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Effects of Soil-Foundation-Bridge Interaction Subjected to Spatially Varying Earthquake Ground Motion

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ABSTRACT

The primary purpose of this study is to investigate stochastic responses of a cable-stayed bridge which is built on the Mississippi River in 1987 in USA, subjected to the spatially varying earthquake ground motion by using the finite element method taking account of soil-structure interaction (SSI) effects. The bridge is modelled as a two- dimensional to determine the stochastic response of the bridge. Spatially varying earthquake ground motions is considered in the analysis. Depending upon the earthquake motion, the response values of the bridge founded on firm, medium and soft soil strata are obtained, separately. The effects of soil–structure interaction on the stochastic response of the cable-stayed bridge are investigated including foundation as a vertical pile groups. The soil–pile interaction is linearly idealized as an upright beam on the Winkler foundation model. Results indicate that taking into account soil-structure interaction could increase element forces and displacement of bridge along the deck and height of tower especially in case of soft foundation soil strata.

Keywords: *Soil-structure interaction, Cable-stayed bridge, Piles, Spatially varying earthquake ground motion, Stochastic analysis*.

INTRODUCTION

Cable-stayed bridges that are their large dimensions and flexibility usually have very long fundamental periods. However, their flexibility and dynamic characteristics depend on several parameters such as the main span length, stay system, support conditions and many other things. Therefore, on cable-stayed bridges it is so significant to conclusively evaluate their response of spatially varying ground motions. The safe end economic seismic designing of that kind of bridges depend on the understanding level of seismic excitation and the influence of supporting soil on the structural dynamic response. Hao and Zhang investigated the effect of the spatially varying ground motions on the relative displacement of adjacent buildings [1]. Dumanoglu and Soyluk studied the spatial variability of ground motions including incoherence, wave-passage and site-response effects on the cable-stayed bridges [2]. 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 [3]. Soyluk and Dumanoglu (2004) carried out stochastic analysis of non-isolated cable-stayed bridges for delayed support excitations and concluded that any seismic analysis of even moderately long span cable-stayed bridges requires the consideration of the wave-passage effects [4]. Ates and et al. considered the stochastic response of an isolated cable-stayed bridge subjected to spatially varying earthquake ground motion [5]. Bi and et al. investigated spatial ground motion excitations and local site amplification effects on bridge responses [6]. Bi and et al. studied the combined effects of ground motion spatial variation, local site amplification and SSI on bridge responses. The soil surrounding the pile foundation is modelled by frequency-dependent spring and dashpots. It was obtained that soil structure interaction significantly influences the structural responses, and cannot be neglected [7]. Soyluk and Sicacik [8] studied that effect of soil–structure interaction (SSI) and spatially varying ground motion depending on incoherence, wave-passage and site-response effects on the dynamic characteristics of cable-stayed bridges. Conclusion of the study is that effects of spatially varying ground motion should be considered in the dynamic analyses of cable-stayed bridges.

As deck of cable-stayed bridges have a large displacement response under ground excitations, the connections between the deck and the tower of bridges become important for earthquake ground motions. In addition to the spatially varying ground motion model has important effects on the dynamic behavior of the structure. Thus, in order to be obtain more realistic bridge responses, spatially varying ground motion and soil conditions should be taken into account in the analysis of cable-stayed bridges.

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 separated 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. Eq. (1) can be reorganized as known and unknown [9];

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

It is possible to separate the total displacement vectors as quasi-static and dynamic components. 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. While analyzing large structures, spatially varying earthquake ground motions should be considered. Effects of spatially varying earthquake ground motion are characterized 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 [10, 11];

$$S_{\ddot{v}_{g_\ell}\ddot{v}_{g_m}}(\omega) = \gamma_{\ell m}(\omega)\sqrt{S_{\ddot{v}_{g_\ell}\ddot{v}_{g_\ell}}(\omega)\, S_{\ddot{v}_{g_m}\ddot{v}_{g_m}}(\omega)} \tag{3}$$

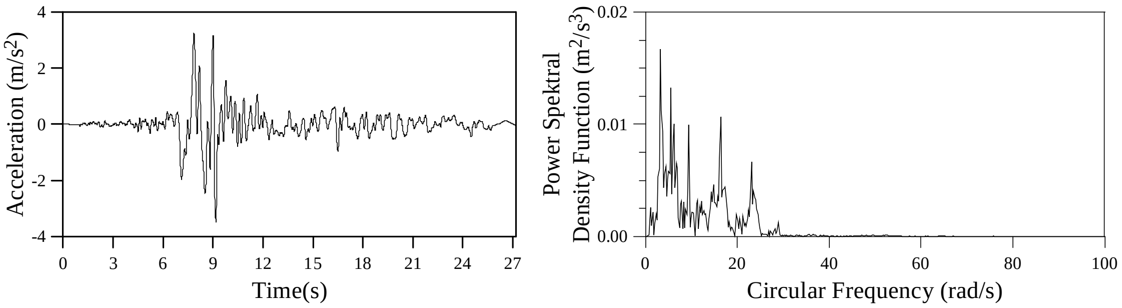
where $\gamma_{\ell m}(\omega)$ denotes the coherency function. The power spectral density function is assumed to be of the following form suggested by Clough and Penzien [12];

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

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.

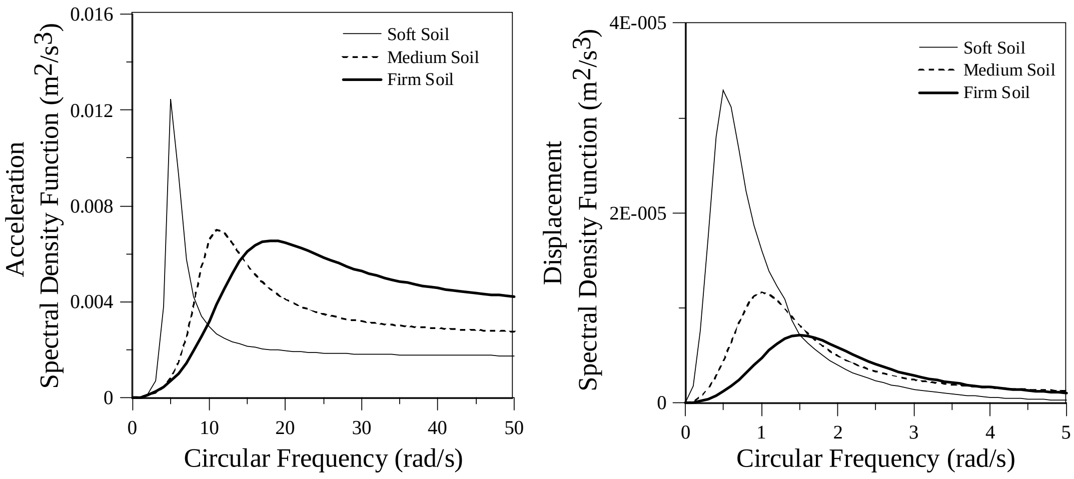
In this paper, S_o is obtained for each soil layer type by equating the variance of the ground acceleration to the variance of Kocaeli Earthquake in 1999. Homogeneous soft, medium and firm layer soil types are used for the cable-stayed bridge supports. Calculated values of the intensity parameter for each soil type and the filter parameters for these soil types, which are proposed Der Kiureghian and Neuenhofer [13], are utilized.

Duzce earthquake records are used in 1999 Kocaeli Earthquake, which is given in Fig. 1(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 Figure 1(b), Figure 1(c) and Figure 1(d), respectively.



a)

b)



c) d)

Figure 1 1999 Kocaeli, Turkey, earthquake; a) acceleration time history b) power spectral density function, c) acceleration spectral density function, d) displacement spectral density function

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

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

Where $\left|\gamma_{\ell m}(\omega)\right|^{i}$ characterizes 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 [14]. The wave-passage effect resulting from the difference in the arrival times of waves at support points is defined as;

$$\gamma_{\ell m}(\omega)^{w} = e^{i(-\omega d_{\ell m}^{L} / v_{app})} \tag{7}$$

Where v_{app} is the apparent wave velocity and, $d_{\ell m}^{L}$ is the projection of $d_{\ell m}$ on the ground surface along the direction of propagation of seismic waves [14].

Modeling of Soil-Pile System of the Cable-Stayed Bridge

The work example in this study is the Quincy Bay-view Bridge at Illinois, USA. 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 70.7 m from the waterline. There are 56 cables, 28 supporting the main span and 14 supporting each side span.

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. There are three changes in the leg cross-section over the height of the towers. The related properties of the bridge deck-towers and the cables are given, respectively, in Table 1 and Table 2. The towers of cable-stayed bridge are supported on rigidly capped vertical pile groups, layered soil overlying rigid bedrock. A % 2 damping coefficient and a lumped mass model is adopted for the response calculations.

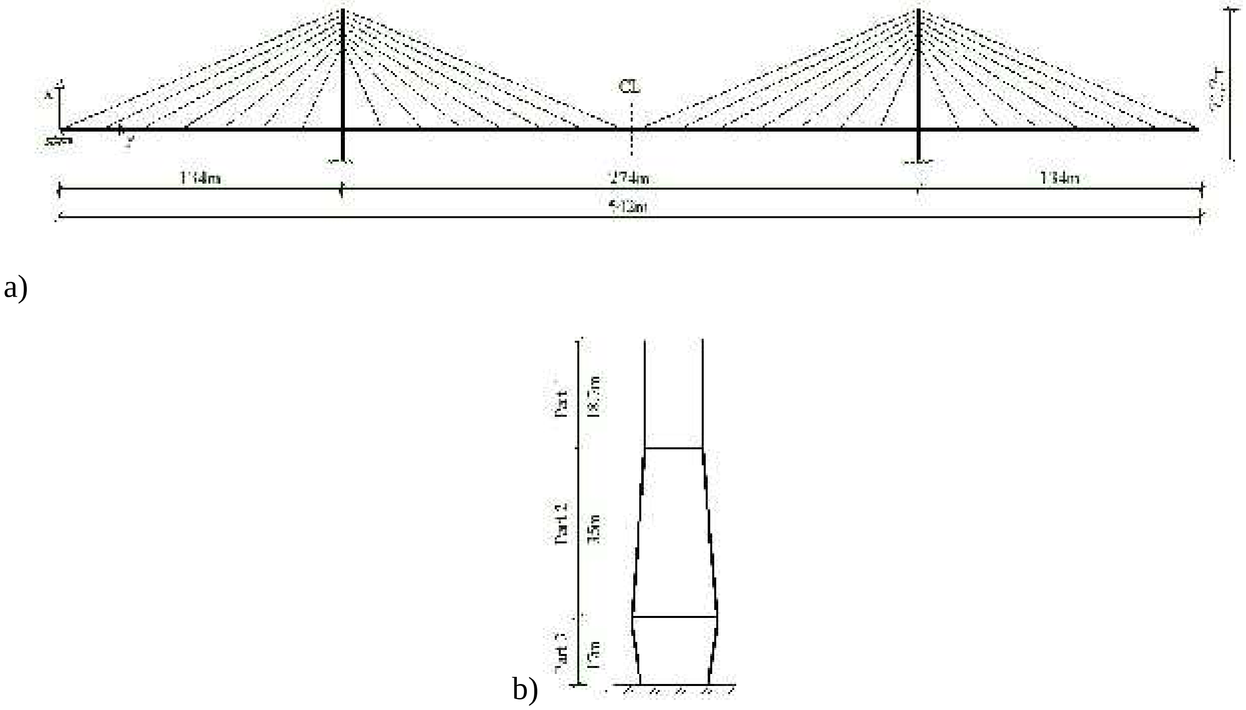


Figure 2 Details of the cable-stayed bridge model (a), and of the towers (b).

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. Nonlinear behavior of cables 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 [15].

Table 1 Properties of the deck and the towers

Element Name	A(m2)	Iz (m4)	E (kN/m2)	W (kN/m)
Deck	0,827	0,34	2,1x10^8	118,59
Tower (Part1)	14,12	532,20	30,787x10^6	339,30
Tower (Part2)	14,12	795,20	30,787x10^6	339,30
Tower (Part3)	30,75	1250,36	30,787x10^6	738,92

Table 2. Properties of the stay cables

Cable Name	A (m^2)	E (kN/m^2)	W (kN/m)
1	0.0180	2.1x10^8	1.76580
2	0.0135	2.1x10^8	1.32435
3	0.0107	2.1x10^8	1.04967
4	0.0070	2.1x10^8	0.68670

Long span bridges are generally supported on pile foundations. Several types of models may be used for the seismic analysis of bridges with pile foundations. 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 Figure 3. The stiffness of the soil is represented with springs and dashpots. 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.

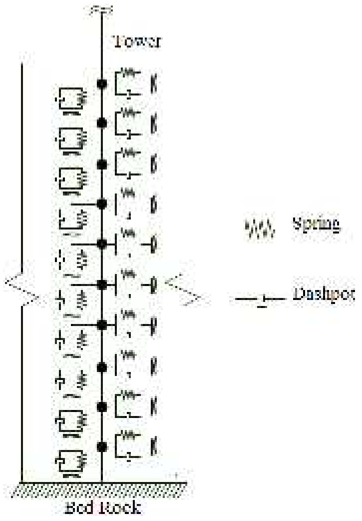


Figure 3. Schematic of beam on Winkler foundation model in the layered soil strata

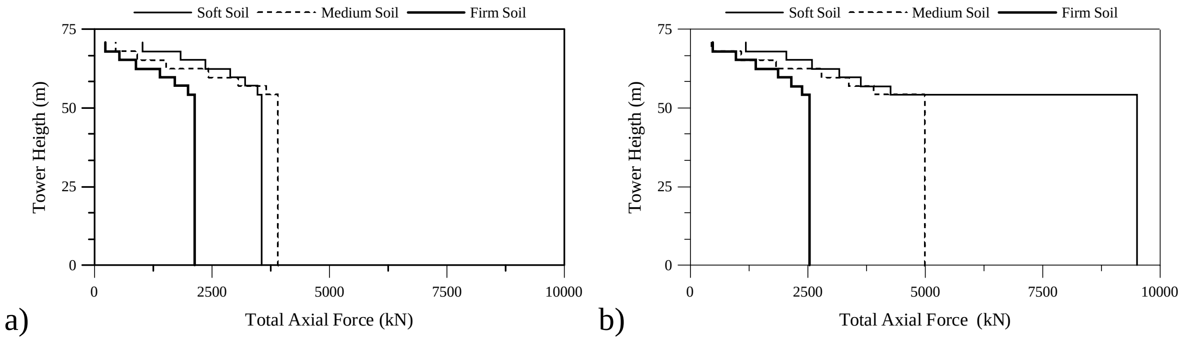
In this study, the rigid bedrock is available at a depth of 25 m, soil springs are distributed at 2.5m centers. Thence, the separation of pile into 11 segments by using 10 springs is enough to achieve sufficient accuracy in the analysis. The dynamic properties of the soils are used in the analyses that vary with the depth are given in Table [16].

Table 3. 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

Numerical Computations

Results of stochastic analyses of bridge obtained with and without SSI are presented in Figures 4–5 for soft, medium and firm soil layers.



a) b)

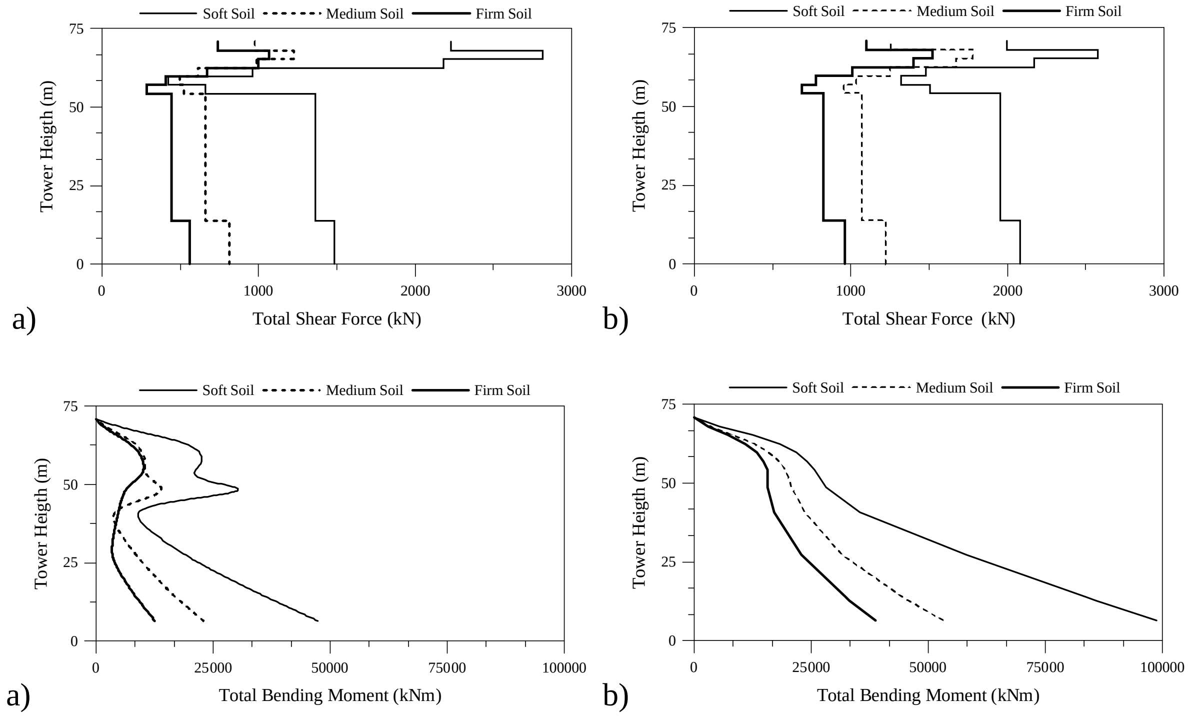
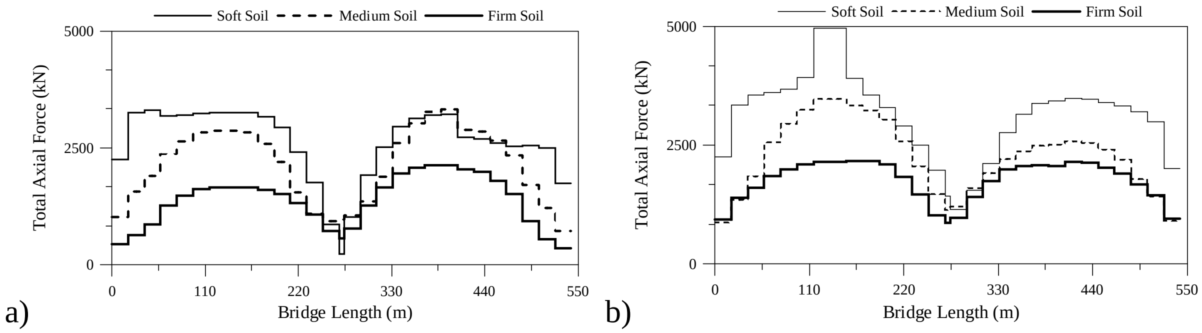


Figure 4 Element forces of the bridge along the tower, a) without SSI and b) with SSI

The results indicate that there are important effects with the type of soil considered especially homogeneous soft soil layer. Figure 4-5 show total element forces along the height of tower and bridge deck. It can be observed that especially for soft soil strata and with SSI, element forces are more excessive than the other soil strata and that especially for soft soil total shear force is much bigger than the other soil strata at the deck-tower junction.



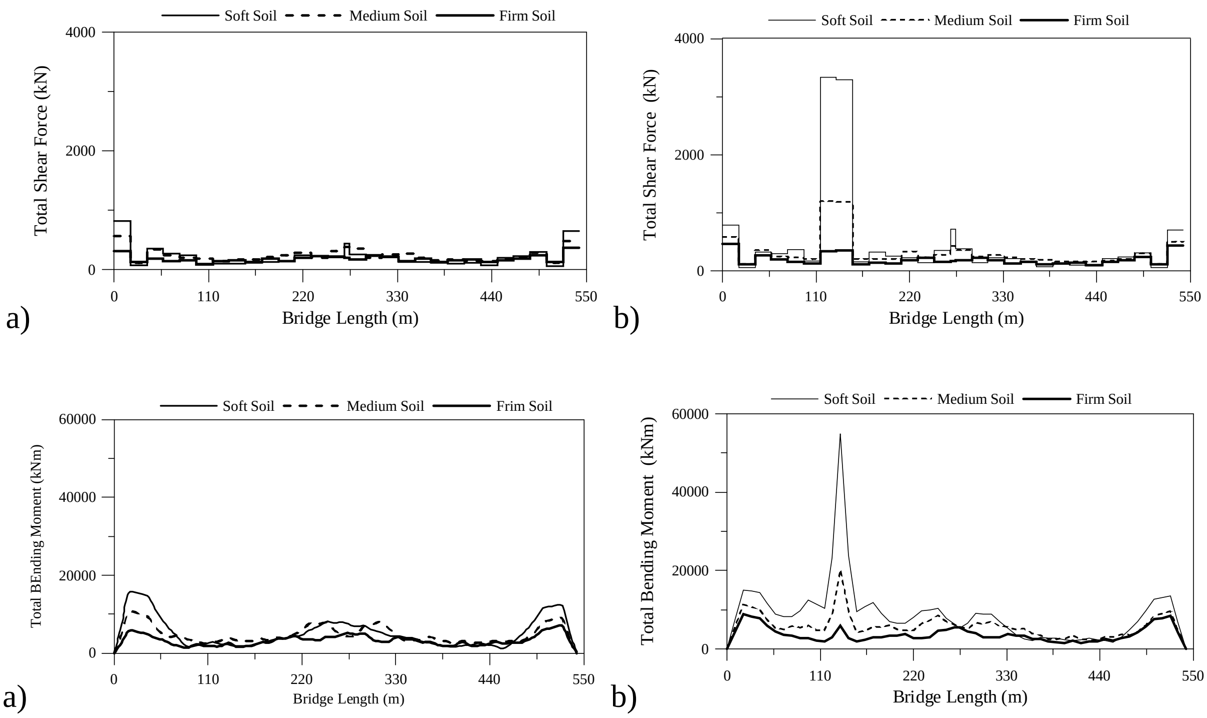


Figure 5. Element forces of the bridge along the deck, a) without SSI and b) with SSI

CONCLUSION

This study summarizes the stochastic response of a cable-stayed bridge in case of wave-passage effects subjected to spatially varying ground motions with and without SSI. The bridge is modeled by using finite element method. Three types of layered soil strata, namely, soft, medium and firm, have been considered for the study. Results obtained from this research indicate that the SSI effects, especially soft soil strata, are important on seismic response in the dynamic behavior of the bridge in case of the wave-passage effects.

REFERENCES

[28] Hao, H. and Zhang, S.R. (1999) Spatial ground motion effect on relative displacement of adjacent building structures, *Earthquake Engineering and Structural Dynamics*, 28, 4, 333–349

[29] 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, 1301–1310.

[30] 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, *JSCE*, 49A,2 , 475-486.

[31] Soyluk, K. and Dumanoglu, A.A. (2004), Spatial variability effects of ground motions on cable-stayed bridges, *Soil Dyn. Earthq. Eng*., 24, 241-250.

[32] Ates, S. Soyluk, K. Dumanoglu, A.A. and Bayraktar, A. (2009) Earthquake response of isolated cable-stayed bridges under spatially varying ground motions, *Structural Engineering and Mechanics*, 31, 6,639-662

[33] Bi, K. Hao, H. and Chouw N. (2010) Required separation distance between decks and at abutments of a bridge crossing a canyon site to avoid seismic pounding, *Earthquake Engng Struct. Dyn*., 39, 3, 303–323.

[34] 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 , *Earthquake Engng. Struct. Dyn.*, 40, 1027–1043

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

[36] 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.

[37] Abrahamson, N.A. Schneider, J.F. and Stepp, J.C. (1991) Empirical Spatial Coherency Functions for Application to Soil-Structure Interaction Analyses, *Earthquake Spectra*, 7,1, 1-27.

[38] Heredia-Zavoni, E. and Vanmarcke, E.H. (1994) Seismic Random Vibration Analysis of Multi-support Structural Systems, *Journal of Engineering Mechanics*, 120, 5, 1107-1129.

[39] Clough, R.W. and Penzien, J. (1993) Dynamic of Structures, Second Edition, McGraw Hill, Inc., Singapore.

[40] Der Kiureghian, A. and Neuenhofer, A. (1991) A Response Spectrum Method for Multiple-Support Seismic Excitations, Earthquake Engineering Research Center, University of California, Berkeley., Report No. UCB/EERC-91/08.

[41] Der Kiureghian A., (1996) A Coherency Model for Spatially Varying Ground Motions, Earthquake Engineering and Structural Dynamics, 25, 1, 99-111.

[42] Ernst, H.J., 1965. Der E-Modul Von Seilen Unter Brucksichtigung Des Durchhangers, Der Bauingenieur, 40, 2 , 52-55.

[43] Wolf, J.P., 1985. Dynamic Soil–Structure Interaction, USA: Prentice-Hall.