2^{nd} *International Balkans Conference on Challenges of Civil Engineering, BCCCE, 23-25 May 2013, Epoka University, Tirana, Albania.*

Dynamic Responses of Bridges under Effects of Asynchronous and Multiple Support Excitations

Fevzi Sarıtaş

Department of Civil Engineering, Pamukkale University, Turkey

ABSTRACT

Nonstationary earthquakes are very complex ground motions and they vibrate structural systems in asynchronous form. Spatial variation of an earthquake mainly originates from three sources; loss of coherence effects, wave passage and local soil conditions. In this study, a long-span bridge having multi-support excitations were analyzed for the effects of spatially varying ground motions in terms of wave passage and local site response effects. Two types of dynamic analyses were performed: a) same or different soil conditions for all supports b) same ground motions but different arrival times for wave propagation. For evaluations, the results obtained by considering asynchronous ground motions were compared with those of the synchronous ground motions. From the comparisons, significant differences were observed in case of spatially varying ground motions and this case show that the assumption of synchronous ground motions and identical local site conditions are inadequate to represent the earthquake load and soil model. Therefore, earthquake motions and actual local site properties should be characterized by their inherent properties to obtain more realistic responses.

Keywords: *Wave-passage, multiple-support excitation, time history, finite element, bridge*

1. INTRODUCTION

Bridges are long and quite important structural systems in engineering fields and they require special attentions for a design or analysis process. Most of them are still located in seismic regions and they can vulnerable to large damages or corruptions in a strong ground motion. Their seismic responses include high variability in time and spatial position. Spatially varying ground motions can be explained by three main reasons; loss of coherence (incoherence effects due to refractions, reflections), different site conditions, wave-passage effect (different arrival times of motion to supports). However, the traditional seismic analyses are commonly realized by uniform ground motions at all supports. It means that, earthquakes are taken into account as same excitations with arrival times and spatial effects are disregarded. On the other hand, the researches and observations obtained from the past earthquakes have shown that the uniform ground motion assumption is not realistic for widely-spaced structures like bridges. Because, earthquake motions originated from bedrock level travel to ground surface with multi-components and unequal spectral contents (amplitudes, phases and etc.) due to refractions, reflections and various site properties. Asynchronous ground motions propagate in spatial varying form because of loss of correlations (coherency), wave passage effects (delay in arrival times), and local site properties. Since 40 years, many investigations and analyses have been performed by various researchers ([1], [2], [3] and followings) to understand the effects of asynchronous ground motions and behavior of bridges. Furthermore, if the considered structure is too long then many parameters such as support distances, local site conditions would have larger influences on the behaviors in compared to short structures. Therefore, earthquakes vibrate a bridge system by multi-component load effects and nonuniform multi-support movements. Especially in long-span bridges, the effects of variability in time arrivals, amplitudes, phase angles and local site properties play critical role in the defining of the structural responses. In the earthquake motion, time delays between the supports cause to different support movements which as named quasi-static loads effects. As the distances between the supports increase, the coherence would decrease. That is to say, the effects of spatial varying ground motions become more significant. The effects of spatially varying earthquake ground motions (SVGEM) have been investigated by many researchers in the past decades with increasing attention. Under effects of stationary random vibrations, a response spectrum method was developed for the multiply supported structures by Kirueghian and Neuenhofer [4]. A method for nonstationary earthquake responses of suspension bridges was presented by multiple support excitations [5]. It was pointed out the correlation effects between different pier-supports cause to large differences on the seismic responses. Vanmarcke and Harichandran [6] considered several earthquake motions as space-time random field processes to determine the variations of the earthquakes in time and space. The results show that coherency values are slightly dependent on direction of the motion and decrease with ascending distances. In multi support excitations, a simplified multisupport response spectrum (MSRS) method has been used to obtain structural behavior by sum of pseudo-static and dynamic responses. The response quantities obtained from MSRS analyses were compared with those of the uniform excitation case and the higher responses where close to support regions were observed due to differential support movements [7]. The effects of asynchronous earthquakes were investigated on suspension together with arch bridges and the responses were obtained by two different models; identical and delayed excitations [8]. This study shows that the assumption of the identical excitation generally gives inaccurate responses for the considered long-span bridges. Asynchronous response of a structural system can be defined as a complex combination of many parameters such as dynamic modal behaviors and pseudo-static displacements. If nonuniform (asynchronous) earthquakes are taken into account for a considered record, response values can either decrease or increase. For irregular bridge structures, geometric incoherence yields greater response amplification than wave delay. In many cases, response amplifications are observed due to asynchronous ground motions [9]. When the ground motions of the considered site yield loss of coherence, they would have low phase differences and the effects of earthquake propagation can be disregarded [10]. Displacement ductility demand of the bridges designed for synchronous earthquakes may be larger in case of asynchronous ground motions [11]. By using the relationship between the power spectral density function and response spectrum of multi-component ground motion, a response spectrum method are available to analyze of bridges on the basis of random vibration as well. From this study, it was found that the mean peak responses were remarkably influenced by the angle of earthquake propagation [12].

In this study, the effects of asynchronous ground motions and different local site conditions were studied on a continuous long-span bridge. The bridge system was modeled by finite element method and its dynamic responses were obtained by time history analyses. The required analyses were performed by using a software package [13]. Structural responses were compared with reference to maximum quantities obtained by considering different velocity of wave propagations and quasi-static effects.

2. TIME DOMAIN REPRESENTATION OF SEISMIC EXCITATION

Under effect of multiple support excitations, the general equations of motion of a linear multi-degree system should contain the degrees of freedom at supports. An extensive investigation about multiple support excitations of cable-stayed bridges was performed with nonlinear analyses by some researchers [14]. The equations of motion of a multi-degree system may be expressed in matrix form [15],

$$\begin{bmatrix} \boldsymbol{M_r} & \boldsymbol{M_{rs}} \\ \boldsymbol{M_{rs}^T} & \boldsymbol{M_s} \end{bmatrix}\begin{Bmatrix} \boldsymbol{\ddot{u}_r} \\ \boldsymbol{\ddot{u}_s} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C_r} & \boldsymbol{C_{rs}} \\ \boldsymbol{C_{rs}^T} & \boldsymbol{C_s} \end{bmatrix}\begin{Bmatrix} \boldsymbol{\dot{u}_r} \\ \boldsymbol{\dot{u}_s} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K_r} & \boldsymbol{K_{rs}} \\ \boldsymbol{K_{rs}^T} & \boldsymbol{K_s} \end{bmatrix}\begin{Bmatrix} \boldsymbol{u_r} \\ \boldsymbol{u_s} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{0} \\ \boldsymbol{F(t)} \end{Bmatrix} \tag{1}$$

where F(t) is the reaction force by $n_s \times 1$ at the support points**.** The parameter n_s states number of support and n_r is defined by number of unconstrained degrees of freedom (DOF)). $\mathbf{K_r}$, $\mathbf{M_r}$ and $\mathbf{C_r}$ are stiffness, mass and damping matrix by r×r for unconstrained DOF. $\mathbf{K_s}$, $\mathbf{M_s}$ and $\mathbf{C_s}$ are matrices by s×s for support DOF; Krs, $\mathbf{M_{rs}}$ and $\mathbf{C_{rs}}$ are matrices by r×s for all other DOF (unconstrained and support). The parameters $\mathbf{u}$, $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$ are displacement with first and second derivatives. Total response consists of dynamic response and support movement; in this case total displacement vector can be written as summation of pseudo static component and vibrational displacements,

$$\begin{Bmatrix} u_r \\ u_s \end{Bmatrix} = \begin{Bmatrix} u_{pr} \\ u_{ps} \end{Bmatrix} + \begin{Bmatrix} u_{vr} \\ 0 \end{Bmatrix} \tag{2}$$

By applying unit displacements at the supports, the pseudo-static displacements at time t can be written with δ(t) displacement function for i-th degree of freedom of a support by,

$$\begin{Bmatrix} u_{pr} \\ u_{ps} \end{Bmatrix} = \sum_{i=1}^{n_s} \begin{Bmatrix} u_{pr_i} \\ u_{ps_i} \end{Bmatrix} \delta_i(t) \tag{3}$$

where the indices p and v denote the displacement components resulted from pseudo-static and vibrational effects, respectively. The dynamic equilibrium of vibrational components are defined by,

$$\ddot{Y}_n(t) + 2\xi_n\omega_n\dot{Y}_n(t) + \omega_n^2 Y_n(t) = -\sum_{i=1}^{N_s}\Gamma_{1n}\ddot{\delta}_i(t) - \sum_{i=1}^{N_s}\Gamma_{2n}\dot{\delta}_i(t) \tag{4}$$

where $Y_n(t)$ is the generalized coordinate of n-th mode, ξ and ω^2 are the damping ratio and eigenvalue of the vibrational motion and N_s is the number of support motion. Γ_{1n} and Γ_{2n} are the modal participation coefficients defined by;

$$\Gamma_{1n} = L_{1n}/M_n \qquad \Gamma_{2n} = L_{2n}/M_n \tag{5}$$

$$\mathbf{L_{1n}}\ \text{Z}\ \text{¤}_{\mathbf{n}}^{\mathbf{T}}\mathbf{M_n D_n} \qquad \mathbf{L_{1n}}\ \text{Z}\ \text{¤}_{\mathbf{n}}^{\mathbf{T}}\mathbf{C_n D_n} \qquad \mathbf{M_n}\ \text{Z}\ \text{¤}_{\mathbf{n}}^{\mathbf{T}}\mathbf{m}\text{¤}_{\mathbf{n}} \qquad (6)$$

D_n is the transpose of the pseudo-static displacements (u_{pri}, u_{psi}) given in the Eq.(3).

3. STRUCTURAL MODEL OF BRIDGE SYSTEM

A five-span bridge system has been considered to investigate the effects of asynchronous ground motions and multi support excitations. The bridge shown in Figure 1 has a box-girder having variable cross-section in the form of V-shape and rectangular piers with hollow sections. The system was discretized at the defined nodal points and by using 3D beam elements; its finite element model is established as seen in Figure 2. The distributed mass of the system is lumped at both nodal points of the each element. Governing equations of equilibrium for the system subjected to static and dynamic loads are developed by considering the nodal forces of the system.

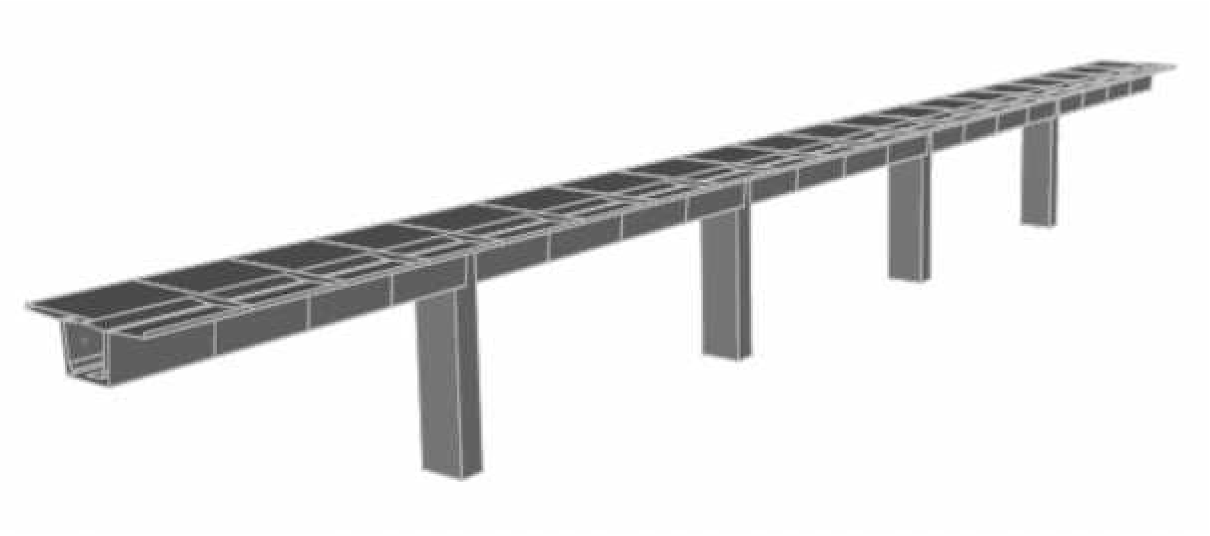


Figure 1. 3D view of the bridge system

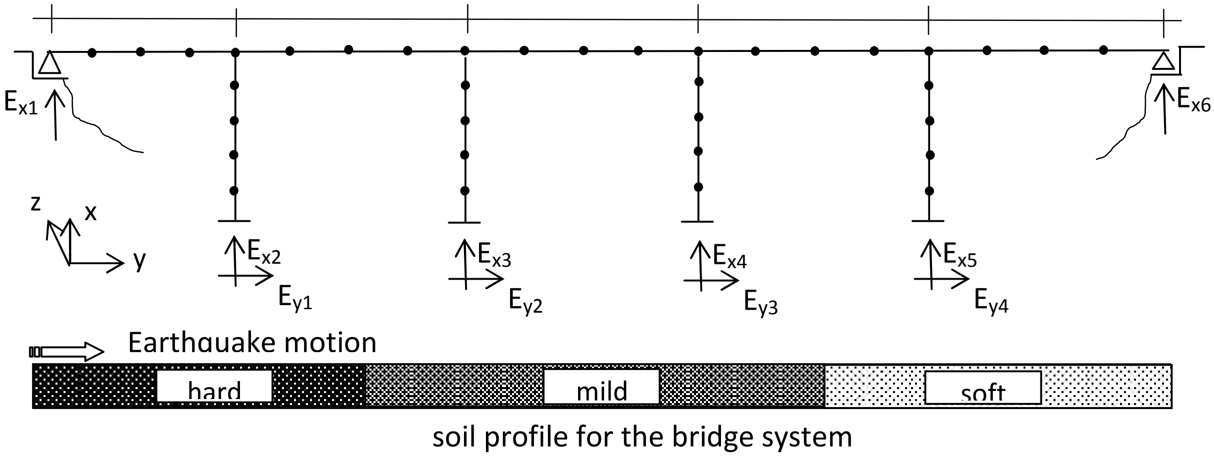


Figure 2. Finite element model under effects of multi-component earthquakes at each

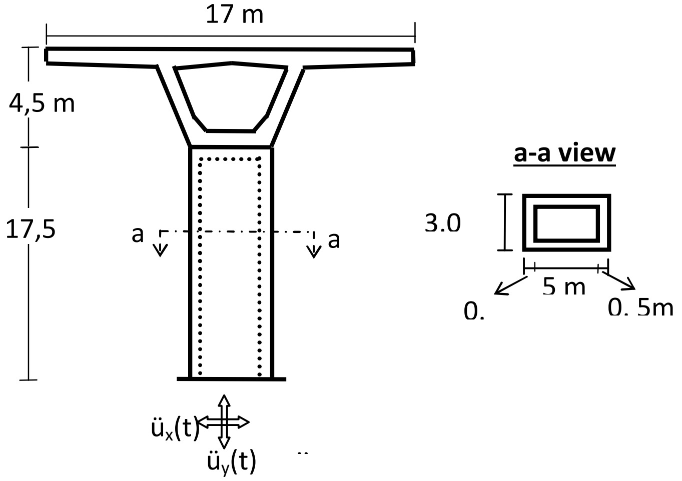


Figure 3. Elevation of a pier and dimensions

4. EARTHQUAKE MOTIONS FOR MULTI-SUPPORT EXCITATIONS

The earthquake loads were applied to the system as three cases; longitudinal (y), lateral (x) and in both directions (x, y). In case of two components, the incidence angle of earthquake propagation was considered by angle of 45° as seen in Figure 4. The required ground motions were generated for time history analysis on the basis of a recorded accelerogram. For local site conditions, three types of ground motion for soft, middle and hard soil were used to use in the multi-support excitations. In structural analyses for uniform soil conditions, the amplitudes and frequency contents of the ground motion were considered as the same motion for all supports. However, nonuniform soil conditions causes to differential site response effects and variations appear in characteristics of the acceleration records. Furthermore, multi support excitations generate pseudo-static effects on a structural system due to different support motions. It is known that dynamic analyses require time history records in terms of accelerations and quasi-static responses require displacement time histories to input support motions.

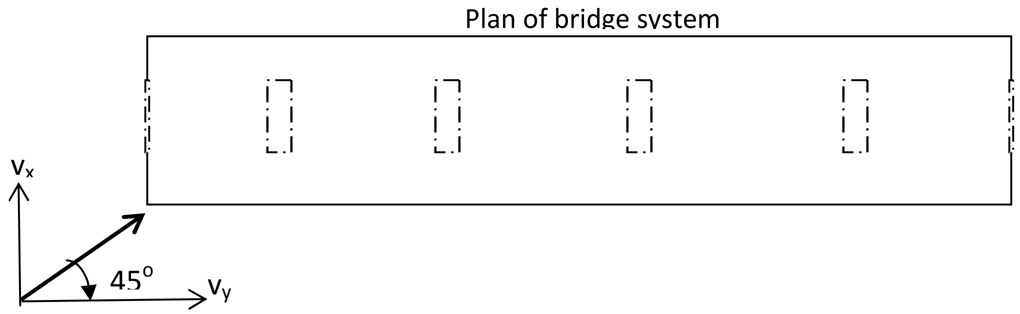


Figure 4 Direction of earthquake wave propagation with two

Each support may have different local soil condition with its acceleration and displacement time history. The acceleration and displacement time histories used in the analyses were given in Figure 5 for each soil type.

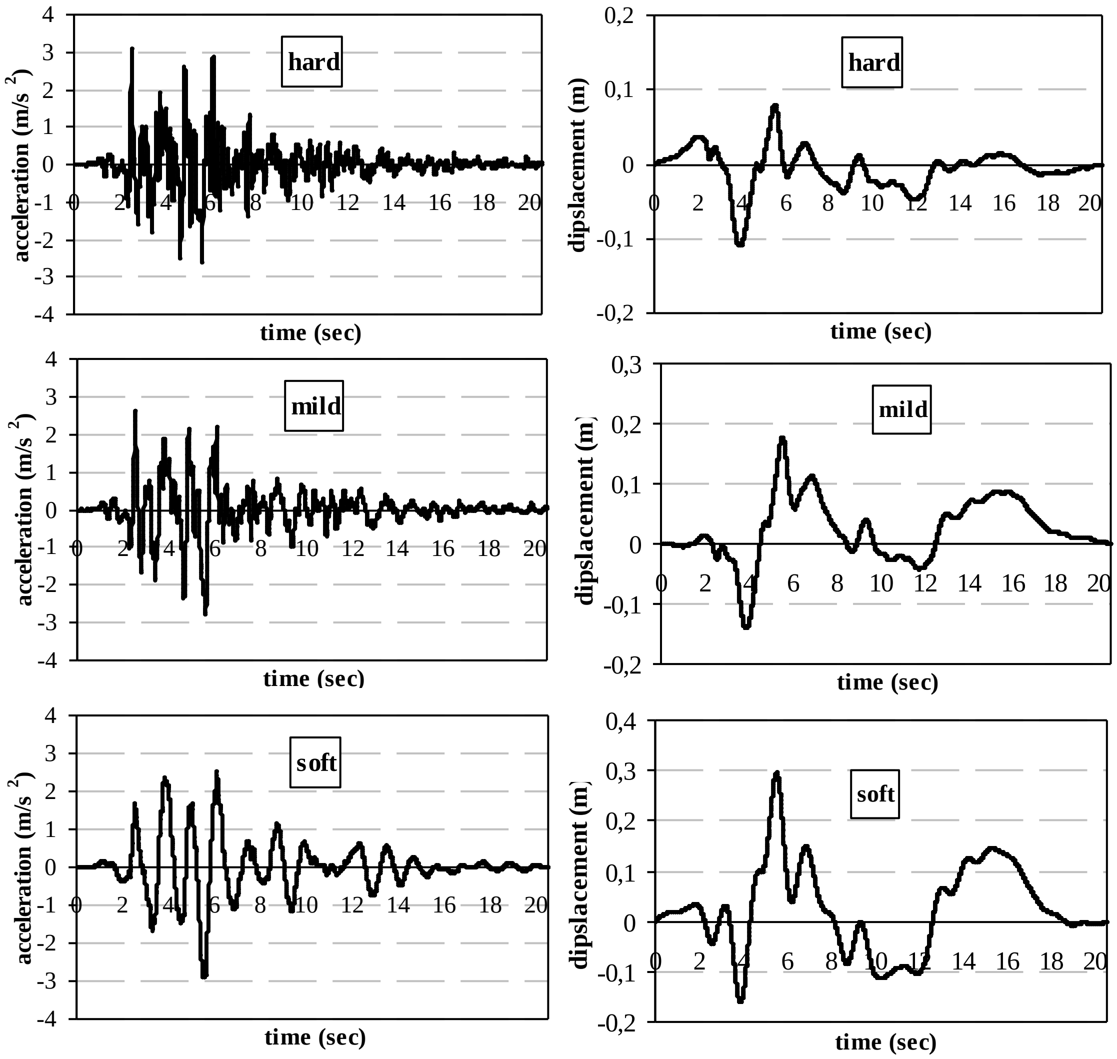
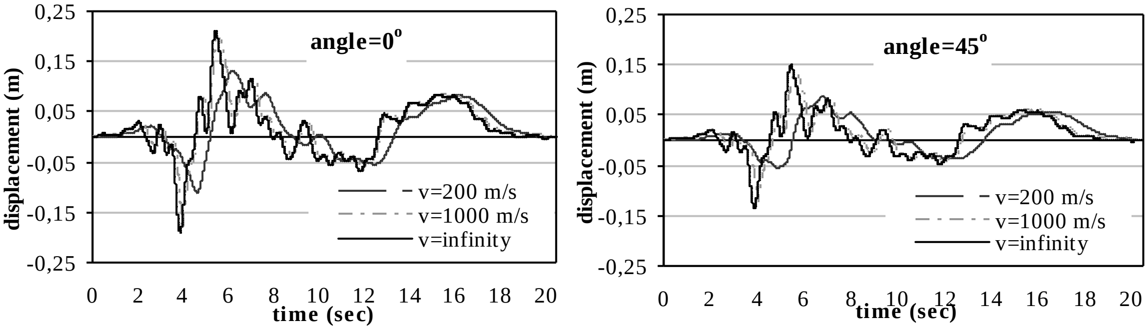


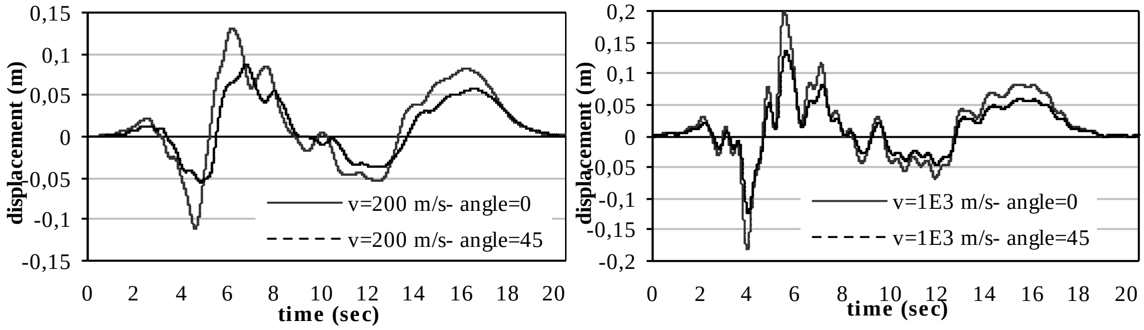
Figure 5. Acceleration and displacement time history records for different soil types

5. TIME HISTORY ANALYSES OF THE BRIDGE SYSTEM

Time history analyses of the bridge system were implemented for different cases by using acceleration and displacement time history records given in Figure 5. Firstly, the effects of velocity of earthquake motion were shown on deck displacements (at middle joint of middle span) in Figure 6 by considering different incidence angles (Figure 4). From the figures, it is understand that as the velocity decreases, the displacements generally differentiate and the deviations from the results of infinity velocity (no delay) become more significantly. It means that while displacements decrease in some time-intervals, they may increase in other intervals. But maximum displacement values were observed at higher velocities of motion (Figure 6b). Furthermore, the incidence angle of 45^o caused to larger differences in displacements especially for the low velocities. Secondly, quasi-static effects caused by different local site characteristics were investigated on the system responses. For this purpose, pier base moment and shear forces were obtained and given for uniform and multiple-soil conditions in Figure 7. If the soil conditions of all piers are not uniform, i.e. multi-support excitations, the responses generally increase and vary distinctly due to relative support displacements. The variations of pier base moments in lateral directions occur more specifically than those of the longitudinal direction.

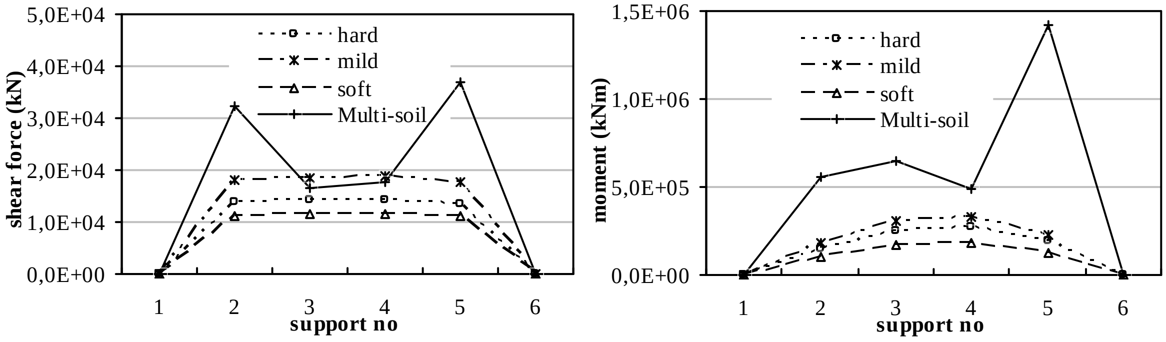


a- comparisons of responses for different velocities of the earthquake motion



b- comparisons of responses for different angles of the earthquake propagation

Figure 6. Comparisons of deck displacements in longitudinal direction



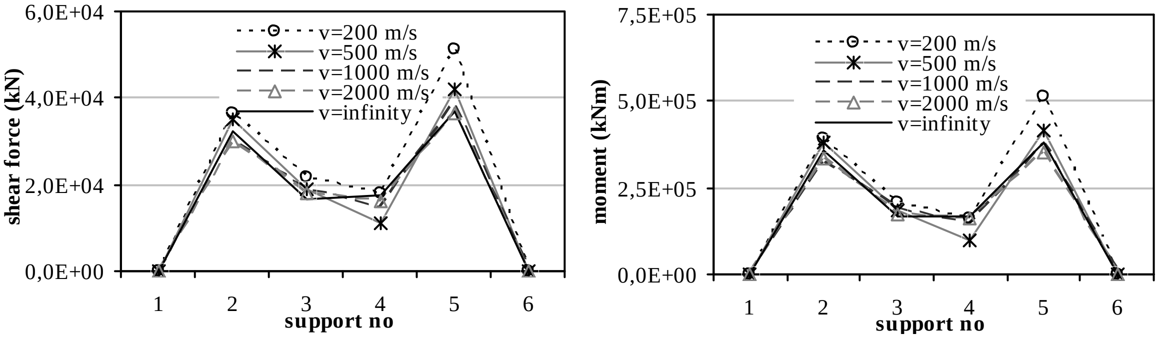
a- shear forces in longitudinal direction

b- moment in lateral

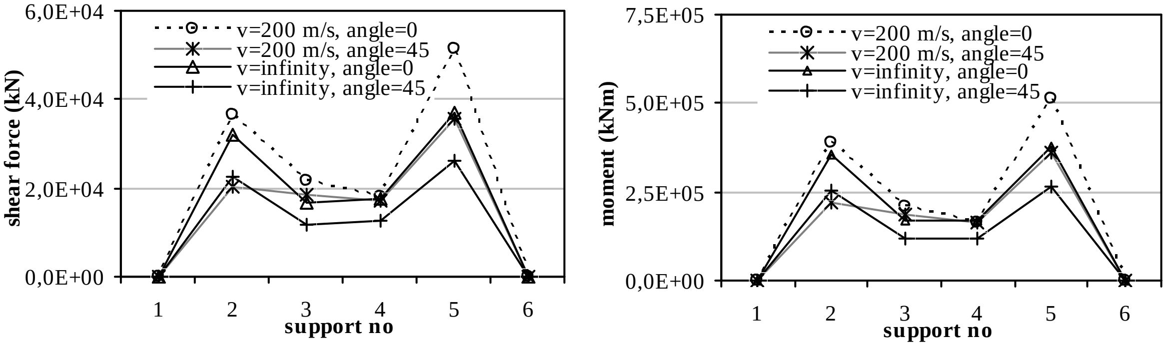
direction

Figure 7. Comparisons of responses by assuming identical soil conditions and multiple

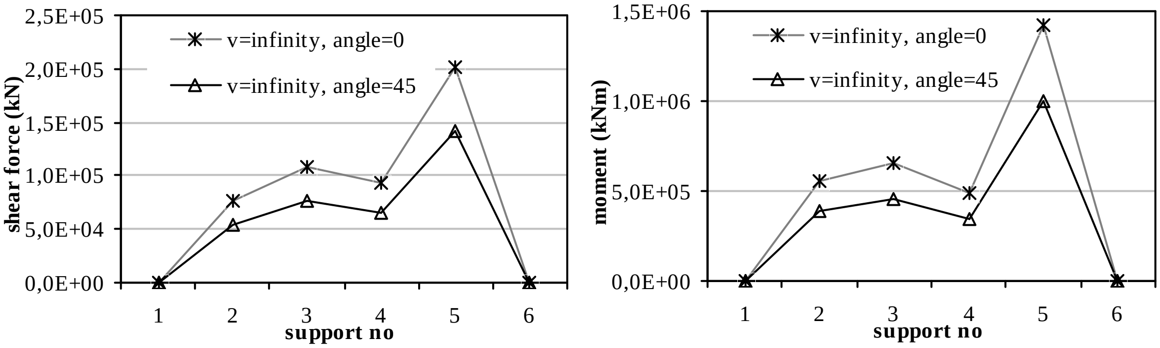
Finally, variations in pier base responses were shown in Figure 8 for various velocities and incidence angles of earthquake propagation in longitudinal and lateral directions. From figure 8a, it can be easily seen that the maximum quantities of the pier base responses developed at the lowest velocities. The same observations were determined in the case of incidence angle of 45^o as well (Figure 8b). The pure effect of incidence angles on the pier responses were shown for infinity velocity of motion in lateral direction in Figure 8c. The most unfavourable response quantities appear in case of earthquake motion on principal axis of the bridge system i.e., zero incidence angle. The increasing of incidence angle results in lower response quantities for the base responses (shear forces and moments).



a- Longitudinal base responses, angle=0



b- Longitudinal base responses by considering different incidence angles



c- Lateral base responses by considering different incidence angles

Figure 8. Various comparisons for the pier- base responses

6. CONCLUSION

Seismic responses of a continuous bridge system were analyzed by finite element method under effects multiple support excitations and asynchronous ground motions. The analyses were realized in time history domain and maximum quantities of deck displacements and pier base reactions were compared with respect to different motion velocities and soil conditions. From the analyses, nonuniform soil conditions (multiple-support excitations) and asynchronous ground motions have significant effects on the dynamic responses. The conclusions can be summarized by following items:

- Delays in wave arrival affect the dynamic behaviour of the bridge system. When the velocity of the wave decreases, deck-displacements generally decrease as well and the deviations become more significantly according to results in case of infinity velocity.
- Incidence angle has a nonignorable role in the determining of the responses and the incidence angle of 45^{o} causes to large differences especially for the low velocities.
- If the local site properties are not uniform, i.e. different soil conditions for piers, then the distribution of responses are quite affected by quasi-static component due to relative support displacements. In this case, the response quantities are mostly larger than those of uniform soil conditions for all piers.
- Maximum response quantities of the piers appeared for the lowest velocities. The most unfavourable response quantities were observed for the earthquake motion on principal axis of the structural system. Any increment in incidence angle causes to lower structural responses according to responses in principal directions.
- The variations in local site conditions and changes (delay, incoherency and etc.) in ground motions should be taken into consideration to obtain more realistic responses.

7. REFERENCES

[1] Bogdanoff, J.L., Goldberg, J.E. and Schiff, A.J. (1965). The effect of ground transmission time on the response of long structures. *Bulletin of Seismological Society of America*, **55**, 627-640.

[2] Dumanoglu, A.A. and Severn, R.T. (1987). Seismic response of modern suspension bridges to asynchronous vertical ground motion. *Proceed. Inst. Civil Eng*, **2**(83), 701-730.

[3] Kiureghian, A. D. (1981). A response spectrum method for random vibration analysis of mdf systems. *Earthquake Engng. Struct. Dyn*, **9**, 419–435.

[4] Der Kiureghian A. and Neuenhofer A., (1991). A response spectrum method for multiple-support seismic excitations. *UCB/EERC-91/08*, University of California, Berkeley.

[5] Hyun, C.-H. (1992). Nonstationary response analysis of suspension bridges for multiple support excitations. *Probabilistic Engineering Mechanics,* **7**(1192), 27-35.

[6] Harichandran R.S. and Vanmarcke E.H. (1986). Stochastic variation of earthquake ground motion in space and time. *J. Engineering Mechanics*, **112**(2),154–174.

[7] Jihong Y., Zhiqiang Z. and Xianming L, (2012). A simplified multisupport response spectrum method. *Earthq. Eng. and Vib.,* **11**(2), 243-25.

[8] Harichandran R.S., Hawwari A. and Sweidan B.N. (1996). Response of Long-Span Bridges to spatially varying ground motion. *J. of Struct. Eng*, **122**(5), 476-484.

[9] Burdette N.J., Elnashai A.S., Lupoi A. and Sextos, A.G., (2008). Effect of Asynchronous Earthquake Motion on Complex Bridges I: Methodology and Input Motion. *Journal of Bridge Engineering*, **13**(2), 158-165.

[10] Zerva, A. (1991). Effect of spatial variability and propagation of seismic ground motions on the response of multiply supported structures. *Prob. Eng. Mech.*, **6**(3–4), 212-221.

[11] Monti, G., Nuti, C. and Pinto, P. (1996). Nonlinear Response of Bridges under Multisupport Excitation. *J. Struct. Eng.*, **122**(10), 1147–1159.

[12] 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**(2000), 1367–1377.

[13] SAP2000 (1995). Structural Analysis Program, Computers & Structures, Inc., Berkeley.

[14] Nazmy, A.S. and Abdel.Ghaffar A.M. (1990). Nonlineer Earthquake Response analysis of long-span cable-stayed Bridges: applications. *Earthq. Eng. and Struct .Dyn.*, **19**, 63-79

[15] Chopra A.K. Dynamics of Structures. Prentice-Hall,1990, New Jersey.