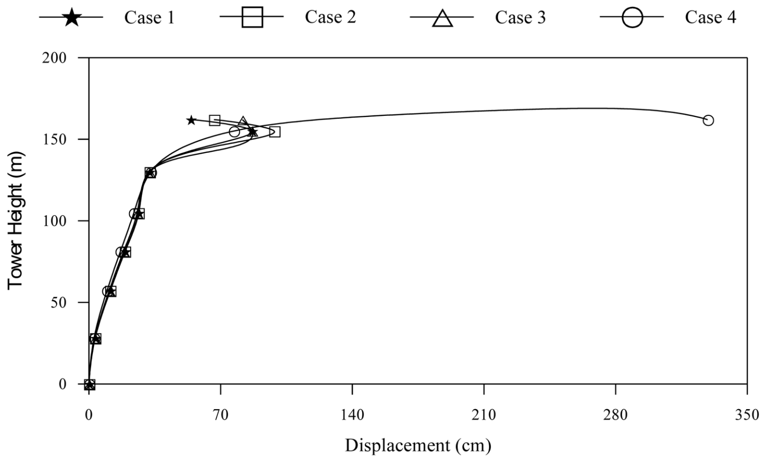
(b) Bending moments



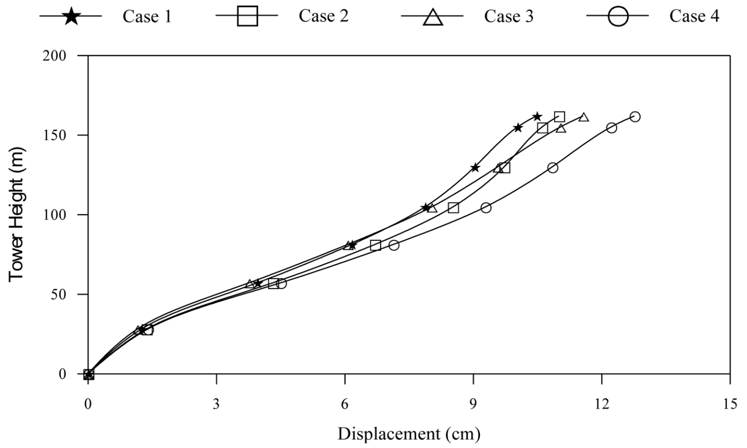
(c) Shear forces

Figure 9. Mean of maximum total response values of the deck under the various apparent wave velocity cases for the SMFF soil condition set.

towers for the constant (Case 1) and varying (Case 4) wave velocity cases are presented in Fig. 8. It can be observed that the variation of the varying wave velocity case is generally consistent with the variation of the constantly case. It is also observed that when the varying local soil condition is considered, the variation of the relative contributions of the response components to the total response values for the varying wave velocity cases



(a) European side tower



(b) Asian side tower

Figure 10. Mean of maximum total horizontal displacements of the European and Asian side towers under the various apparent wave velocity cases for the SMFF soil condition set.

is insignificant.

Mean of maximum total response values of ground motions with variable wave velocities depending on the local soil conditions are compared with those of the constant wave velocity. For this purpose, the previously defined four different apparent wave velocity cases are considered for the SMFF soil condition case. Mean of maximum total response values of the deck and the towers are compared for variable and constantly travelling wave velocity cases in Figs. 9-10.

It is obvious that the total response values will cause larger response values for varying wave velocity cases compared to those of the constantly travelling wave velocity case. It can be also observed that the variation of the wave velocity has important effect on the deck and towers total response values as compared with those of the constantly travelling wave velocity case (Case 1). At the middle of the bridge deck where maximum vertical displacement occur, the displacement value obtained for constantly wave velocity case (Case 1) cause the response by 6, 12, and 25% decrease when compared to the response due to varying wave velocity cases defined as Case 2, Case 3 and Case 4, respectively. The variation obtained for the deck displacements is also similar and valid for the deck bending moments and shear forces.

At the top point of the European side tower where maximum horizontal displacement take place, the displacement values overestimate the response by 23, 51, and 509% obtained for varying wave velocity cases defined as Case 2, Case 3 and Case 4, respectively when compared to the response due to constantly wave velocity case (Case 1). On the other hand, at the top point of the Asian side tower the displacement value obtained for constantly wave velocity case (Case 1) underestimates the response by 5, 10, and 22% when compared to the responses due to varying wave velocity cases defined as Case 2, Case 3 and Case 4, respectively. It is obvious that the ratios of the response values for varying apparent wave velocity cases at the European side tower are larger than those of the Asian side tower. This is because of the decreasing apparent wave-velocity depending on the variation of the soil conditions at the European side from firm to soft. It is also shown that the response values generally increase with decreasing apparent wave velocity.

5. Conclusions

In this paper, the stochastic response of a suspension bridge subjected to spatially varying ground motions is performed for variable local soil and wave velocity cases. The main findings from this study can be categorised as follows:

The variance values are dominated by the dynamic component at the deck and at the Asian side tower. On the other hand, at the European side tower, the total displacements are dominated by the dynamic component for the constant (homogeneous) soil condition case while the pseudo-static component dominates the total displacements for the varying (heterogeneous) soil condition cases. Furthermore, the relative contribution of the pseudo-static component to the total response generally increases by ranging the local soil conditions from firm to soft.

The response values obtained for the varying (heterogeneous) soil condition cases cause larger response values than those of the constant (homogeneous) soil condition case. Also the more difference between the soil conditions, the more response values occur.

The variation of the relative contributions of the pseudo-static, dynamic and covariance components to the total displacement responses for the varying wave velocity case is generally consistent with the variation for the constant wave velocity case. And also the variation of the relative contributions of the response components to the total response values for the varying wave velocity cases is insignificant when the varying local soil condition is considered.

The total response values for varying wave velocity cases are larger than those of the constantly travelling wave velocity case and the response values generally increase with decreasing apparent wave velocity. The variation of the wave velocities depending on the local soil conditions where the bridge supports are constructed has important effects on the dynamic behaviour of the bridge. Also, to be more realistic in calculating the bridge responses, the variability of the ground motions should be considered in the analysis of suspension bridges.

References

Abdel-Ghaffar, A.M and Rubin, L.I (1983), "Vertical seismic behaviour of suspension bridges", *Earthquake Engineering and Structural Dynamics*, 11(1), pp. 1-10.

Abdel-Ghaffar, A.M. and Stringfellow, R.G. (1984), "Response of suspension bridges to travelling earthquake excitations, Part 1: Vertical response, Part 2: Lateral response". *Soil Dynamics and Earthquake Engineering*, 3(2), pp. 62-81.

Adanur, S., Altunışık, A.C., Soyluk, K., Bayraktar, A. and Dumanoğlu, A.A. (2016a), "Multiple-support seismic response of bosporus suspension bridge for various random vibration methods", *Case Studies in Structural Engineering*, 5, pp. 54-67.

Adanur, S., Altunışık, A.C., Soyluk, K., Dumanoðlu, A.A. and Bayraktar, A. (2016b), "Contribution of local site-effect on the seismic response of suspension bridges to spatially varying ground motions", *Earthquakes and Structures*, 10(5), pp. 1233-1251.

Allam, S.M. and Datta, T.K. (2000), "Analysis of cable-stayed bridges under multi-component random ground motion by response spectrum method", *Engineering Structures*, 22, pp. 1367-1377.

Ates, S., Dumanoglu, A.A. and Bayraktar, A. (2005), "Stochastic response of seismically isolated highway bridges with friction pendulum systems to spatially varying earthquake ground motions", *Engineering Structures*, 27(13), pp. 1843-1858.

Bai, C., Ma, H. and Shim, V.P.W. (2015), "Stochastic elastic wave analysis of angled beams", *Structural Engineering and Mechanics*, 56(5), pp. 767-785.

Basu, B. and Gupta, V.K. (2000), "Stochastic seismic response of SDOF systems through wavelets", *Engineering Structures*, 22(12), pp. 1714-1722.

Chakraborty, A. and Basu, B. (2008), "Nonstationary response analysis of long span bridges under spatially varying differential support motions using continuous wavelet transform", *Journal of Engineering Mechanics*, 134(2), pp. 155-162.

Clough, R.W. and Penzien, J. (1993), *Dynamics of Structures*, Second Edition, McGraw Hill, Inc., Singapore.

Der Kiureghian, A. (1996), "A coherency model for spatially varying ground motions", *Earthquake Engineering and Structural Dynamics,* 25(1), pp. 99-111.

Der Kiureghian, A. and Neuenhofer, A. (1991), "A response spectrum method for multiple-support seismic excitations", Report No. UCB/EERC-91/08, Berkeley (CA), Earthquake Engineering Research Center, College of Engineering, University of California.

Dinh, N.V. and Basu, B. (2012), "Zero-pad effects on conditional simulation and application of spatially-varying earthquake motions", *Proc., 6th European Workshop on Structural Health Monitoring*, 3-6 July, Germany.

Dinh, V.N., Basu, B. and Brinkgreve, R.B.J. (2014), "Wavelet-based evolutionary response of multi-span structures including wave-passage and site-response effects", *Journal of Engineering Mechanics*, 140(8), 04014056-1-12.

Dumanoglu, A.A and Soyluk, K. (2002), "SVEM, A stochastic structural analysis program for spatially varying earthquake motions", TDV/KT 023-76, Turkish Earthquake Foundation, Istanbul.

Dumanoglu, A.A and Soyluk, K. (2003), "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.

Dumanoglu, A.A. and Severn, R.T. (1989), "Seismic response of modern suspension bridges to asynchronous longitudinal and lateral ground motion", *Proc. Instn Civ. Engrs*, Part 2, 87, pp. 73-84.

Falsone, G. Settineri, D. (2013), "Exact stochastic solution of beams subjected to delta-correlated loads", *Structural Engineering and Mechanics*, 47(3), pp. 307-329.

Fang, Y., Xiong, J. and Tee, K.F. (2015), "Time-variant structural fuzzy reliability analysis under stochastic loads applied several times", *Structural Engineering and Mechanics*, 56(3), pp. 525-534.

Hacýefendioðlu, K. (2017), Stochastic dynamic response of short-span highway bridges to spatial variation of blasting ground vibration, *Applied Mathematics and Computation*, 292, pp. 194-209.

Hao, H. (1993), "Arch responses to correlated multiple excitations", *Earthquake Engineering and Structural Dynamics,* 22(5), pp. 389-404.

Harichandran, R.S. and Vanmarcke, E.H. (1986), "Stochastic variation of earthquake ground motion in space and time", *Journal of Engineering Mechanics*, 112(2), pp. 154-174.

Harichandran, R.S., Hawwari, A. and Sweiden, B.N. (1996), "Response of long-span bridges to spatially varying ground motion", *Journal of Structural Engineering*, 122(5), pp. 476-484.

Hyun, C.H., Yun, C.B. and Lee, D.G. (1992), "Nonstationary response analysis of suspension bridges for multiple support excitations", *Probabilistic Engineering Mechanics*, 7(1), pp. 27-35.

Jia, H-Y., Zhang, D-Y., Zheng, S-X., Xie, W-C. and Pandey, M.D. (2013), Local site effects on a high-pier railway bridge under tridirectional spatial excitations: Nonstationary stochastic analysis, *Soil Dynamics and Earthquake Engineering*, 52, pp. 55-69.

Konakli, K. and Der Kiureghian, A. (2012), "Simulation of spatially varying ground motions including incoherence, wavepassage and differential siteresponse effects", *Earthquake Engineering and Structural Dynamics*, 41, pp. 495-513.

Kuyumcu, Z. and Ateş, Ş. (2012), "Soil-structure-foundation effects on stochastic response analysis of cable-stayed bridges", *Structural Engineering and Mechanics*, 43(5), pp. 637-655.

Li, B. and Chouw, N. (2014), "Experimental investigation of inelastic bridge response under spatially varying excitations with pounding", *Engineering Structures*, 79(15), pp. 106-116.

Lin, J.H., Zhang, Y.H., Li, Q.S. and Williams, F.W. (2004), "Seismic spatial effects for long-span bridges, using the pseudo excitation method", *Engineering Structures*, 26(9), pp. 1207-1216.

Lou, L. and Zerva, A. (2005), "Effects of spatially variable ground motions on the seismic response of a skewed, multi-span, RC highway bridge", *Soil Dynamics and Earthquake Engineering*, 25(7-10), pp. 729-740.

Lupoi, A., Franchin, P., Pinto, P.E. and Monti, G. (2005), "Seismic design of bridges accounting for spatial variability of ground motion", *Earthquake Engineering and Structural Dynamics,* 34(4-5), pp. 327-348.

Rassem, M., Ghobarah, A. and Heidebrecht, A.C. (1996), "Site effects on the seismic response of a suspension bridge", *Engineering Structures*, 18(5), pp. 363-370.

Shrestha, B., Hao, H. and Bi, K. (2014), "Effectiveness of using rubber bumper and restrainer on mitigating pounding and unseating damage of bridge structures subjected to spatially varying ground motions", *Engineering Structures*, 79(15), pp. 195-210.

Soyluk, K. and Sýcacýk, E.A. (2012), "Soil-structure interaction analysis of cable-stayed bridges for spatially varying ground motion components", *Soil Dynamics and Earthquake Engineering*, 35, pp. 80-90.

Wang, J., Hu, S. and Wei, X. (1999), "Effects of engineering geological condition on response of suspension bridges", *Soil Dynamics and Earthquake Engineering*, 18(4), pp. 297-304.

Zembaty, Z. and Rutenberg, A. (1998), "On the sensitivity of bridge seismic response with local soil amplification", *Earthquake Engineering and Structural Dynamics*, 27, pp. 1095-1099.

Zhang, Y.H., Li, Q.S., Lin, J.H. and Williams, F.W. (2009), "Random vibration analysis of long-span structures subjected to spatially varying ground motions", *Soil Dynamics and Earthquake Engineering*, 29(4), pp. 620-629.

Zhang, Y.H., Lin, J.H., Williams, F.W. and Li, Q.S. (2005), "Wave passage effect of seismic ground motions on the response of multiply supported structures", *Structural Engineering and Mechanics*, 20(6), pp. 655-672.