Structural Engineering and Mechanics, Vol. 43, No. 5 (2012) 637-655
DOI: http://dx.doi.org/10.12989/sem.2012.43.5.637

Soil-structure-foundation effects on stochastic response analysis of cable-stayed bridges

Zeliha Kuyumcu[a] and Sevket Ates*

Department of Civil Engineering, Karadeniz Technical University, Trabzon, 61080, Turkey

(Received January 20, 2012, Revised May 22, 2012, Accepted August 9, 2012)

Abstract. In this study, stochastic responses of a cable-stayed bridge subjected to the spatially varying earthquake ground motion are investigated by the finite element method taking into account soil-structure interaction (SSI) effects. The considered bridge in the analysis is Quincy Bay-view Bridge built on the Mississippi River in between 1983-1987 in Illinois, USA. The bridge is composed of two H-shaped concrete towers, double plane fan type cables and a composite concrete-steel girder deck. In order to determine the stochastic response of the bridge, a two-dimensional lumped masses model is considered. Incoherence, wave-passage and site response effects are taken into account for the spatially varying earthquake ground motion. Depending on variation in the earthquake motion, the response values of the cable-stayed bridge supported on firm, medium and soft foundation soil are obtained, separately. The effects of SSI on the stochastic response of the cable-stayed bridge are also investigated including foundation as a rigidly capped vertical pile groups. In this approach, piles closely grouped together beneath the towers are viewed as a single equivalent upright beam. The soil-pile interaction is linearly idealized as an upright beam on Winkler foundation model which is commonly used to study the response of single piles. A sufficient number of springs on the beam should be used along the length of the piles. The springs near the surface are usually the most important to characterize the response of the piles surrounded by the soil; thus a closer spacing may be used in that region. However, in generally springs are evenly spaced at about half the diameter of the pile. The results of the stochastic analysis with and without the SSI are compared each other while the bridge is under the sway of the spatially varying earthquake ground motion. Specifically, in case of rigid towers and soft soil condition, it is pointed out that the SSI should be significantly taken into account for the design of such bridges.

Keywords: soil-structure interaction; cable-stayed bridge; piles; spatially varying earthquake ground motion; stochastic analysis

1. Introduction

Bridges are critical lifeline facilities systems, which should remain functional without damage after an earthquake to facilitate the rescue and relief operations. In recent decades, the long span structures such as cable-stayed bridges have gained much popularity, due to their aesthetic appearance, efficient utilization of structural materials, increase of the horizontal navigation clearances and the economic trade off of span length cost of deep water foundation. Moreover,

*Corresponding author, Associate Professor, E-mail: sates@ktu.edu.tr
[a]E-mail: zelihakuyumcu@hotmail.com

cable-stayed bridges, due to their large dimensions and flexibility, usually experience very long fundamental periods, which is an aspect that differentiates them from other structures, and of course, that affects their dynamic behavior. However, the flexibility and dynamic characteristics of that kind of bridges depend on several parameters such as the main span length, stay system and their layout, support conditions and many other things. For this reason, it is very important to accurately evaluate their response of the earthquake motions. In designing of these structures, one of the most important problems is designing them for lateral loads especially sudden lateral loads as earthquakes. Also the safe end economic seismic designs of bridge structures depend directly on the understanding level of seismic excitation and the influence of supporting soil on the structural dynamic response. Long span bridges are susceptible to relatively more severe soil-structure interaction effect during earthquakes as compared to buildings due to their spatial extent, varying soil condition at different supports and possible incoherence in the seismic input (Abdel-Raheem *et al.* 2003). The earthquake response of long span cable-stayed bridges is very dependent upon knowledge of their dynamic characteristics, such as modal frequencies, mode shapes and damping values, and also a description of the dynamic loading (Wilson and Gravelle 1991). The main damage reason has been differential motion at the supports, when the earthquake acts in the longitudinal or traverse direction, conforming today a special problem called spatial variability effects (Valdebenito *et al.* 2006)

The estimation of earthquake motions at the site of a structure is the most important phase of seismic design as well as strengthening of a structure. Seismic design of bridges depends directly on the understanding level of seismic excitation and the influence of supporting soil on the structural dynamic response. Long span bridges are susceptible to relatively more severe soil-structure interaction effect during earthquakes as compared to buildings due to their spatial extent, varying soil condition at different supports and possible incoherence in the seismic input. In classical methods used in structural analysis, it is assumed that, the motion in the foundation level of structure is equal to ground free field motion. This assumption is correct only for the structures resting on rock or very stiff soils. For the structures constructed on soft soils, foundation motion is usually different from the free field motion and a rocking component caused by the support flexibility on horizontal motion of foundation has been added. A number of studies have been conducted in recent years to comprehend the effects of SSI on the seismic behavior of bridges (Spyrakos 1992, Takemiya and Kai 1983), which have shown that SSI generally tends to elongate the natural periods of bridge-foundation-soil systems, and may significantly affect internal forces in structural members and displacement response of bridges. Vlassis and Spyrakos (2001) investigated soil structure interaction in seismically isolated bridge piers placed on a shallow soil stratum overlying rigid bedrock and subjected to horizontal seismic excitations in order to demonstrate the significant effect of soil-structure interaction on the longitudinal response of short span seismically isolated bridge. Conclusions of the study are that fundamental period of the bridge-soil system significantly increased when soil-structure interaction is taken into account, especially when the isolation devices are not much more flexible than the supporting soil and SSI does not appear to play a major role as far as damping is concerned. This should be mainly attributed to the presence of the isolation bearings that cause a significant decrease in the total stiffness of the system. That is to say the beneficial effect of SSI on seismic behavior of rather stiff structures is limited. It has also been recognized that the way in which SSI affects the seismic behavior of bridges depends on the conditions of the bridge-foundation-soil system (Kawano and Furukawa 1988), suggesting a necessity to perform many detailed case studies. Betti *et al.* (1993) investigated an overall procedure to study the dynamic soil-structure interaction effect on the responses of cable-supported bridges subjected to spatially varying ground motion at the supporting foundations. The spatial variability of the ground motion was taken into account with the propagation of the seismic waves. It was obtained that the importance of the multiple-support seismic excitation and kinematic soil-foundation interaction on the structural responses. Ates *et al.* (2005) researched stochastic responses of seismically isolated highway bridges with friction pendulum systems subjected to spatially varying earthquake ground motions are investigated. The spatially varying earthquake ground motion model includes incoherence, wave-passage and site-response effects. The effect of the wave-passage is investigated by using various wave velocities. Homogeneous soft, medium and firm soil types are selected for considering the site-response effect where the bridge supports are constructed. The ground motion is described by filtered white noise and applied to each support point. It was observed that the changing of the local soil conditions at the support points affects response values of non-isolated and isolated bridges. The more difference between the local soil conditions, the more response values take place, and the response values of the isolated bridge subjected to spatially varying earthquake ground motion are almost four times smaller than those of the non-isolated bridge. Chouw and Hao (2008) studied that the non-uniform ground conditions on ground motions. Results of the study showed that the development of ground motions at bridge local sites depends not only on the seismic wave propagation and the wave properties but also on local soil conditions. Soneji and Jangid (2008) studied that the influence of dynamic SSI on the behavior of seismically isolated cable-stayed bridge supported on a rigidly capped vertical pile groups, which pass through moderately deep, layered soil overlying rigid bedrock. In this study piles closely grouped together beneath the towers are viewed as a single equivalent upright beam. The soil-pile interaction is idealized as a beam on nonlinear Winkler foundation using continuously distributed hysteretic springs and viscous dashpots placed in parallel. It was obtained that for soft soil condition, the bearing displacement may be underestimated if SSI is ignored, especially in the longitudinal direction, and the response is much higher as compared to that of the bridge with fixed tower base when the soil is soft to medium. As the stiffness of the soil strata increases the effect of SSI diminishes. Allam (2010) examined the influence of the wave passage effect on the response of an open-plane frame building with soil-structure interaction. The ground acceleration was modeled by a suitably filtered white noise. The results were discussed with regard to the wave passage and SSI effects.

The dynamic interaction between the pier-foundation and soil has a significant effect on the earthquake response of bridges. The dynamic characteristics of soil structure-structure interaction system change due to materials and geometrical nonlinearity during severe earthquakes. This nonlinearity is sometimes treated by equivalent linear model (Abdel-Raheem *et al.* 2002, Spyrakos 1997). The dynamic characteristics of soil structure interaction system, such as the shape of the peak of frequency transfer function change from high frequency-low damping type to low frequency-high damping type, are depending on the stress level of the surrounding soil during a severe earthquake (Abdel-Raheem *et al.* 2003). Spyrakos (1992) has assessed the significance of SSI on the seismic response of short span bridges. The focus has been placed on pier behavior, since piers together with the abutments are the most critical elements in securing the integrity of bridge superstructures during earthquakes. His studies conclude that safer and more economical bridge designs can be obtained by properly accounting for SSI. Soyluk and Dumanoglu (2000) carried out asynchronous and stochastic dynamic analyses of cable-stayed bridges in which the ground motion was assumed to be of the uniform ground motion form for stochastic analysis. It was observed that the velocity of the ground motion greatly influences the response of the bridge for asynchronous dynamic analysis. Recently, Dumanoglu and Soyluk (2002) compared stationary and transient responses of cable-stayed bridges subjected to spatially varying ground motions. The spatial variability of ground motions is considered with incoherence and wave-passage effects. It was observed that the assumption of stationarity gives reasonable approximation for typical durations of strong shaking. Soyluk and Yucel (2007) performed the random vibration analyses of two different steel arch bridge models for the spatial variation of the ground motion including the wave passage effect. In the random vibration analysis theory, the filtered white noise ground motion model is widely used as a power spectral density function of the ground motion. It is aimed to determine the accuracy of the filtered white noise ground motion model to represent the actual ground motion. With this purpose, the considered arch bridges are analyzed for the actual ground motion and filtered white noise ground motion model. The record of the 1999 Taiwan, Chi-Chi earthquake at the firm soil condition is considered as actual ground motion. It is observed that the results obtained for the filtered white noise ground motion model are comparable with the results obtained for the actual ground motion.

In fact, earthquake ground motions are not the same at support point of long span structures like bridges, dams and pipelines. This is because of complex nature of the earth crust. In recent years, the earthquake response analyses of long span structures subjected to spatially varying earthquake ground motion have been special interest (Hawwari 1992). Bilici *et al.* (2009) investigated those stochastic dynamic responses of dam-reservoir-foundation systems subjected to spatially varying earthquake ground motions. The spatially varying earthquake ground motion model includes incoherence, wave-passage and site-response effects. The ground motion is described by filtered white noise and applied to each support point of the 2D finite element model of the dam-reservoir-foundation system. It was observed that spatially varying earthquake ground motions have important effects on the stochastic dynamic response of dam-reservoir-foundation systems. Bail *et al*. (2010) were researched that response of a realistic large dimension steel trussed arch structure subjected to the combined spatially varying horizontal and vertical ground motions. The ground motion spatial variations associated with wave passage effect, coherency loss effect and local site effect are considered. It was seen that each factor of ground motion spatial variations has a significant effect on the dynamic response of the structure. Therefore, to have an accurate structural response assessment and a better design of long span steel trussed arch structures, a reliable ground motion spatial variation model is essential. Mezouer *et al*. (2010) studied that the effects spatial variability of ground motion on the stochastic response of structures subjected to this phenomenon (wave passage effect and incoherence effect) for both soft and stiff soil, using response spectrum method. The responses were evaluated along a two-span beam. The relative influence of each effect on the three components of the total response (dynamic component, pseudo-static component and the cross-term between the dynamic and pseudo-static) were examined. It was observed that non uniform excitation effect on shear forces around the middle support is more significant in presence of stiff soil especially for flexible structures, and spatial variability of ground motion affects structure response in a very significant way and must definitively be taken into account for the design of long structures. Abdel-Raheem *et al.* (2011) studied that effect of spatial variability of ground motion at supporting foundations with different wave propagation apparent velocities in the structural seismic response of cable-stayed bridges. The assumption of uniform earthquake motion along the entire bridge could result in quantitative and qualitative differences in seismic response as compared with those produced by uniform motion at all supports. General result of the study is that the effect of spatial variability of ground motion on the seismic response control of a bridge is a very complex problem, and depends on various parameters describing the structure and the characteristics of the seismic ground motion. The spatial variation of seismic ground motions plays a significant role in the safety of long span bridges and affects the efficiency of the structural control. Bi *et al*. (2011) worked on the combined effects of ground motion spatial variation, local site amplification and soil structure interaction on bridge responses. The soil surrounding the pile foundation was modeled by frequency-dependent springs and dashpots. The peak structural responses were estimated using the standard random vibration method. Results of the study showed that SSI significantly affects the structural responses, and could not be neglected. Soyluk and Sicacik (2012) are carried out a study to determine the dynamic performance of a cable stayed bridge model under the spatially varying ground motions including the soil structure interaction effect. Spatially varying ground motions are generated to be compatible with the spatially varying ground motion components of incoherence, wave-passage and site-response effects. It was observed that diversity of the soil conditions where the bridge supports are located on, has important effects on the dynamic bridge responses, as difference between soil conditions increase dynamic bridge responses increase and the spatially varying ground motion components of earthquake ground motion and soil-structure interaction have very important effects on the dynamic behavior of cable-stayed bridges, and should be considered in the dynamic analyses of these bridges.

The SSI effects have also been studied many researchers (Smith-Pardo 2011, Chore *et al.* 2010, Rajashekhar Swamy *et al.* 2011). Chore *et al.* (2010) examined the effect of soil-structure interaction on a single-storey, two-bay space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap. Rajashekhar Swamy *et al.* (2011) studied two extreme cases of compatibility of the horizontal displacements between the foundation and soil.

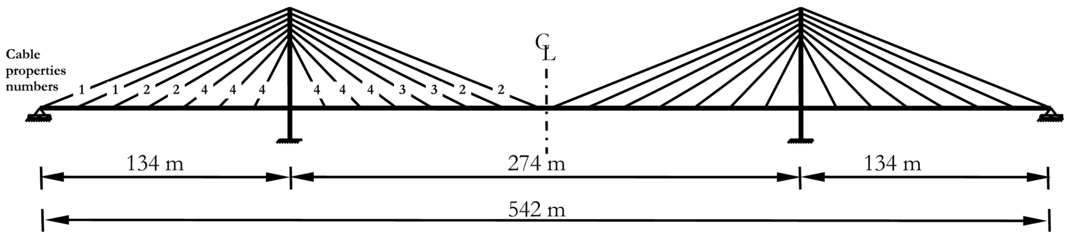
The main aim of the study is that the influences of dynamic soil-structure interaction on the stochastic response of cable-stayed bridge subjected to the spatially varying earthquake ground motion are to investigate by the finite element method. The soil-pile interaction is idealized as a beam on Winkler foundation using continuously distributed nonlinear springs and dashpots.

2. Description of the cable-stayed bridge model

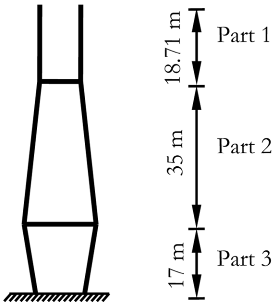
The work example in this study is the Quincy Bay-view Bridge crossing the Mississippi River at Quincy, Illinois, USA. The Bridge, shown in Fig. 1, was designed in 1983 and construction was completed in 1987. The bridge consists of two H-shaped concrete towers, double-plane fan type cables, and a composite concrete-steel girder bridge deck. The main span is 274 m and there are two equal side spans of 134 m for a total length of 542 m. The tops of the towers are 70.71 m from the waterline. There are a total of 56 cables, 28 supporting the main span and 14 supporting each side span. The cable members are spaced at 2.75 m at the upper part of the towers and equally spaced at the deck level on the side as well as main spans. The width of the deck from center to center of cables is 12 m.

In this study, finite element model of the bridge developed for the investigation is as shown in Fig. 2(a). The model of the towers is separately shown in Fig. 2(b). Each tower, consists of two concrete legs, with dimensions of 4.4×2.1 m a cross-beam supporting the deck and an upper strut connecting the upper legs. There are three changes in the leg cross-section over the height of the towers. The relevant properties of the bridge deck and towers are given in Table 1 while those of

Fig. 1 Quincy Bay-view Köprüsü



(a)



(b)

Fig. 2 Details of (a) the cable-stayed bridge model, and of (b) the towers

Table 1 Properties of the deck and the towers

Element Name	A (m^2)	I_z (m^4)	E (kN/m^2)	W (kN/m)
Deck	0.827	0.341	2.1×10^8	118.59
Tower (Part1)	14.12	532.200	30.787×10^6	339.30
Tower (Part2)	14.12	795.200	30.787×10^6	339.30
Tower (Part3)	30.75	1250.36	30.787×10^6	738.92

Table 2 Properties of the stay cables

Cable Name	A (m^2)	E (kN/m^2)	W (kN/m)
1	0.0180	2.1×10^8	1.76580
2	0.0135	2.1×10^8	1.32435
3	0.0107	2.1×10^8	1.04967
4	0.0070	2.1×10^8	0.68670

the cables are given in Table 2. The bridge deck is assumed to be a continuous beam rigidly connected to the towers such that the deck moment will not be transferred to the tower through the deck-tower connection. The towers of cable-stayed bridge are supported on rigidly capped vertical pile groups passing through moderately deep, layered soil overlying rigid bedrock. When piles are closely grouped together, the piles and soil work like a single rigid unit, and the problem becomes of the group working like a large pier (Zeevaert 1982, Konagai *et al.* 2003). Hence in present approach, piles closely grouped together beneath the towers are viewed as a single equivalent upright beam. The piles are spaced at three pile diameters, and the properties of the single equivalent beam include group effects. A % 2 damping coefficient and a lumped mass model is adopted for the response calculations.

Regarding modeling of the bridge components, the deck and the tower members are modeled as space frame elements. The cables are modeled as linear elastic truss elements. The stiffness characteristics of an inclined cable can exhibit a nonlinear behavior caused by cable sag. This nonlinear behavior can be taken into account by linearization of the cable stiffness using an equivalent modulus of elasticity that is less than the true material modulus (Ernst 1965). For the analysis of the bridge under consideration, Wilson and Gravelle (1991) found the value of equivalent modulus essentially equal to the true modulus of elasticity.

3. Formulation

The equation of motion of a structural system can be written as

$$[M]\{\ddot{v}\} + [C]\{\dot{v}\} + [K]\{v\} = \{F\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, respectively; $\{\ddot{v}\}, \{\dot{v}\}$ and $\{v\}$ are vectors of total accelerations, velocities and displacements, respectively and $\{F\}$ is a vector of input forces.

The degrees of freedom can be defined as known and unknown. The known degrees of freedom are associated with those of the structure-foundation interface. The unknowns are related to degrees of freedom of the structure. The former degrees of freedom will be denoted hereafter as the vector v_g, and the latter as v_r. Here, the subscript g denotes the ground degrees of freedom and r denotes the response degrees of freedom. Eq. (1) can be rearranged by separating the degrees of freedom into two groups as known and unknown (Dumanoglu and Severn 1985, Dumanoglu and Severn 1987, Clough and Penzien 1993)

$$\begin{bmatrix} M_{rr} & M_{rg} \\ M_{gr} & M_{gg} \end{bmatrix} \begin{Bmatrix} \ddot{v}_r \\ \ddot{v}_g \end{Bmatrix} + \begin{bmatrix} C_{rr} & C_{rg} \\ C_{gr} & C_{gg} \end{bmatrix} \begin{Bmatrix} \dot{v}_r \\ \dot{v}_g \end{Bmatrix} + \begin{bmatrix} K_{rr} & K_{rg} \\ K_{gr} & K_{gg} \end{bmatrix} \begin{Bmatrix} v_r \\ v_g \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{2}$$

It is possible to separate the total displacement vectors as quasi-static and dynamic components as follows

$$\begin{Bmatrix} v_r \\ v_g \end{Bmatrix} = \begin{Bmatrix} v_{sr} \\ v_{sg} \end{Bmatrix} + \begin{Bmatrix} v_{dr} \\ v_{dg} \end{Bmatrix} \tag{3}$$

Because of complex nature of the earth crust, earthquake ground motions will not be the same at distances of the dimensions of long span structure as bridges. While analysing large structures, spatially varying earthquake ground motions should be considered and total displacements have to be used in expressing the governing equation of motion. The spatially varying earthquake ground motion includes incoherence, wave-passage and site-response effects. These effects are characterised by the coherency function in frequency domain.

The cross-spectral density functions of the earthquake ground motion, between support points ℓ and *m* is expressed as (Abrahamson *et al.* 1991, Heredia-Zavoni and Vanmarcke 1994)

$$S_{\ddot{v}_{g_\ell}\ddot{v}_{g_m}}(\omega) = \gamma_{\ell m}(\omega)\sqrt{S_{\ddot{v}_{g_\ell}\ddot{v}_{g_\ell}}(\omega)S_{\ddot{v}_{g_m}\ddot{v}_{g_m}}(\omega)} \tag{4}$$

where $\gamma_{\ell m}(\omega)$ denotes the coherency function. The power spectral density function is assumed to be of the following form suggested by Clough and Penzien (1993)

$$S_{\ddot{v}_g}(\omega) = S_o\left(\frac{\omega_f^4 + 4\xi_f^2\omega_f^2\omega^2}{(\omega_f^2-\omega^2)^2 + 4\xi_f^2\omega_f^2\omega^2}\right)\left(\frac{\omega^4}{(\omega_g^2-\omega^2)^2 + 4\xi_g^2\omega_g^2\omega^2}\right) \tag{5}$$

are the frequency responses of first and second filters representing characteristics of the layers of soil medium above the rock bed; S_o is the amplitude of the white-noise process; ω_f and ξ_f are the resonant frequency and damping of the first filter, and ω_g and ξ_g are those quantities of the second filter.

In this paper, S_o is obtained for each soil layer type by equating the variance of the ground acceleration to the variance of the DZC270 component of Duzce, Turkey, Kocaeli Earthquake in 1999. Homogeneous soft, medium and firm layer soil types are used for the cable-stayed bridge supports. Calculated values of the intensity parameter for each soil type and the filter parameters for these soil types which are proposed Der Kiureghian and Neuenhofer (1991) are utilised as shown in Table 3.

Table 3 Intensity and filter parameter for different soil types

Type of Soil	ω_f (rad/sm)	ξ_f	ω_g (rad/sm)	ξ_g	S_o (m^2/s^3)
Firm	15.0	0.6	1.5	0.6	0.00171
Medium	10.0	0.4	1.0	0.6	0.00255
Soft	5.0	0.2	0.5	0.6	0.00357

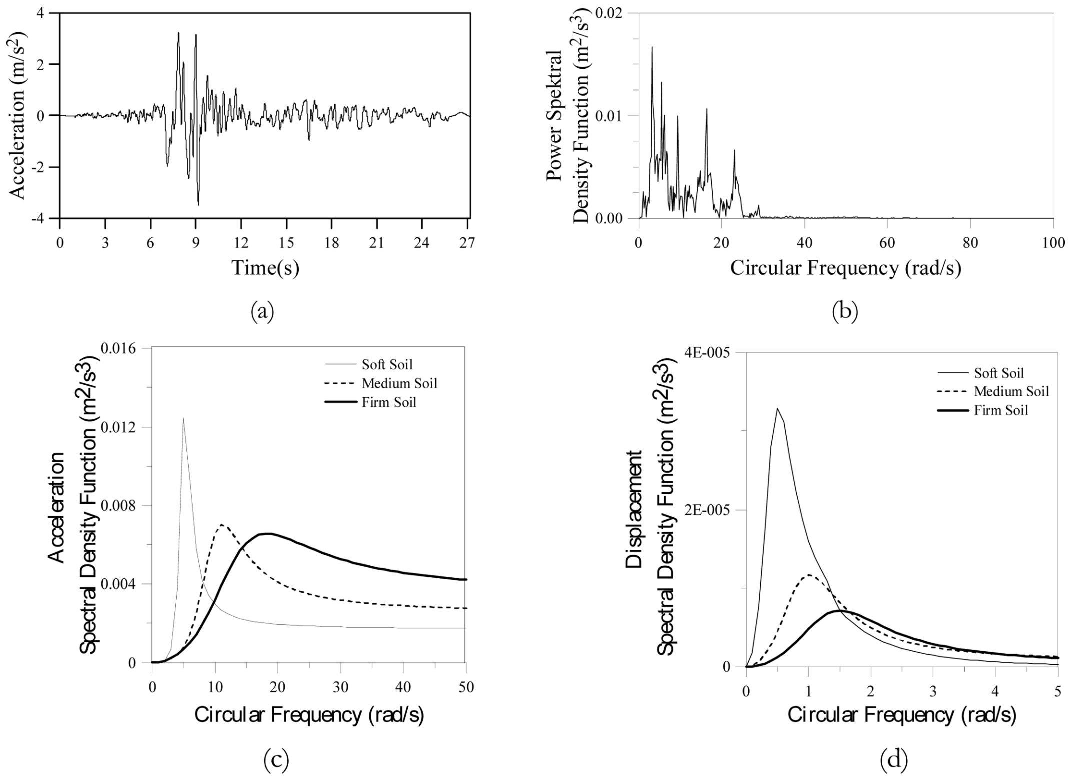


Fig. 3 The DZC270 component of the 1999 Kocaeli, Turkey, earthquake; (a) acceleration time history, (b) power spectral density function, (c) acceleration spectral density function, (d) displacement spectral density function

The record used is that of the DZC270 component of Duzce, Turkey, Kocaeli Earthquake in 1999, which is given in Fig. 3(a) and lasts for 27.2sec; its power spectral density function, acceleration spectral density function and displacement spectral density function for different soil types are given Fig. 3(b), Fig. 3(c) and Fig. 3(d), respectively.

The coherency function is dimensionless and of complex value. The coherency function is defined as

$$\gamma_{\ell m}(\omega) = |\gamma_{\ell m}(\omega)|^i \gamma_{\ell m}(\omega)^w \gamma_{\ell m}(\omega)^s \tag{6}$$

where $|\gamma_{\ell m}(\omega)|^i$ characterises the incoherence effect, $\gamma_{\ell m}(\omega)^w$ indicates the complex valued wave-passage effect and $\gamma_{\ell m}(\omega)^s$ denotes the complex valued site-response effect (Der Kiureghian 1996).

For the incoherence effect, an extensively used model is considered. The model proposed by Harichandran and Vanmarcke (1986) is defined as

$$|\gamma_{\ell m}(\omega)|^i = A\exp\left[-\frac{2d_{\ell m}}{\alpha\theta(\omega)}(1-A+\alpha A)\right]+(1-A)\exp\left[-\frac{2d_{\ell m}}{\theta(\omega)}(1-A+\alpha A)\right] \tag{7}$$

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

where $d_{\ell m}$ is the distance between support points ℓ and m; A, α, k, f_o and b are 0.636, 0.0186, 31200, 1.51 Hz and 2.95, respectively (Harichandran *et al.* 1996, Zerva 1991).

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

$$\gamma_{\ell m}(\omega)^w = e^{i(-\omega d^L_{\ell m}/v_{app})} \tag{9}$$

where v_{app} is the apparent wave velocity and $d^L_{\ell m}$ is the projection of $d_{\ell m}$ on the ground surface along the direction of propagation of seismic waves (Der Kiureghian 1996, Nakamura *et al.* 1993). The apparent wave velocities employed in this study are selected as 300, 600 and 2000 m/s for soft layer, medium layer and firm layer soil types, respectively.

The site-response effect due to the differences in the local soil conditions is obtained as

$$\gamma_{\ell m}(\omega)^s = e^{i(\tan^{-1}(\mathrm{Im}[H_\ell(\omega)H_m(-\omega)]/\mathrm{Re}[H_\ell(\omega)H_m(-\omega)])} \tag{10}$$

where $H_\ell(\omega)$ is the local soil frequency response function representing the filtration through soil layers (Der Kiureghian 1996, Nakamura *et al.* 1993)

4. Modeling of soil-pile system

Many bridges, especially long span bridges, are supported on pile foundations. Several types of models may be used for the seismic analysis of bridges with pile foundations. A finite element analysis for soil-pile-structure interaction for the spatially varying earthquake ground motion has been investigated. The proposed soil-pile-bridge model is a two-dimensional finite element model as shown Fig. 4. The piles may penetrate several layers of soil with varying strength and stiffness.

Soil-structure interaction has been initially deemed beneficial during seismic motion, but trends in research are changing and this causes different notions of the phenomenon. Soil-structure interaction consistently appears to be beneficial for seismic response. Large pile foundations, for example, dissipate energy into the soil. This phenomenon, known as radiation damping, reduces the force imposed on the structure above. Even though soil-structure interaction increases dampening, which is beneficial, it can also cause additional displacement to the overall structure. This demand in the structure can, in some cases, have detrimental effects. The SSI has dangerous effects during an earthquake depending on the type of soil and seismic input. Rigid structures on softer soil, the interaction can cause large increases in the natural period of the structure, leading to much larger relative displacements.

Recently, several numerical and analytical methods have been developed to compute the dynamic stiffness and seismic response factors of pile foundations accounting for soil-pile interaction. Under strong seismic loading, pile foundations undergo significant displacements and the behavior of the soil-pile system can be nonlinear. In this study, the soil-pile interaction is idealized as a beam on Winkler Foundation as shown Fig. 5. The Winkler foundation is a model that can be created in order to represent the stiffness and the damping effects of the soil surrounding a pile group. The stiffness of the soil is represented with springs and the dampening effect of the soil is represented with dashpots. The presence of the damper makes the model very efficient for the prediction of the pile response under dynamic loads since it accounts realistically for the energy that radiates

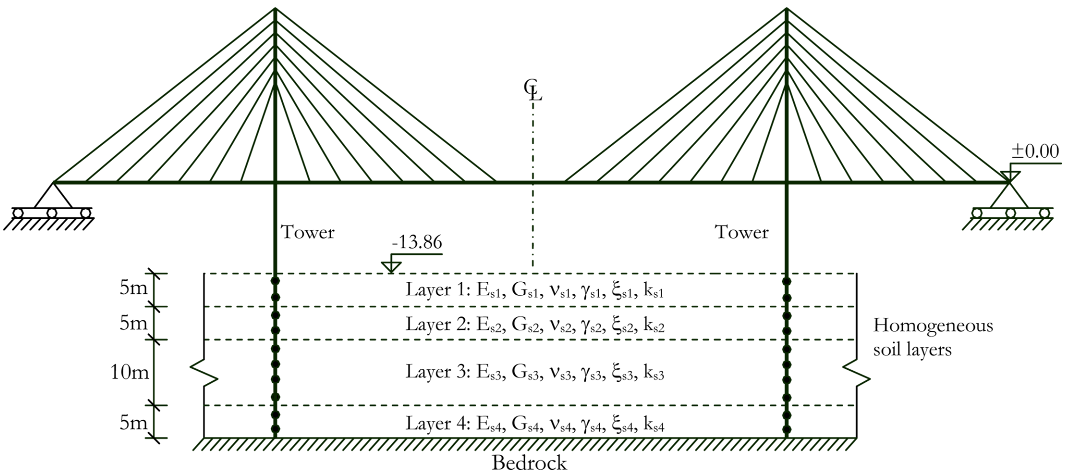


Fig. 4 Two dimensional finite element model of the soil-pile system

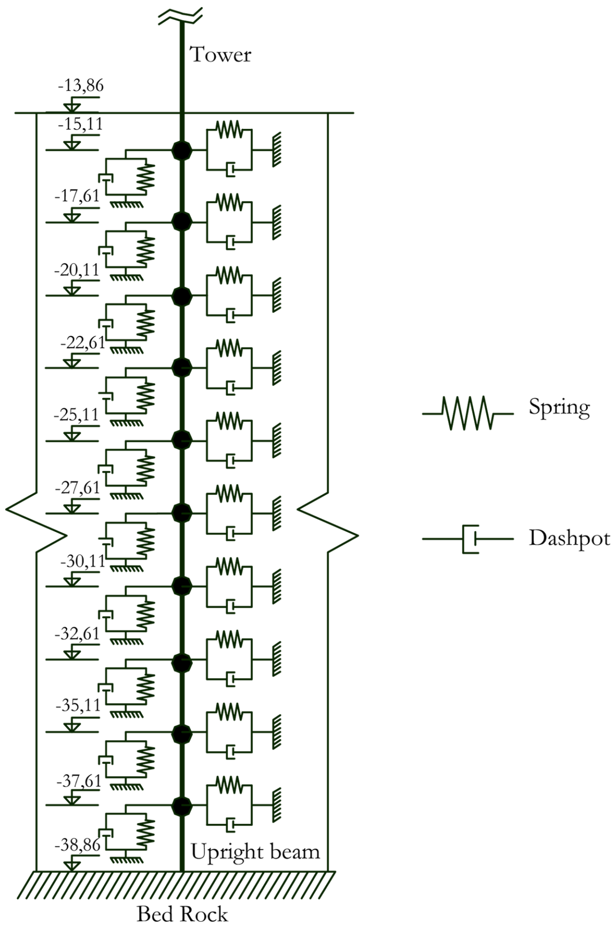


Fig. 5 Schematic of beam on Winkler foundation model in the layered soil strata

outward. The response of the superstructure is investigated under three different types of soil surrounding the pile foundation, namely, homogeneous soft layer, medium layer and firm layer.

A sufficient number of springs should be used along the length of the pile shaft, such that the response of the system is not sensitive to the number of springs used. In general, more springs are better, but only to the point where the results no longer change with increased numbers of springs. In this study, the rigid bedrock is available at a depth of 25 m, soil springs are distributed at 2.5 m centers. Therefore, the separation of pile into 11 segments by using 10 springs is enough to achieve sufficient accuracy in the analysis. Additionally, the springs near the surface are usually the most important for characterizing the response, thus a closer spacing may be used in that region. The spring coefficients can be computed as

$$k = k_S LD \tag{11}$$

where k_S is the coefficient of subgrade reaction, L is the effective distance, D is the equivalent pile diameter (Berger/Abam Engineers 1996). Young's modulus for soil layers can be evaluated using the relation

$$E_s = 2G_s(1+\nu_s) \tag{12}$$

where G_s is the shear modulus and ν_s is Poisson's ratio for soil.

The second key parameter for soil is damping. Two fundamentally different damping phenomena are associated with soil, namely material damping and radiation damping. Expressions for damping coefficients are available in literature (Gazetas and Dobry 1984)

The dynamic properties of the soils that vary with the depth are given in Table 4 (Wolf 1985).

Table 4 Dynamic properties of the soil layers

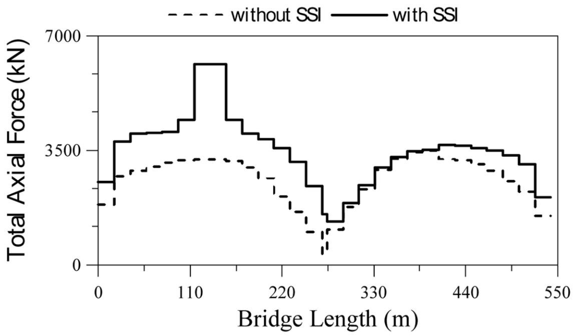
Depth (m)		0-5	5-10	10-20	20-25
Shear Modulus, G_S (10^3 kN/m^2)	Soft	80	125	245	550
	Medium	400	625	1.225	2750
	Firm	900	1350	2.550	6500
Damping Ratio, ξ_S (%)	Soft	0.07	0.06	0.05	0.05
	Medium	0.04	0.04	0.04	0.04
	Firm	0.02	0.02	0.02	0.02
Young's modulus, E (10^3 kN/m^2)	Soft	224	350	686	1540
	Medium	1080	1687	3307	7425
	Firm	2340	3510	6630	16900
Mass Density, γ_S (kN/m^3)	Soft	20	20	20	22
	Medium	20	21	22	22
	Firm	21	21	23	25
Poisson's Ratio, ν_s	Soft	0.04	0.04	0.04	0.04
	Medium	0.35	0.35	0.35	0.35
	Firm	0.30	0.30	0.30	0.30

5. Numerical computations

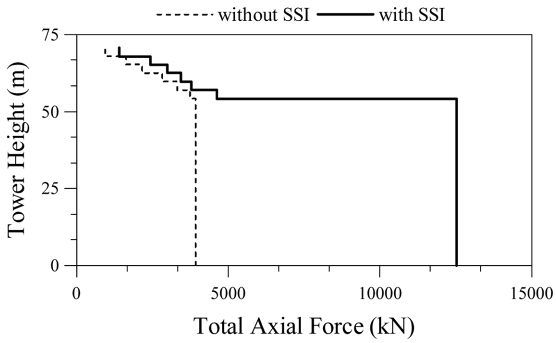
Results of stochastic analyses of cable-stayed bridge subjected to the 1999 Kocaeli, Turkey, earthquake ground motion are presented in Figs. 6-17 for homogeneous soft, medium and firm soil layers, respectively. The results obtained with and without SSI are plotted in the same graphs for comparison purpose. The results indicates that there is not much variation in axial force, shear force and bending moment with the type of soil considered especially homogeneous soft soil layer.

Fig. 6(a)-8(a) and Figs. 6(b)-8(b) show total axial forces of bridge deck and along the height of tower, respectively. It can be observed that for soft soil strata, total axial force is more excessive than medium and firm soil strata. Figs. 6(a)-8(a) and Figs. 6(b)-8(b) the peak values of the response of axial force are at the deck-tower junction along the deck and height of tower, respectively.

Figs. 9(a)-11(a) and Figs. 9(b)-11(b) indicate total shear force of bridge along the deck and height of tower, respectively. It can be concluded that especially for soft soil strata total shear force is much bigger than the other soil strata at the deck-tower junction. Figs. 9(a)-11(a) can observe that results of with and without SSI of the deck total shear force is quite small than the other soils. Figs. 9(b)-11(b) maximum values of the shear forces is close points of top of tower and for soft soil strata it can be more important.

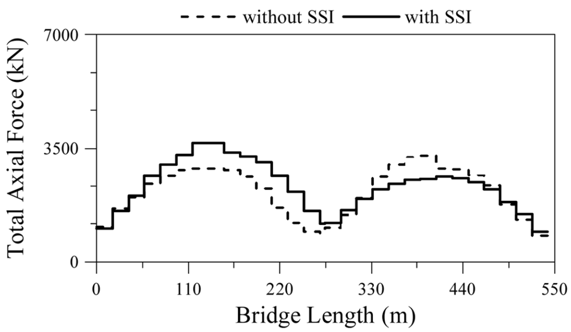


(a)

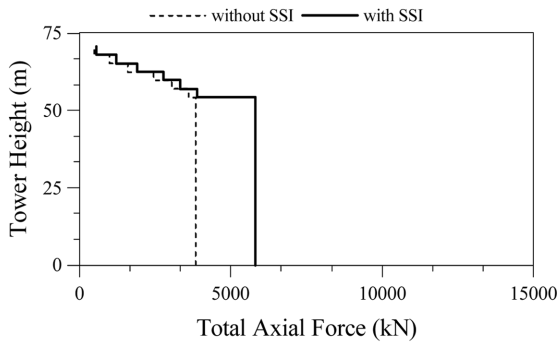


(b)

Fig. 6 Total axial forces of the bridge founded on soft soil; (a) deck, (b) tower



(a)



(b)

Fig. 7 Total axial forces of the bridge founded on medium soil; (a) deck, (b) tower

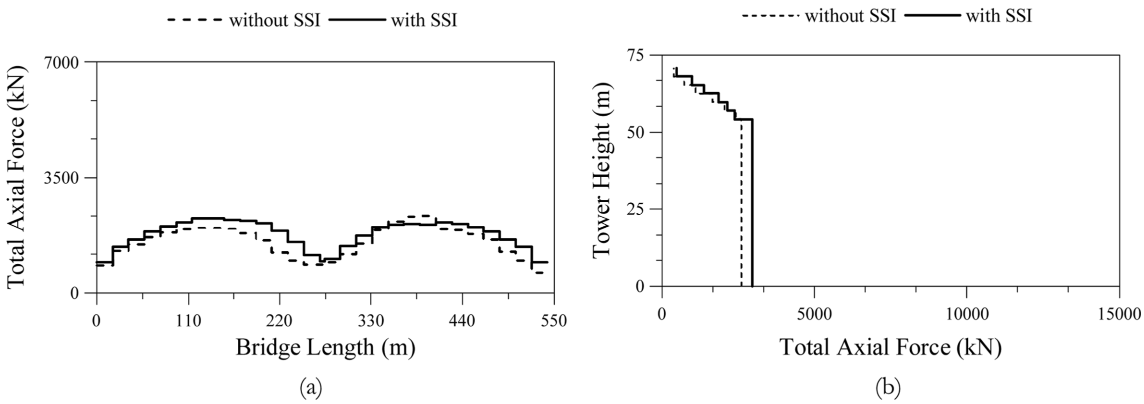


Fig. 8 Total axial forces of the bridge founded on firm soil; (a) deck, (b) tower

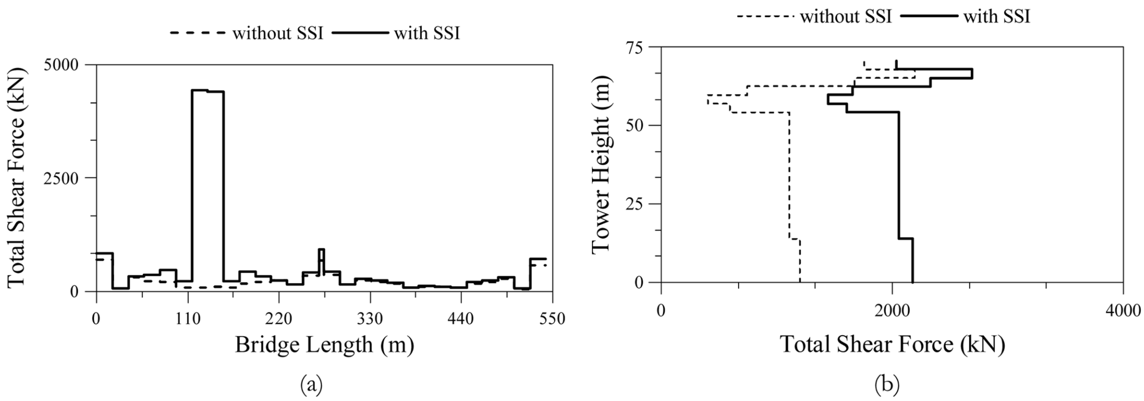


Fig. 9 Total shear forces of the bridge founded on soft soil; (a) deck, (b) tower

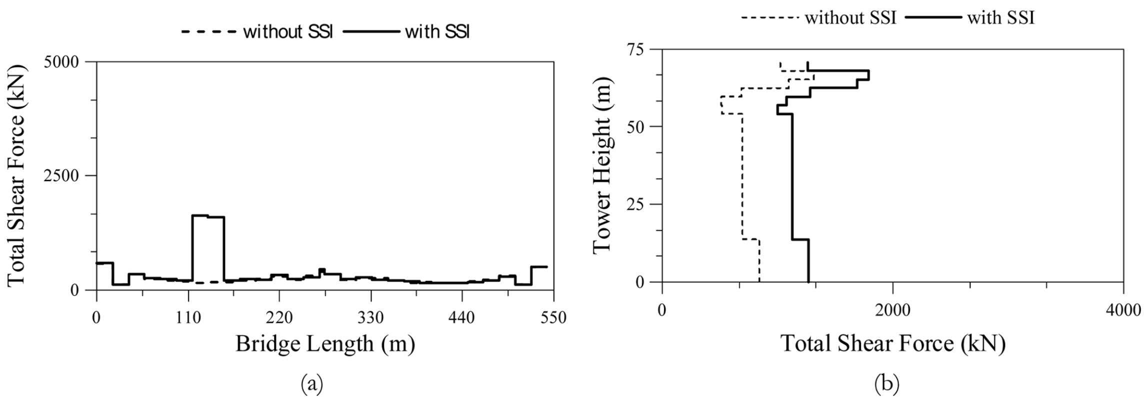


Fig. 10 Total shear forces of the bridge founded on medium soil; (a) deck, (b) tower

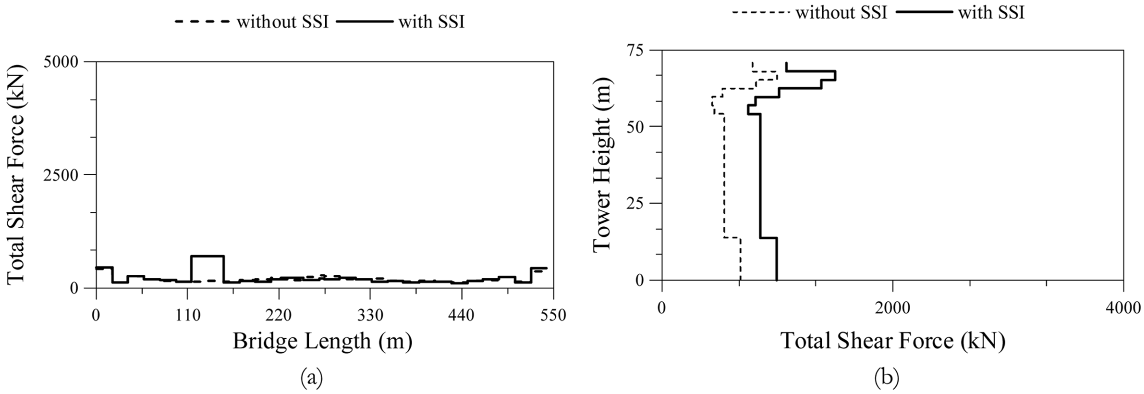


Fig. 11 Total shear forces of the bridge founded on firm soil; (a) deck, (b) tower

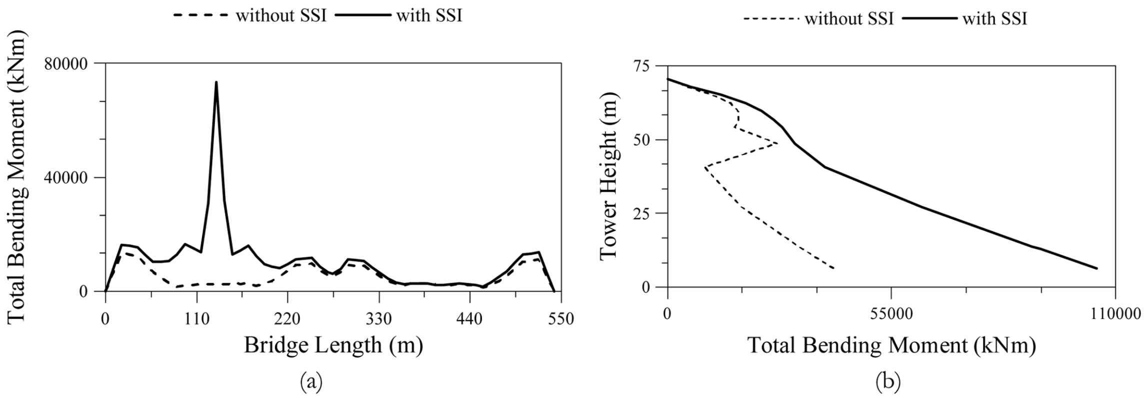


Fig. 12 Total bending moment of the bridge founded on soft soil; (a) deck, (b) tower

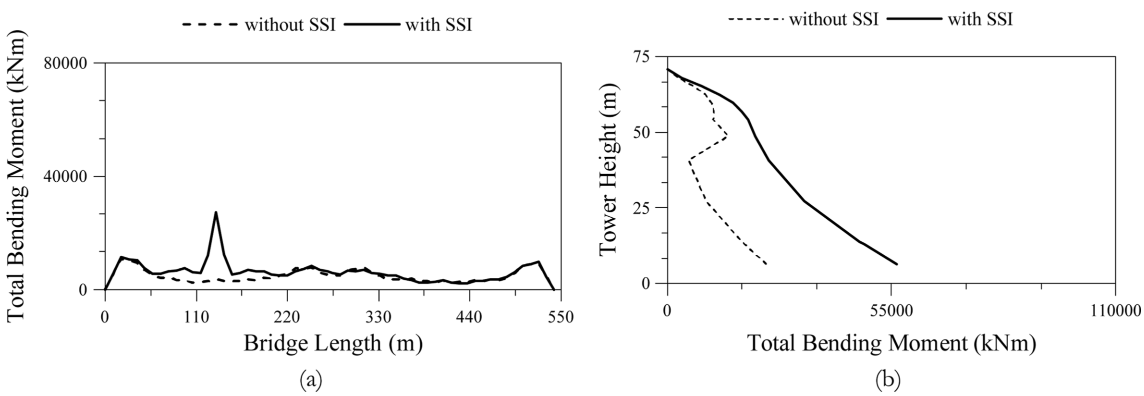


Fig. 13 Total bending moment of the founded on medium soil; (a) deck, (b) tower

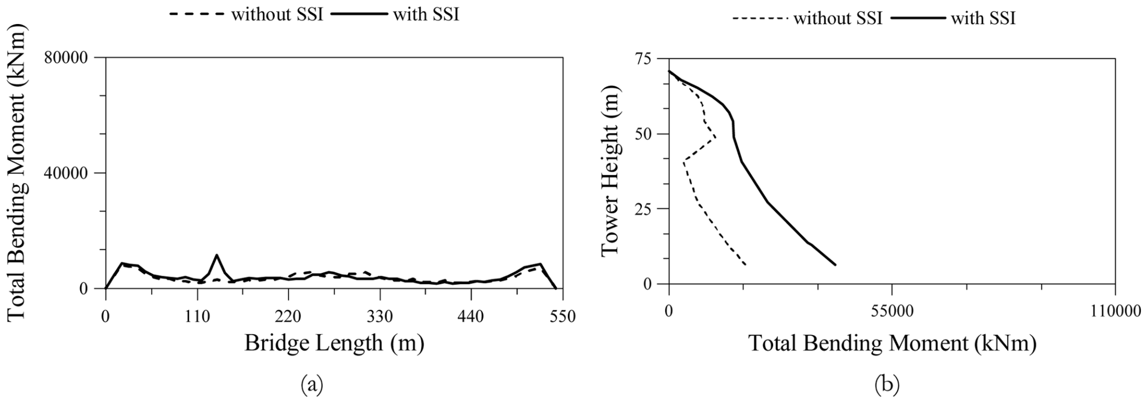


Fig. 14 Total bending moment of the bridge founded on firm soil; (a) deck, (b) tower

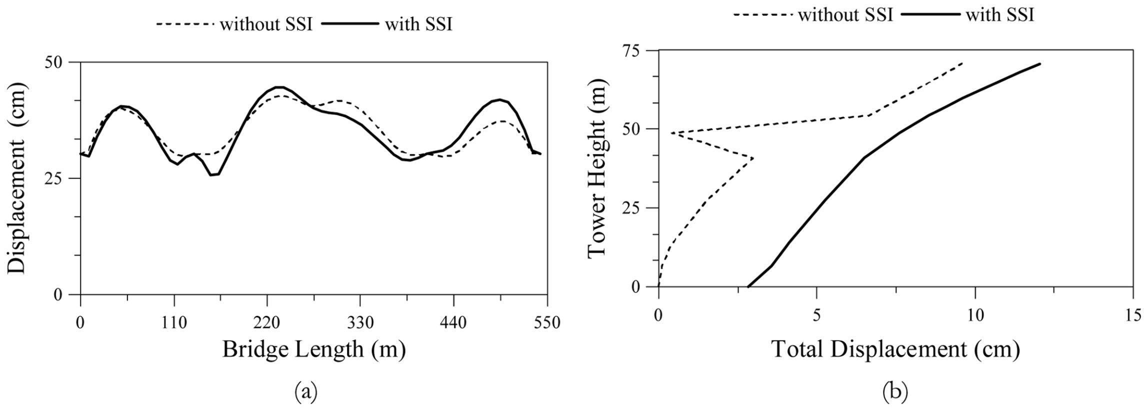


Fig. 15 Displacement of the bridge founded on soft soil; (a) deck, (b) tower

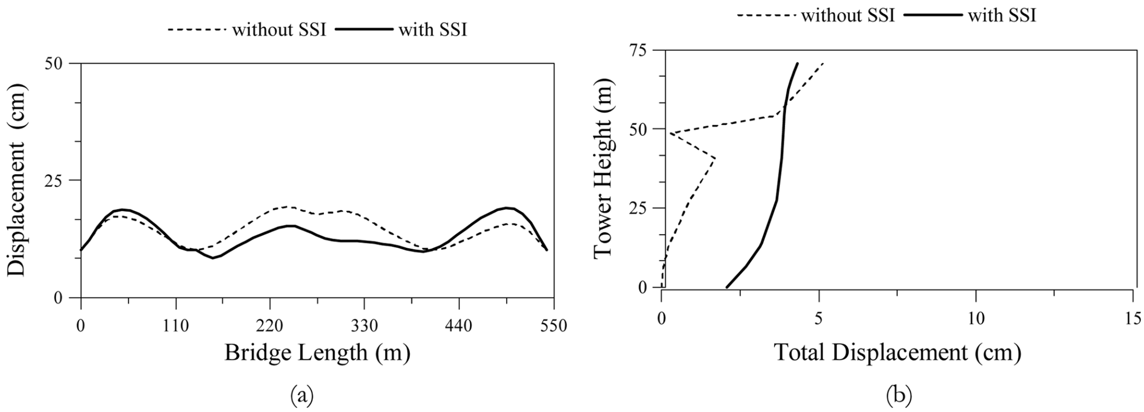


Fig. 16 Displacement of the bridge founded on medium soil; (a) deck, (b) tower

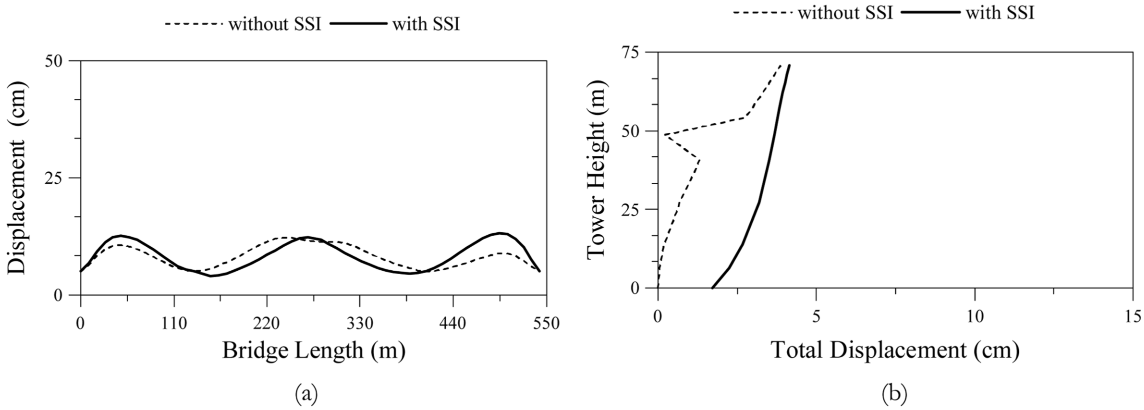


Fig. 17 Displacement of the bridge founded on firm soil; (a) deck, (b) tower

Figs. 12(a)-14(a) and Figs. 12(b)-14(b) represent total bending moment of bridge along the deck and height of tower, respectively. It can be observed that especially for soft soil strata and results of response with SSI are more excessive than the other conditions. Figs. 12(a)-14(a) and Figs. 12(b)-14(b) indicate that maximum values of the bending moment are at the deck-tower junction along the deck and height of tower.

Figs. 15(a)-17(a) and Figs. 15(b)-17(b) indicate displacement of bridge along the deck and height of tower, respectively. It can be concluded that especially for soft soil strata and results of response with SSI are much bigger than medium and firm soil strata.

6. Conclusions

This study summarizes a far-going investigation of the stochastic response of a cable-stayed bridge subjected to spatially varying ground motions with and without SSI. In order to investigate the stochastic response of the bridge, two-dimensional long-span bridge model, including the effect of soil-structure interaction is developed and utilized in the study. The considered bridge is modeled by using finite element method. The bridge is subjected to spatially varying earthquake ground motion by taking into account in the incoherence, the wave-passage and the site-response effects with and without SSI. For this purpose, three types of layered soil strata, namely, soft, medium and firm, have been considered for the study. The soil-pile interaction is linearly idealized as an upright beam on Winkler foundation model using continuously distributed springs and viscous dashpots placed in parallel. Results obtained from this study indicate the use of spatially varying ground motions on cable-stayed bridges. From the point of view of the investigation carried out, the following conclusions and recommendations are reached.

a) The SSI has a major effect on seismic response in the bridge, and such affect is more important at soft soil strata and at the connection points of the tower and the bridge deck.

b) Although the spatial variability effects; namely the incoherence, the wave-passage and the site-response effects have important effects on the dynamic behavior of the bridge, the influence of the soil-structure interaction effect should be incorporated.

c) The changing of the local soil conditions at the support points considerably affects response values of the bridge. The more difference between the soil conditions, the more pronounce response value can occur. So, site response effect and SSI should be considered in the analysis.

d) It may be concluded that variation of the local soil condition has important effects on the seismic behavior of the bridge. Therefore, in calculating the bridge responses, the variability of the ground motions depending soil type should be incorporated in the analysis of long span structures like as bridges.

References

Abdel Raheem, S.E., Hayashikawa, T. and Hashimoto, I. (2003), "Effects of soil-foundation-superstructure interaction on seismic response of cable-stayed bridges tower with spread footing foundation", *J. Struct. Eng., JSCE*, **49A**(2), 475-486.

Abdel Raheem, S.E., Hayashikawa, T. and Hashimoto, I. (2002), "Study on foundation flexibility effects on steel tower seismic response of cable-stayed bridges under great earthquake motion", *J. Constr. Steel*, **10**, 349-354.

Abdel-Raheem, S.E., Hayashikawa, T. and Dorka, U. (2011), "Ground motion spatial variability effects on seismic response control of cable-stayed bridges", *Earthq. Eng. Eng. Vib.*, **10**(1), 37-49.

Abrahamson, N.A., Schneider, J.F. and Stepp, J.C. (1991), "Empirical spatial coherency functions for application to soil-structure interaction analyses", *Earthq. Spectra.*, **7**(1), 1-27.

Allam, A.M. (2010), "Multiple-support excitations of open-plane frames by a filtered white-noise and soil-structure interaction", *J. Sound Vib.*, **329**(20), 4212-4226.

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", *Eng. Struct.*, **27**, 1843-1858.

Bail, FL., Hao, H. and Lil, H.N. (2010), "Seismic response of a steel trussed arch structure to spatially varying earthquake ground motions including site effect", *Adv. Struct. Eng.,* **13**(6), 1089-1103.

Berger/Abam Engineers (1996), Federal Highway Administration Seismic Design Course, Design Example No. 6, Publication No. FHWA-SA-97-011 and Barcode No. PB97-14211.

Betti, R., Abdel-Ghaffar, A.M. and Niazy, A.S. (1993), "Kinematic soil-structure interaction for long-span cable-supported bridges", *Earthq. Eng. Struct. D.*, **22**, 415-430.

Bi, K., Hao, H. and Chouw, N. (2011), "Influence of Ground motion spatial variation, site condition and SSI on the required separation distances of bridge structures to avoid seismic pounding", *Earthq. Eng. Struct. D.*, **40**(9), 1027-1043.

Bilici, Y., Bayraktar, A., Soyluk, K., Hacıefendioğlu, K., Ateş, S. and Adanur, S. (2009), "Stochastic dynamic response of dam-reservoir-foundation systems to spatially varying earthquake ground motions", *Soil Dyn. Earthq. Eng.*, **29**(3), 444-458.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2010), "Building frame-pile foundation-soil interaction analysis: a parametric study", *Interact. Multis. Mech.*, **3**(1), 55-79.

Chouw, N. and Hao, H. (2008), "Significance of SSI and non-uniform near-fault ground motions in bridge response I: effect on response with conventional expansion joint", *Eng. Struct.*, **30**, 141-153.

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

Der Kiureghian, A. (1996), "A coherency model for spatially varying ground motions", *Earthq. Eng. Struct. D.*, **25**(1), 99-111.

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

Dumanoglu, A.A. and Soyluk, K. (2002), "Comparison of stationary and transient responses of cable-stayed bridges", *Proceedings of the Fifth International Congress on Advances in Civil Engineering*, Istanbul, **1**, 233-242.

Dumanoglu, A.A. and Severn, R.T. (1987), "Seismic response of modern suspension bridges to asynchronous vertical ground motion", *Proceedings Institution of Civil Engineers*, **83**(4), 701-730.

Dumanoglu, A.A. and Severn, R.T. (1985), “Dynamic response of dams and other structures to differential ground motion”, *Proceedings Institution of Civil Engineers*., **2**(79), 429-430.
Ernst, H.J. (1965), “Der E-Modul Von Seilen Unter Brucksichtigung Des Durchhangers”, *Der Bauingenieur*, **40**(2), 52-55.
Gazetas, G. and Dobry, R. (1984), “Horizontal response of piles in layered soils”, *J. Geotech. Eng.*, **110**(1), 20-41.
Harichandran, R.S., Hawwari, A. and Sweidan, B.N. (1996), “Response of long-span bridges to spatially varying ground motion”, *J. Struct. Eng.*, **122**(5), 476-485.
Harichandran, R.S. and Vanmarcke, E.H. (1986), “Stochastic variation of earthquake ground motion in space and time”, *J. Eng. Mech.*, **112**(2), 154-175.
Hawwari, A.R. (1992), “Suspension bridge response to spatially varying ground motion”, PhD Thesis, Michigan State University, Michigan.
Heredia-Zavoni, E. and Vanmarcke, E.H. (1994), “Seismic random-vibration analysis of multisupport- structural systems”, *J. Eng. Mech.*, **120**(5), 1107-1129.
Kawano, K. and Furukawa, K. (1988), “Random seismic response analysis of soil cable stayed bridge interaction”, *Proceedings of the Ninth World Conference on Earthquake Engineering*, Tokyo-Japan, 6, 495-500.
Konagai, K., Yin, Y. and Murono, Y. (2003), “Single beam analogy for describing soil-pile group interaction”, *Soil Dyn. Earthq. Eng.*, **23**(3), 31-39.
Mezouer, N., Silhadi, K. and Afra, H. (2010), “Importance of spatial variability of seismic ground motion effects on long beams response”, *J. Civil Eng. Constr. Technol.*, **1**(1), 1-13.
Rajashekhar Swamy, H.M., Krishnamoorthy, A., Prabakhara, D.L. and Bhavikatti, S.S. (2011), “Evaluation of the influence of interface elements for structure-isolated footing-soil interaction analysis”, *Interaction and Multis. Mech.*, **4**(1), 65-83.
Smith-Pardo, J.P. (2011), “Performance-based framework for soil-structure systems using simplified rocking foundation models”, *Struct. Eng. Mech.,* **40**(6), 763-782.
Soneji, B.B. and Jangid, R.S. (2008), “Influence of soil-structure interaction on the response of seismically isolated cable-stayed bridge”, *Soil Dyn. Earthq. Eng.*, **28**(4), 245-257.
Soyluk, K. and Dumanoglu, A.A. (2000), “Comparison of asynchronous and stochastic dynamic response of a cable-stayed bridge”, *Eng. Struct.*, **22**(5), 435-445.
Soyluk, K. and Sicacik, E.A. (2012), “Soil-structure interaction analysis of cable-stayed bridges for spatially varying ground motion components”, *Soil Dyn. Earthq. Eng.*, **35**, 80-90.
Soyluk, K. and Yucel, K. (2007), “Verification of the filtered white noise model in the random vibration analysis of steel arch bridges”, *J. Fac. Eng. Arch. Gazi Univ.*, **22**(4), 933-939.
Spyrakos, C.C. (1992), “Seismic behavior of bridge piers including soil-structure interaction”, *Comput. Struct.*, **43**(2), 373-384.
Spyrakos, C.C. (1997), “Soil-structure-water interaction of intake-outlet towers allowed to uplift”, *Soil Dyn. Earthq. Eng.*, **16**(2), 151-159.
Takemiya, H. and Kai, S. (1983), “Seismic analysis of a multi-span continuous elevated bridge on deep pile foundations”, *Proceedings Japan Society of Civil Engineers*, **332**, 1-10.
Valdebenito, G.E. and Aparicio, A.C. (2006), “Seismic behavior of cable-stayed bridges: a state of the-art review”, *Proceedings of the 4th International Conference on Earthquake Engineering*, Taiwan, Paper No. 45.
Vlassis, A.G. and Spyrakos, C.C. (2001), “Seismically isolated bridge piers on shallow soil stratum with soil-structure interaction”, *Comput. Struct.*, **79**, 2847-2861.
Wilson, J.C. and Gravelle, W. (1991), “Modelling of a cable-stayed bridge for dynamic analysis”, *Earthq. Eng. Struct. D.*, **20**(8), 707-721.
Wolf, J.P. (1985), *Dynamic Soil-Structure Interaction*, Prentice-Hall, USA.
Zeevaert, L. (1982), *Foundation Engineering for Difficult Subsoil Conditions*, 2nd Edition, Van Nostrand Reinhold, New York, USA.
Zerva, A. (1991), “Effect of spatial variability and propagation of seismic ground motions on the response of multiply supported structures”, *Probab. Eng. Mech.*, **6**(3-4), 212-221.