ENGLISH VERSION...

Excitación sísmica asíncrona en puentes: patrones de asincronismo, métodos de análisis y tipologías estudiadas

Asynchronous seismic excitation in bridges: asynchronous patterns, analysis methods and structural types studied

J. Ardila[1]*, G. Chio*, J. Benjumea*

*Universidad Industrial de Santander, Bucaramanga. COLOMBIA

Abstract

This paper shows the importance of performing an asynchronous dynamic analysis for some bridge types. First, the existence and damage caused by the asynchronous seismic excitation are explored. Then, the general mathematic expression that describes the movement of structures under non-uniform seismic excitation in its supports and the asynchronous patterns that characterize the asynchronous phenomenon (wave passage, loss of correlation, and local site effect) are introduced. In a general approach, the analysis methods that have been implemented and the design codes that emphasize the importance of asynchronous analysis on bridges are also presented. Finally, the results obtained by some authors interested in bridges subjected to asynchronous seismic excitation for several structural types are discussed.

Keywords: Asynchronous analysis, uniform analysis, asynchronous seismic excitation, uniform seismic excitation, bridge

Resumen

El presente documento pretende exponer la importancia de realizar un análisis dinámico asíncrono para algunos tipos de puentes. Primero, se exploran los antecedentes que evidencian la existencia y los daños producidos por la excitación sísmica asíncrona. Luego, se presenta la expresión matemática general que describe el movimiento de estructuras con excitación sísmica no uniforme en los apoyos y se determinan los patrones de asincronismo que caracterizan adecuadamente el fenómeno de asincronismo: onda pasajera, pérdida de coherencia y efecto local de sitio. Además, de manera general, se presentan los métodos de análisis que han sido implementados y las normativas que enfatizan la importancia del análisis asíncrono en puentes. Por último, se discuten los resultados obtenidos por algunos autores interesados en puentes sometidos a excitación sísmica asíncrona según la tipología.

Palabras clave: Análisis asíncrono, análisis uniforme, excitación sísmica asíncrona, excitación sísmica uniforme, puente

1. Introduction

From the beginning, linear and nonlinear seismic analyses on cable-stayed bridges were carried out through deterministic methods. In those analyses the seismic movements are assumed to reach to every structure support at the same time, that is to say, there is a uniform seismic excitation considering the propagation velocities of the infinite seismic wave (Soyluk and Dumanoglu, 2000). According to (Luco and Won,g 1986), the seismic records obtained from accelerometer arrays, such as SMART1 in Taiwan, revealed variations in the seismic wave in space and time. For that reason, in the 1060s, began the inclusion of methods in which the seismic excitation was asynchronous, that is to say, that the seismic movements reached the supports with a time lag since the propagation velocities of the seismic wave were assumed as finite in terms of soil stiffness (Valdebenito and Aparicio, 2005) and (Burdette et al., 2008).

The first asynchronous analyses were carried out in large structures with multiple supports such as power transmission lines (Mehanny et al., 2014), (Ghobarah et al., 1996), dams (Bayraktar et al., 1996), symmetrical and

asymmetrical buildings, where, according to (Hao, 1997), the torsional component due to multiple excitation in their supports could be assessed, and lifelines (Deodatis, 1996).

Researchers interested in the asynchronous phenomenon have focused their efforts on studying its effect on bridges with several structural types. Some examples of these studies include (Wang, 1999) and their analyses on long span bridges; (Alvarez, 2002), (Álvarez and Aparicio, 2003) with asynchronism in medium span bridges, such as arched bridges; (Nuti and Vanzi, 2005), who were interest in short-length bridges; and other researches like (Fernandez, 2013), who generally found out that if the length of the bridge is greater than the wavelength of the seismic movement or if there is a significant topographic accident, then some parts of the bridge will be subjected to different and significant excitations in its supports. In the same line, (Kaiming, 2013) also emphasize the importance of carrying out an asynchronous analysis in bridges subjected to abrupt topographic changes.

The present review is intended to show the current status of the knowledge regarding the contributions made by different researchers, who have studied the behavior of bridges subjected to asynchronous seismic excitation. The aim of the above is to gather the necessary evidence to determine the conditions under which an asynchronous analysis must be carried out in bridges and the tools available to carry out the

---

[1] *Corresponding Author:*

Universidad Industrial de Santander, Colombia
E-mail: john.ardila1@correo.uis.edu.co

aforementioned analysis. For this purpose, the document gathers the background information, that is to say, structural damages attributed to asynchronism, analysis methods available and their advantages and disadvantages, the requirements embodied in regulations and design guidelines, which introduce the asynchronous analysis by taking into account parameters such as the total length of the bridge, the type of supporting soil, etc., and the results obtained from asynchronous analyses on bridges grouped by structural types. This document ends with the presentation of the relevant conclusions for the performed review.

2. Background Information

The need of carrying out an asynchronous analysis on bridges has been justified to a great extent by the failures of the interstate 10 viaduct and the Gavin Canyon Bridge during the Northridge earthquake in 1994, and the partial collapse of some viaducts in the city of Kobe in 1995. Such failures were attributed to geometrical complexities such as the skewed abutments in the case of the Gavin Canyon Bridge, inadequate expansion joints, differential movements at the foundation level and torsional movements similar to those of a snake (snaking effect), associating the last two movements with the asynchronous seismic excitation (Burdette et al., 2006). It is important to mention that the partial collapse of some viaducts in the city of Kobe was partly caused by the effects of the soil on the structure at a local level, especially in the soft soils, where the ground filters the content of frequencies of the earthquake, thus producing superficial waves having the characteristic soil period and generating important damages on the structure when the fundamental period of the structure is similar to the characteristic soil period (Barbat, 2005).

Additionally, through constant monitoring of the Evripos Bridge in Greece since 1994, there are records of low-intensity seismic events that support the presence of differential displacements at the support level attributed to the asynchronous seismic excitation. According to (Karakostas et al., 2011) this phenomenon can be positive by reducing the displacements in the center of the span and the bending moments in the base of the piers. However, they can be damaged by increasing the movements in the top of the piers and the internal strengths out of the plane of bending movements.

3. Multiple Support Excitation

In the case of structures with multiple support excitation, which are required to include the degrees of freedom in the supports, the general dynamic equilibrium equation can be written as follows (Chopra, 2014):

$$\begin{bmatrix} M & M_c \\ M_c^T & M_g \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{u} \end{Bmatrix} + \begin{bmatrix} C & C_c \\ C_c^T & C_g \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{u} \end{Bmatrix} + \begin{bmatrix} K & K_c \\ K_c^T & K_g \end{bmatrix} \begin{Bmatrix} x \\ u \end{Bmatrix} = \begin{Bmatrix} 0 \\ F \end{Bmatrix} \qquad (1)$$

Where,

M, C and K are respective the matrices of mass, damping and stiffness, associated with the unrestricted degrees of freedom.

M_g, C_g and K_g are the respective matrices of mass, damping and stiffness, associated with the degrees of freedom from the supports.

M_c, C_c and K_c are the respective coupling matrices of mass, damping and stiffness, associated with both groups of degrees of freedom.

x is the total displacement vector of the unrestricted degrees of freedom.

u is the displacement vector in the supports.

F is the force vector in the degrees of freedom of the supports.

(Bayraktar, Dumanoğlu and Calayir, 1996), (Hao, 1997), (Konakli and Kiureghian, 2011), among other authors, determined that the total displacement (x in equation 1) of a point in the structure under the asynchronous analysis could be expressed as the sum of two components: a dynamic component (x_d), produced by inertial forces, and a pseudo-static component (x_{ps}), produced by differential movements at the base. See equation 2:

$$\begin{Bmatrix} x \\ u \end{Bmatrix} = \begin{Bmatrix} x_{ps} \\ u \end{Bmatrix} + \begin{Bmatrix} x_d \\ 0 \end{Bmatrix} \qquad (2)$$

The first part of equation 2 provides the necessary forces (F_s) in the supports, which statically impose the differential displacements x_{ps}, at the foundation level for every moment in time through the following expression:

$$\begin{bmatrix} K & K_c \\ K_c^T & K_g \end{bmatrix} \begin{Bmatrix} x \\ u \end{Bmatrix} = \begin{Bmatrix} 0 \\ F_s \end{Bmatrix} \qquad (3)$$

Now, taking the first line of equation 1, we have:

$$M\ddot{x} + M_c\ddot{u} + C\dot{x} + C_c\dot{u} + Kx + K_cu = 0 \qquad (4)$$

Replacing equation 2 in equation 4, we obtain:

$$M\ddot{x}_d + C\dot{x}_d + Kx_d = F_{ef}(t) \qquad (5)$$

Where the effective seismic force vector will be given by:

$$F_{ef}(t) = -(M\ddot{x}_{ps} + M_c\ddot{u}) - (C\dot{x}_{ps} + C_c\dot{u}) - (Kx_{ps} + K_cu) \qquad (6)$$

The effective seismic force vector could be written in a more simplified way, taking equation 3 into account.

Revista Ingeniería de Construcción   RIC
Vol 33 N°1 2018   www.ricuc.cl

SPANISH VERSION...

$$Kx_{ps} + K_c u = 0 \qquad (7)$$

In this way, the pseudo-static displacements x_{ps} could be expressed in terms of specific displacements in the supports u.

$$x_{ps} = lu \qquad (8)$$

$$l = -K^{-1}K_c \qquad (9)$$

Where l is the influence matrix in charge of describing the influence every displacement has in the supports on each degree of freedom attributed to the superstructure. By replacing equations 7 and 8 in equation 6, we have:

$$F_{ef}(t) = -(Ml + M_c)\ddot{u}(t) - (Cl + C_c)\dot{u}(t) \qquad (10)$$

If accelerations $\ddot{u}(t)$ and the velocities $\dot{u}(t)$ of the ground in the supports are prescribed, with equation 10 the effective seismic forces are known, thus completing the formulation of the equation that controls the asynchronous movement.

The main disadvantage of applying the concept of asynchronous movement has been to establish the appropriate way of characterizing and introducing the asynchronous seismic excitation in the dynamic analysis (Lou and Zerva, 2005), specifically in the way of obtaining or generating the seismic records for each support of the structure. (Ramadam and Novak, 1993) proposed a technique to generate ground displacements randomly, including non-stationary characteristics, by using a sinusoidal function in accordance with time. However, at the present time, there are three ways of obtaining seismograms artificially (Sgambi, et al., 2014):

i) Selecting and modifying actual accelerograms.

ii) Generating artificial accelerograms based on a seismic source model.

iii) Generating artificial accelerograms consistent with the local response spectrum.

It is important to mention that none of the aforementioned techniques are free of errors or approximations in comparison with an actual seismic event. For example, (Deodatis, 1996) tried to provide computing efficiency to the artificial seismogram generation methods, including Fourier transform, but the proposed method leaves the non-stationary component aside, which is inherent in earthquakes.

4. Asynchronous Patterns

According to (Mezouer, Silhadi and Afra, 2010), (Ramadam, Mehanny and Elhowary, 2015) and (Snaebjornsson and Sigbjornsson, 2008), four asynchronous patterns are attributed to the asynchronous seismic excitation. However, in general terms, there are six asynchronous patterns according to (Valdebenito and Aparicio, 2005): wave passage, incoherence phenomenon, local soil conditions, inelastic attenuation, geometrical expansion, and seismic source extent. The last three patterns have no major impact on the asynchronous seismic excitation; therefore, the most commonly used asynchronous patterns according to (Sextos, J. Kappos and Mergos, 2004) are:

i) Wave passage: the difference in the arrival times of the waves at each structure support. The wave passage effect in accordance with the angular frequency (ω) and the distance between the supports (d_{kl}), is determined as follows:

$$\gamma_{kl}{}^{(w)}(\omega) = exp\left[-\frac{i\omega d_{kl}^L}{V_{app}}\right] \qquad (11)$$

Where,

d_{kl}^L is the projection of d_{kl} in the direction of propagation, and

V_{app} is the apparent wave velocity in the rocky environment.

ii) The incoherence or loss of correlation phenomenon: loss of similarity between signals due to multiple reflections, refractions and superpositions during wave propagation in discontinuous and heterogeneous environments. The loss of correlation effect in accordance with the angular frequency (ω), is determined as follows:

$$\gamma_{kl}{}^{(i)}(\omega) = cos[\beta(d_{kl},\omega)]exp\left[-\frac{1}{2}\alpha^2(d_{kl},\omega)\right] \qquad (12)$$

Where,

d_{kl} is the horizontal spacing between supports k and l, and

α and β are angles depending on d_{kl} and ω.

iii) Local soil conditions: the significant variation of the type of soil on which the different structure supports are founded results in modifications to the peak acceleration of the soil and the frequency of the telluric current on the surface, characteristics that depend on the type of soil, the conditions of the place and the contrast of velocities between superposed layers. The local site effect in accordance with the angular frequency (ω), is determined as follows:

$$\gamma_{kl}{}^{(s)}(\omega) = exp\left[i\theta_{kl}{}^{(s)}(\omega)\right] \qquad (13)$$

$$\theta_{kl}{}^{(s)}(\omega) = \\ tan^{-1}\left[\frac{-2\xi_k\omega_k\omega^3}{\omega_k^2(\omega_k^2-\omega^2)+4\xi_k^2\omega_k^2\omega^2}\right] - tan^{-1}\left[\frac{-2\xi_l\omega_l\omega^3}{\omega_l^2(\omega_l^2-\omega^2)+4\xi_l^2\omega_l^2\omega^2}\right] \quad (14)$$

Where,

ξ_k and ξ_l are soil damping ratios in points k and l, respectively.

ω_k and ω_l are soil resonance frequencies in points k and l, respectively.

Then, the asynchronous seismic excitation is broken down into three parts through the coherence function (γ_{kl}):

$$\gamma_{kl}(\omega) = \gamma_{kl}^{(i)}(\omega)\,\gamma_{kl}^{(w)}(\omega)\,\gamma_{kl}^{(s)}(\omega) \qquad\qquad (15)$$

Where,

ω is the angular frequency, and γ_{kl} is the coherence function between the supports k and l, in accordance with the angular frequency ω.

Subscripts k and l indicate points k and l of the structure with $k, l = 1, 2, …, N$ supports.

Superscripts (i), (w) and (s) refer to the incoherence effect, the wave passage effect and the local site effect, respectively.

(Luco and Wong, 1986), found out that some patterns are more critical than others with regard to the increase of the total response of the structure. Therefore they recommend taking them into account separately and in combination. Apart from that, (Soyluka and Avanoglu, 2012) propose that the asynchronous seismic excitation must always be accompanied by the soil-structure interaction in cable-stayed bridges in order to faithfully represent the asynchronous phenomenon.

## 5. Analysis methods: Evolution

In 1986, (Harichandran and Vanmarcken, 1986) proposed the first empirical model to characterize the loss of correlation between the seismic signals of two stations located at a determined distance. The authors based its model on the data obtained from the accelerogram array SMART1 in Taiwan. In the same line, (Luco and Wong, 1986) proposed an analytical correlation model based on physics of wave propagation in random environments.

In order to compare the results obtained when applying the models proposed by (Harichandran and Vanmarcke, 1986) and (Luco and Wong, 1986), Model 1 and Model 2, respectively, (Soyluk and Dumanoglu, 2004) used the Jindo Bridge in South Korea as a case of study. This bridge is composed of the main span of 344 m and two lateral spans of 70 m each. The authors found out that Model 1 produced greater bending moments in the spans and the deck than Model 2 since the low-frequency ranges were controlled by the first model. See Figure 1 and Figure 2.

Currently, there are several methods that characterize the asynchronous seismic excitation. (Konakli and Kiureghian, 2011) carried out a thorough review of methodologies that characterize the asynchronism, which the authors considered as tools for the analysis of bridges subjected to asynchronous seismic excitation. A brief description of these tools is detailed as follows:
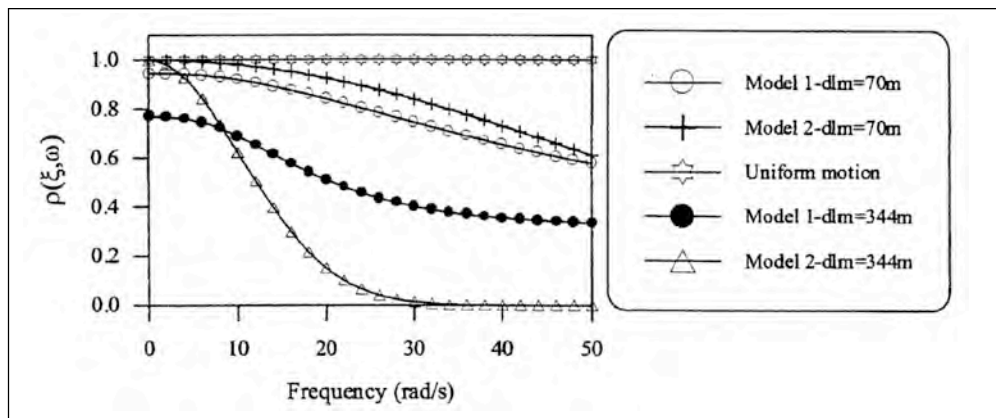
Figure 1. Incoherence effect variation depending on the spacing between supports and the frequency

(Soyluk and Dumanoglu, 2004)
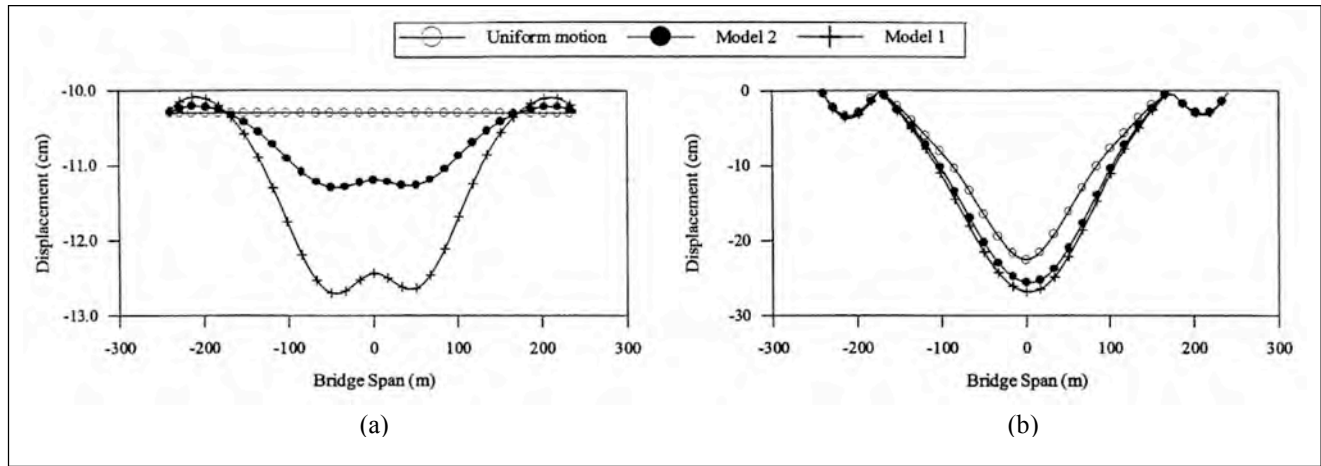
Figure 2. *Maximum displacement values in the deck of the Jindo Bridge (general excitation in middle ground, $v_{app} = 600\ m/s$): (a) pseudostatic component and (b) dynamic component (Soyluk and Dumanoglu, 2004)*

5.1 Random vibrations (statistical mechanics)

In 2003, (Dumanogluid and Soyluk, 2003) used the random vibration method, which is based on relating statistical values of the exciting forces with the corresponding internal forces arising as an excitation response. This method suggests a set of mutually stationary movements, finally generating three displacement components in the structural response: dynamic, pseudo-statical and covariance components. The latter represents the statistics part of the problem, but due to practical issues, it is disregarded due to its low contribution to the total response. In addition, (Soyluk, 2004) compared three analysis methods based on the random vibration theory: the spectral analysis, the power spectral density function, based on the response spectrum, and the response spectrum method. The three methods used the cross-spectral density function ($S_{\ddot{u}_k\ddot{u}_l}$) in accordance with the angular frequency. See equation 7.

$$S_{\ddot{u}_k\ddot{u}_l}(\omega) = \gamma_{kl}(\omega)[S_{\ddot{u}_k\ddot{u}_k}(\omega)S_{\ddot{u}_l\ddot{u}_l}(\omega)] \qquad (16)$$

$$S_{\ddot{u}_k\ddot{u}_k}(\omega) = S_0\left[\frac{\omega_g^4+4\zeta_g^2\omega_g^2\omega^2}{\left(\omega_g^2-\omega^2\right)^2+4\zeta_g^2\omega_g^2\omega^2}\right]\left[\frac{\omega^4}{\left(\omega_f^2-\omega^2\right)^2+4\zeta_f^2\omega_f^2\omega^2}\right] \qquad (17)$$

Where,

S_0 is the white noise amplitude of acceleration in bedrock.

ω_g and ζ_g are the angular frequency and the damping coefficient of the first filter, respectively.

ω_f and ζ_f are the angular frequency and the damping coefficient of the second filter, respectively.

γ_{kl} is the coherence function between stations k and l.

The main difference between the methods was the way the maximum response was obtained. In Figure 3 shows the response of an arched bridge and a cable-stayed bridge analyzed through the three methods. The first two methods showed certain similarity, while the third method produces greater displacements at the span of both bridges.
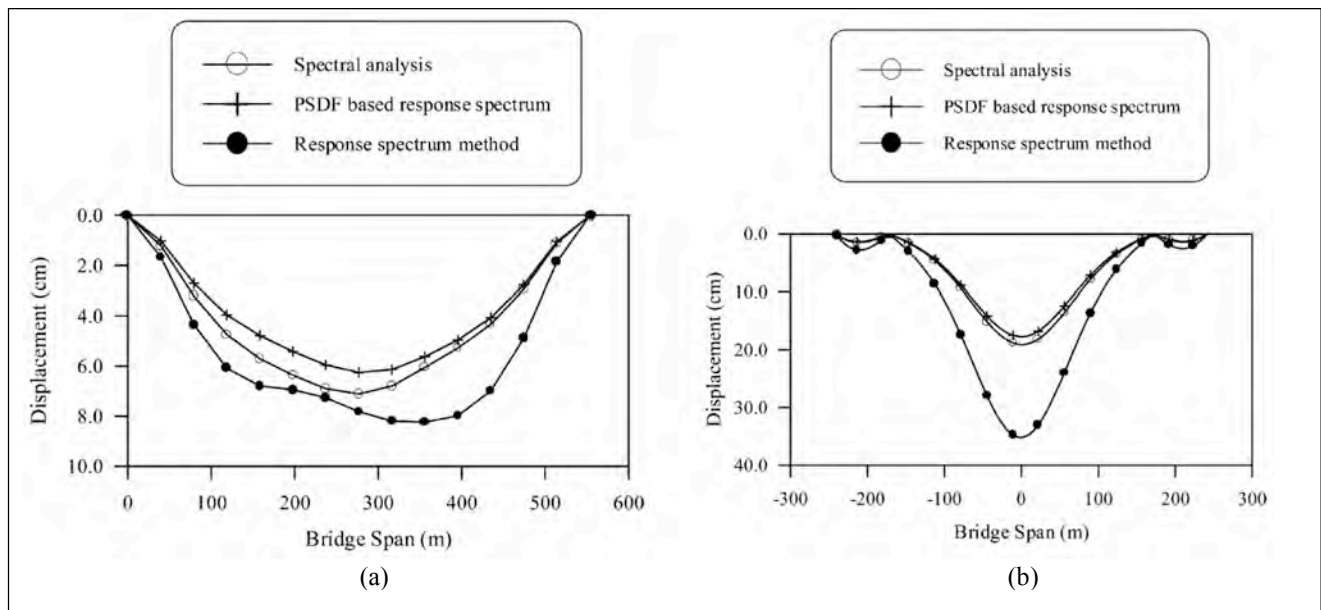
Figure 3. *Absolute maximum vertical displacement of the bridge model: (a) arched, (b) cable-stayed (Soyluk and Dumanoglu, 2004)*

It is important to mention that the random vibration method suggests a set of mutually stationary movements, which implies a great disadvantage since the random nature of seisms produces energy processes that vary in accordance with time and space. Another disadvantage is that in the engineering practice this method is not frequently applied since the typical practice is to determine input seismic forces through chronological analyses or spectral analyses.

5.2 Linear/nonlinear chronological analysis

The method consists in generating seismograms for each of the supports by using the coherence function, which contains the wave passage effects, loss of correlation and local site effect. The coherence is characterized by the triple product shown in equation (5) (Zhang, et al., 2009), or using actual records obtained from an accelerometer array, such as SMART1, Pinyon Flat Geophysical Observatory in California used by (A. Abrahamson, 2007) or the group of accelerograms from the Evripos Bridge in Greece (Sextos, Karakostas, et al., 2015). However, (Kassawara and Sandell, 2006) propose an acceptable model based on the analysis of 12 seismographic arrays, which is recommended for any site condition, seism size and spacing between stations, except for abrupt topographical conditions.

For the generation of accelerograms including asynchronous seismic excitation there are methods such as that used by (Ghobarah, Aziz and El-Attar, 1996), which uses a random stationary displacement generation technique that has the advantage of adjusting in time the stationary simulation in order to provide the temporary nonstationarity, as described in the following expression:

$$u_{rn}(t) = u_r(t)sen\left(\frac{\pi t}{T}\right) \tag{18}$$

Where
u_{rn} is the nonstationary displacement function,
u_r is the stationary displacement function,
T is the independent variable that represents time, and
T is the length of ground motion.

However, the temporary nonstationarity does not guarantee the spectral nonstationarity of the movement and this last characteristic must be taken into account for the analysis of hysteretic structures according to (Konakli and Kiureghian, 2011). The spectral nonstationarity can be attributed through an evolving function of potential spectral density. The disadvantage is that we still do not have a general method or studies that confirm whether kinematic in the movement is performed when an evolving function of potential spectral density is used.

5.3 Response spectrum

The response spectrum method used in the asynchronous analysis is based on the random vibration approach. It has the advantage of implicitly introducing a response spectrum to the structure, which is practical from the viewpoint of the designer (Liang and Shou-lei, 2013) and (Cacciola and Deodatis, 2011). In addition, the response spectrum obtained inherently includes the nonstationarity. The great disadvantage is that the method only uses modal superposition and it is limited to the linear analysis.

5.4 Simulation from actual accelerograms

The simplest method to model the asynchronous seismic excitation only taking into account the wave passage effect is the modification of an actual seismogram. There are seismic stations worldwide that are continuously monitoring and storing information of significant seismic events. This material could be implemented in the asynchronous analysis

taking into account the wave passage effect. It is about assigning an accelerogram to every structure support temporarily displacing it in the direction of the wave attack (Valdebenito and Aparicio, 2005) (Álvarez et al., 2012) (Konakli and Der Kiureghian, 2012). The method extends to nonlinear analysis according to (Ghobarah et al., 1996) and (Álvarez et al., 2006), this method is not very elaborate if it is compared with the method described in point 5.1 and its main disadvantage resides in not including the other asynchronous patterns.

6. Regulations and Codes

There are regulations and design guidelines such as AASHTO (American Association of State Highway and Transport, 1996), ATC (Applied Technology Council, 1996), ATCM (Applied Technology Council and Multidisciplinary Center, 2003), the report on soil-structure interaction presented by the advisory committee of CALTRANS (Caltrans, 1999), and DSHB (Japan Road Association, 2000) that limit the asynchronous analysis on bridges only if the total length exceeds 600 m (Sextos and Kappos, 2009). Apart from that, the Eurocode 8 (EC8) (European Committee for Standardization, 2012) proposes considering the asynchronism only if: i) there are geological discontinuities, near faults or abrupt topographic characteristics; ii) the length of the bridge exceeds 600 m. The second consideration has been called into question through studies such as that carried out by (A. S. and E. G., 1994), which emphasizes the importance of carrying out asynchronous analyses in metal arched bridges with a span greater than 400 m. Following the same line, (Álvarez et al., 2012) found out that in the case of concrete arched bridges, the asynchronous movement generates an increase in the rotation demand of the arch springs by bending and in the axial load fluctuation in bridges larger than 400 m. However, proposals based on the research of the EC8 have been made in order to include lower limits with regard to the total length of the bridge, depending on the type of soil it is supported (Sextos and Kappos, 2009).

The EC8 proposes three asynchronous analysis methods: the first method has to do with the description of the movement in the supports as a component of a random, homogeneous field that is stationary in time; the second method is about a simplified random model, and the third method is a pure kinematic model, which is based on developing a set of relative static displacements (Valdebenito and Aparicio, 2005). These methods are not very reliable because from the viewpoint of quantities of material there is no difference between designing under asynchronous seismic excitation and designing under uniform seismic excitation since the response does not vary substantially, while more elaborate methods do generate significant differences. In addition, the methods of the EC8 are unable to identify fault points and do not allow working with high vibration modes, which characterize the asynchronous seismic excitation.

Also, according to (Sextos and Kappos, 2009), they are not applicable to curved bridges.

In 2005, (Nuti and Vanzi, 2005) carried out a study in order to establish design criteria for bridges under asynchronous seismic excitation in order to update the Italian code for bridges. The analysis method used by Nuti was based on the fundamental principles of the random vibration theory and the structural elements were idealized elastic and linear, which generates a disadvantage when an inelastic and nonlinear analysis is required. In addition, the method was created in order to apply it to structures with two supports, and even though it can be extended to multiple supports, there is no correlation between supports and the site effect is not taken into account. In that study, (Nuti and Vanzi, 2005) analyzed a bridge with only one span of 32 m in total length, supported in soft soil. They found out that in the asynchronous case the differential displacements in the abutments exceeded in 98 mm the 14 mm proposed in the Eurocode and the Italian Code of Civil Protection, thus emphasizing the importance of including the asynchronous analysis even in short-length bridges and the need to update the design codes.

7. Structural Types Analyzed

In general, (Fernandez et al., 2013) found out that if the length of a bridge is greater than the wavelength of the seismic movement or if there is a significant topographic accident (Kaiming, 2013) then some parts of the bridge will be subjected to different and significant excitations in its supports. The results of the works performed by researchers interested in comparing the classic analysis with the asynchronous analysis for some structural types of bridges are detailed as follows.
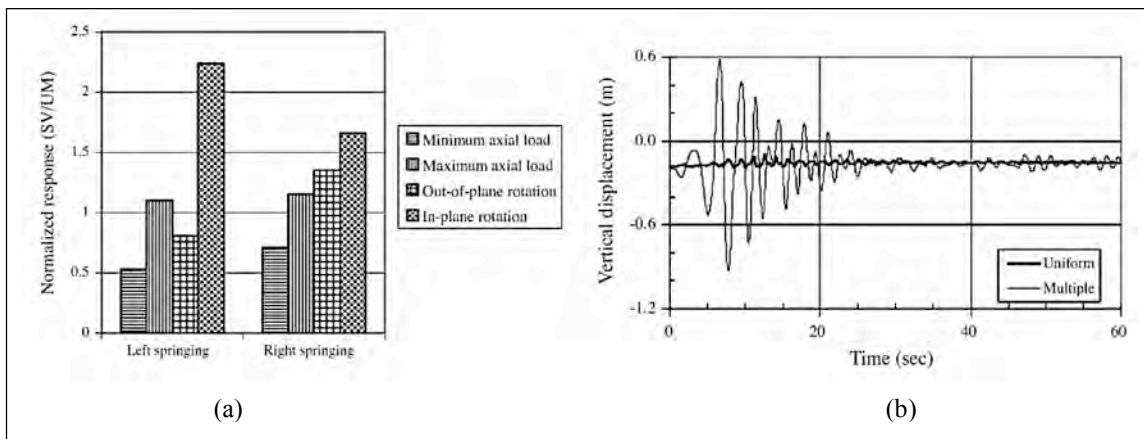
7.1 Arched bridges
(Alvarez et al., 2002) and (Álvarez and Aparicio, 2003) emphasize the need of carrying out the asynchronous analysis in arched bridges with main spans greater than 427 m due to the increase in the axial forces in the haunches of the arch.

(Álvarez et al., 2012) analyzed the prototype bridge of Figure 4, with a total length of 600 m and a 400 m main span. The asynchronous analysis generated an increase in the average rotation of the left support of 124% with regard to the classic analysis (see Figure 5a), mainly due to the increase of the vertical displacement in the center of the span as it can be observed in Figure 5b. However, the rotation capacity in the supports was not exceeded and the displacements in stringers and cross girders decreased approximately by 50%. The authors do not generalize the arched bridge response under asynchronous seismic excitation; therefore, they emphasize the importance of comparing the responses under asynchronous seismic excitation and uniform seismic excitation (Álvarez et al., 2006).
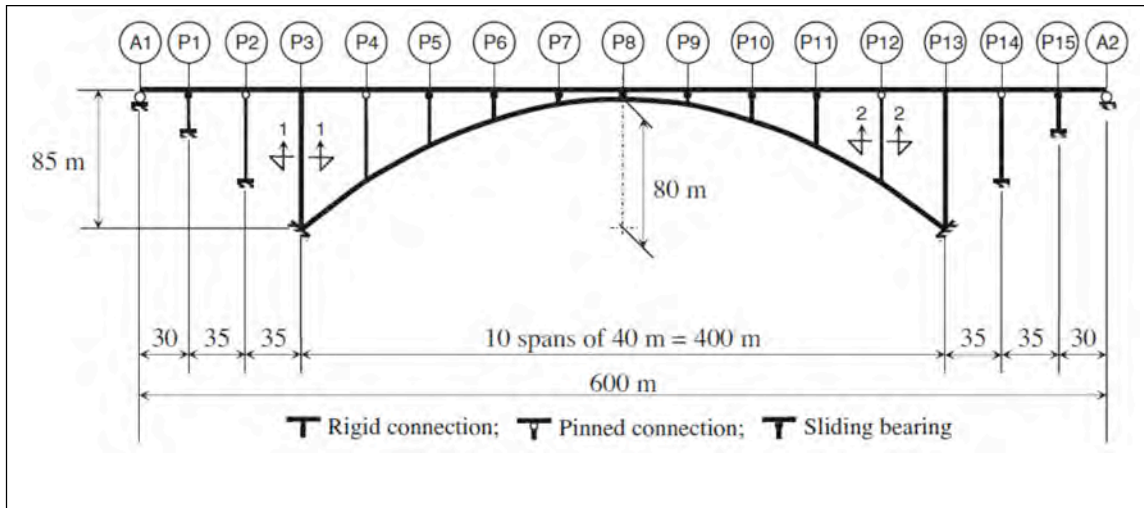
Figure 4. Longitudinal view of the prototype bridge studied by Álvarez and Jara (Arched bridge) (Álvarez et al., 2012)

(a)   (b)

Figure 5. (a) Abutment response of the arched bridge, subjected to asynchronous seismic excitation. (b) Vertical displacements

with the chronological analysis in the center of the span (Campano-Lucano seism, Sturno Station) (Álvarez et al., 2012)

On the other hand, (Kaiming et al., 2013) using the metal arched bridge on the Yeshan river (China) (Figure 6) as a case of study, with a main span of 124 m, they found out that when the wave passage effect is combined with the loss of correlation, they altogether generate an increase of up to 90% in the axial forces in the center of the top chord of the arch, while the bending moments inside an outside the plane do not present a significant variation. Also an increase in the axial forces along the top and bottom cords of up to 60% was detected, comparing the asynchronous seismic excitation for homogeneous and heterogeneous soil conditions, evidencing that not taking the three asynchronous patterns into account, only including the wave passage effect or not taking the support soil conditions of this type of bridges into account, could underestimate the axial load demand in certain structural elements of the arch.
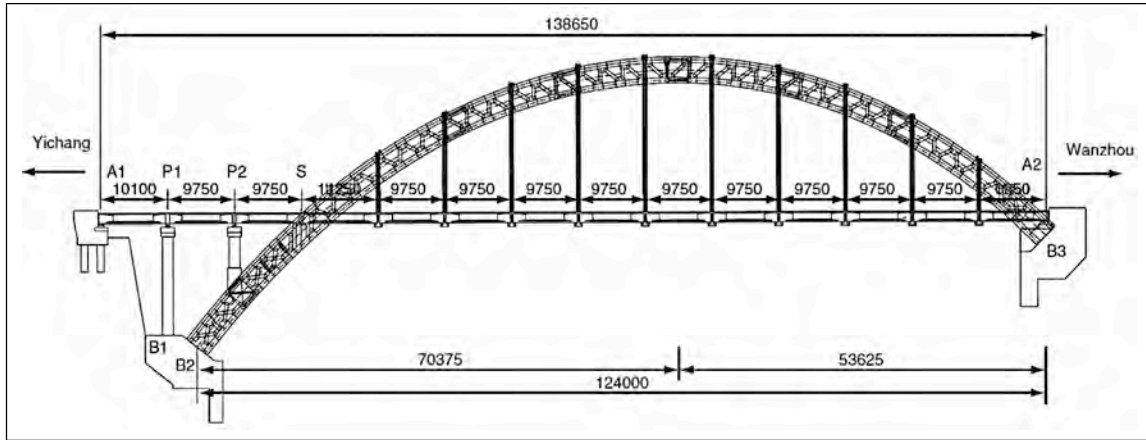
Figure 6. *Elevated view of the arched bridge of the Yeshan river in China. Units: mm (Kaiming et al., 2013)*

7.1 Box girder bridges

For the first study of box girder bridges under asynchronous seismic excitation, (Konakli and Kiureghian, 2011) used four bridges with irregularities both in level and height (see Table 1). The authors found out that in more flexible bridges such as the Penstock Bridge and the South Ingram Slough Bridge, the pier drifts increase significantly when the wave passage and a strong loss of correlation between the signals are taken into account, but the most critical scenario is the combination of the three asynchronous patterns, that is to say, wave passage, loss of correlation and local site effect. Apart from that, the authors classify the synchronous analysis as conservative in the case of box girder bridges with low fundamental periods such as the Auburn Ravine Bridge and the Big Rock Wash Bridge.

Table 1. *Characteristics of model bridges (Konakli and Kiureghian, 2011)*

Bridge	Total Length	Deck Width	No. of Columns	Fundamental Period
Auburn Ravine	166.40 m	13.50 m	5	0.59 s
Big Rock Wash	100.00 m	24.87 m	2	0.61 s
South Ingram Slough	69.30 m	16.20 m	1	1.24 s
Penstock	167.31 m	12.90 m	3	2.38 s

(Mehanny et al., 2014) and (Ramadam et al., 2015) carried out a nonlinear chronological asynchronous analysis to a continuous box girder bridge (see Figure 7) with a total length of 430 m, comprised of nine spans, in order to determine the wave passage effect in the seismic behavior of this type of bridges. The analysis was developed in the Opensees software and 20 seismic records from the Pacific Earthquake Engineering Center database were used. The authors determined that in the longitudinal direction, the continuous deck works as a rigid diaphragm that minimizes the wave passage effect, making the uniform seismic excitation the most conservative for the seismic design. However, in the transverse direction, the authors recommend taking into account the wave passage effect whose severity depends on the frequency content of the seism, being more critical for high-frequency ranges in order not to underestimate the probability of structural failure.

(a)

(b)
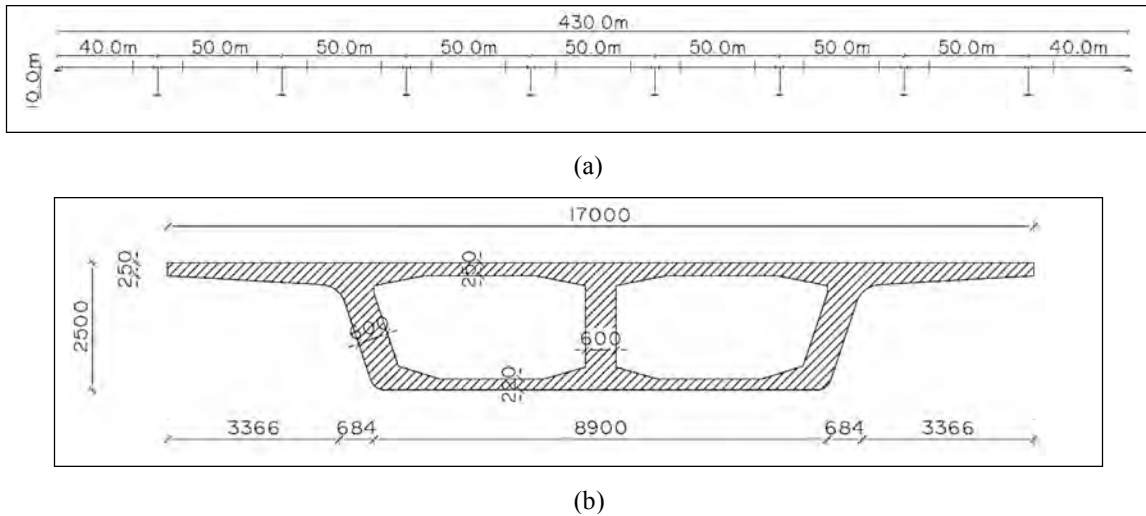
Figure 7. *Case of study bridge: (a) longitudinal view, (b) typical deck section (dimensions in mm) (Mehanny et al., 2014)*

(Mehanny et al., 2014) built fragility curves that constitute a representation of the ratio between the probability of reaching limit states and exceeding the seismic intensity level. With this, it was determined that in the case of soft soils, the seismic sensitivity and seismic vulnerability under asynchronous seismic excitation are greater than in stable soils with an excess of the annual frequency of up to 7.1 times in the longitudinal direction. However, the approach presents uncertainties in modeling since the annual average collapse frequency can be underestimated up to 80%.

7.3 Multiple-span bridges

According to (Wang et al., 2003), the asynchronous analysis must be taken into account in multiple-span bridges, so as to guarantee the safety and functionality of the structure. In a study carried out by (Sextos and Kappos, 2009), where 27 types of multiple-span bridges with different span lengths were analyzed, the authors found out that in bridges with a total length greater than 333 m the results of the asynchronous analysis predominate over the classic analysis. For example, in Figure 8, for the bridge with 400 m in total length, an increase over 60% regarding the bending moments at the base of the piers can be observed, being the asynchronous scenario the most detrimental in that case.
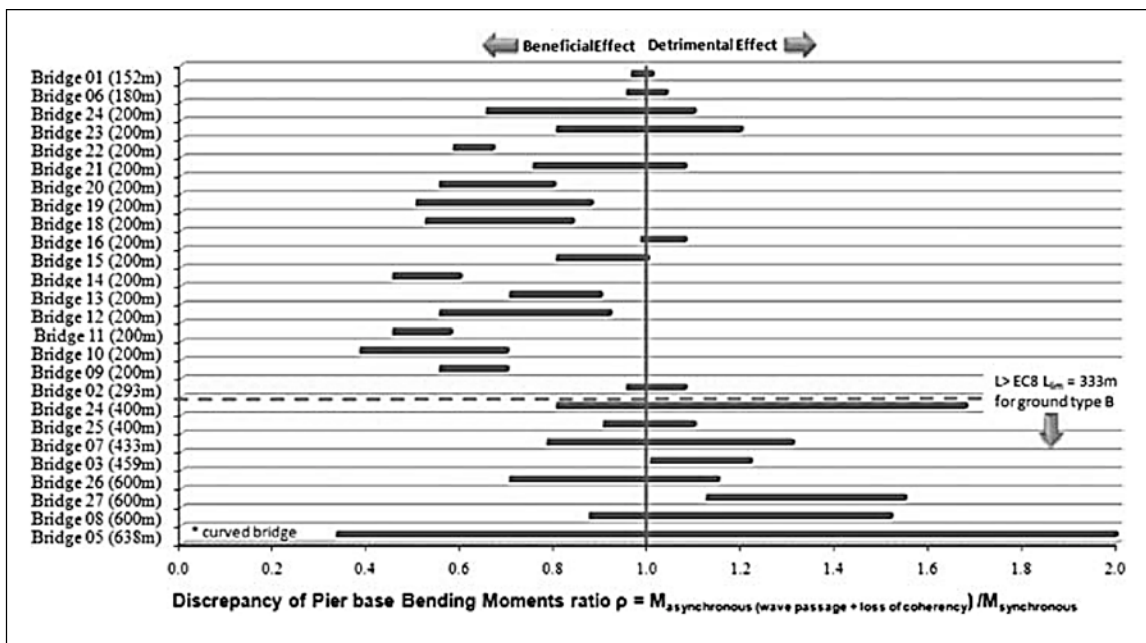
Figure 8. *Variation of the effect of 27 bridges subjected to asynchronous seismic excitation, taking the wave passage effect and the loss of correlation into account (Sextos and Kappos, 2009)*

In 1998, (Price and Eberhard, 1998) proposed a method to determine in advance whether an asynchronous analysis in bridges should be carried out, based on the participation constant C_p (see equation 19). If the participation constant tends to infinity, the dynamic component of displacement predominates, that is to say, the asynchronism is irrelevant. Otherwise, the asynchronous analysis should be taken into account. Although the method works in the models proposed by (Price and Eberhard 1998), the behavior of this typology could not be generalized. Apart from that, it was detected that in a 62% of the models, the dynamic component of the reactions in the extreme supports was exceeded by the asynchronous seismic excitation between 75% and 180%, only taking into account the loss of correlation. However, the dynamic component of the reactions in the central supports was exceeded by the uniform seismic excitation in 80% of the models.

$$C_p = \frac{T_0 V_{app}}{L_s} \qquad (19)$$

Where,
T_0 is the fundamental period of the bridge,
V_{app} is the apparent wave velocity in the rocky environment, and
L_s is the length of each span.

The loss of correlation is the pattern that produces a higher increase in internal forces and displacements according to (Saxena et al., 2000), (Price and Eberhard, 1998), (Lou and Zerva, 2005) and (Burdette and Elnasha,i 2008). However, the authors recommend taking into account the three asynchronous patterns separately and in combination. (Mezouer et al., 2010) determined that when the fundamental period of the soil (T_s) is equal to the fundamental period of the bridge (T_p), the asynchronous analysis is not necessary. If T_p tends to 1.85s, the wave passage has a greater impact on the structural response. As the structure becomes more flexible, the loss of correlation effect dominates the response of the bridge, and for T_p >2.1 s, the loss of correlation dominates the response even in stiff soil.

Additionally, (Kleoniki et al., 2015) analyzed a bridge of 168 m in total length, comprised of 4 spans supported on 3 central columns monolithically bonded to the deck. The geological profile was the key variable in the models (see Figure 9), thus determining the influence in the nonlinear dynamic response of multiple-span bridges subjected to asynchronous seismic excitation. Moreover, the authors propose taking into account in the asynchronous analysis factors such as the topography, the geological characteristics of the superposed layers where the structure is supported, and every discontinuity in the soil that produces changes in the frequency content of the wave in the surface due to the direct influence in the bridge response.
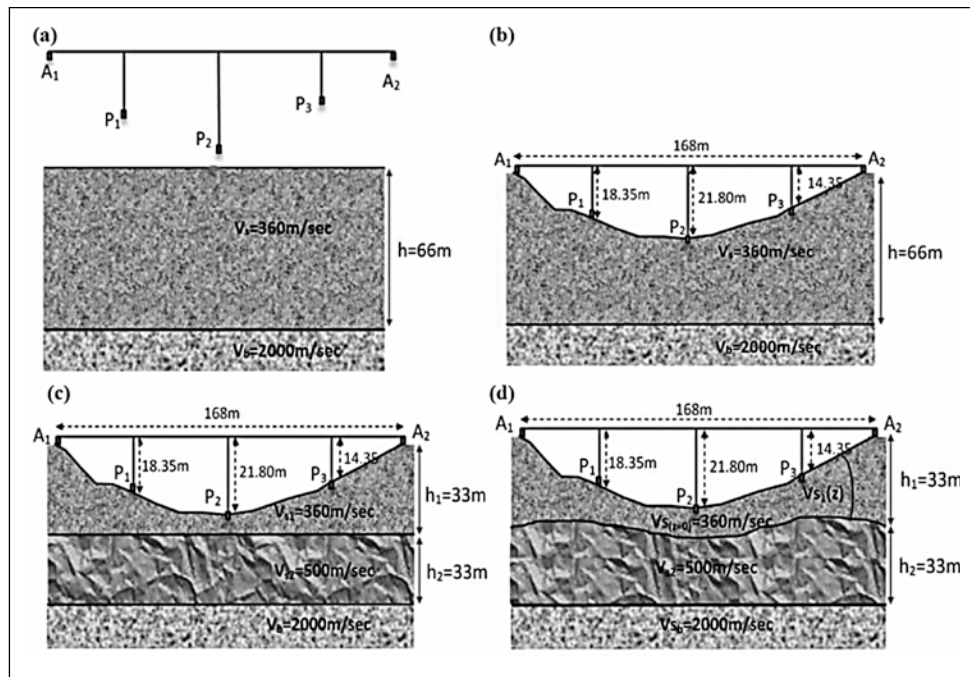

Figure 9. Four types of geological profile types for the case of study: a) type A, b) type B, c) type C and d) type D (Kleoniki et al., 2015)

(Burdette and Elnashai, 2008), (Price and Eberhard, 1998); (Wang et al., 2008), among other authors, found out that the fundamental periods of the structure were suppressed when performing the asynchronous analysis and the asymmetric modes began to play an important role, producing torsional effects such as snaking (see Figure 10). This type of displacement could be disregarded in the design phase if an asynchronous seismic excitation or a uniform seismic excitation is considered.
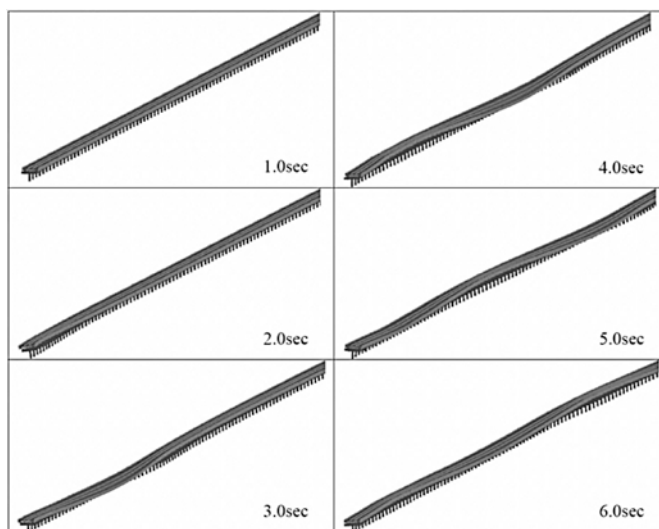

Figure 10. *Snapshots of displacements suffered by the bridge due to asynchronous seismic excitation (Wang et al., 2008)*

(Sextos et al., 2004) were interested in the Krystallopigi bridge due to its irregularity in level and height (see Figure 11) and carried out an asynchronous analysis varying the wave attack angle. The results of this analysis allowed them to conclude that the attack angle (horizontal plane) plays a secondary role in the asynchronous analysis. However, according to (Fernández et al., 2013) the incidence angle (vertical plane) of the wave is important. This conclusion was obtained after analyzing two bridges with three spans, each span of 50 m and piers of approximately 55 m in height; the difference laid in the type of support between the girder and the pier, considered as two support types: M1 elastomeric support and M2 monolithic support. The critical incidence angle for the first type of support was 60° and for the rigid connection was 30°.
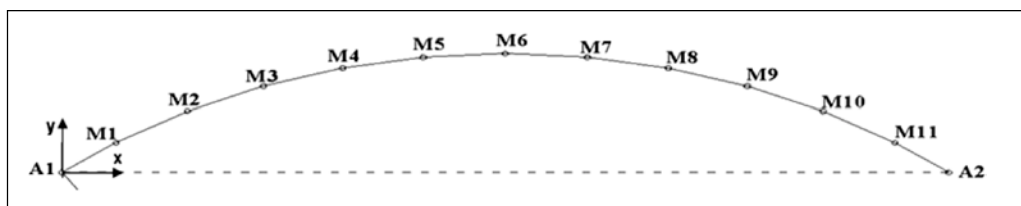

(a)
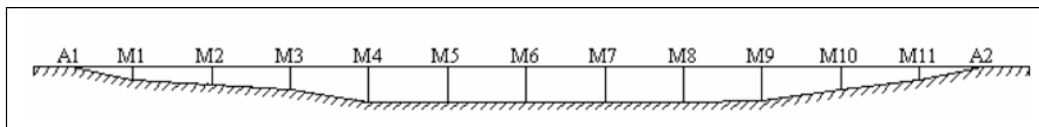
(b)

Figure 11. *Krystallogipi bridge: (a) plan view, (b) bridge altimetry (Sextos, J. Kappos and Mergos, 2004)*

(Feng and Kim, 2003) and (Saxena et al., 2000), took the Santa Clara bridge (comprised of 12 spans, and a total length of 500 m) and the TY0H bridge (comprised of 5 spans and a total length of 242 m) as cases of study. Through nonlinear analyses, the authors identified an increase in the ductility demand for the columns, in comparison with the classic analysis. The study of (Feng and Kim, 2003) is the first study proposing fragility curves under asynchronous seismic excitation conditions, which provide useful information to be taken into account in the update of design codes. According to (Feng and Kim, 2003), the probability of failures in the structure could increase up to 2.3 times, if the asynchronous seismic excitation is taken into account within the analysis and subsequent design.

7.4 Cable-stayed bridges

Different authors have been interested in analyzing the effects of the asynchronous seismic excitation in the Jindo metal cable-stayed bridge, which was based on a variable soil and has a central span of 344 m and two lateral spans of 70 m each.

(Soyluka and Avanoglu, 2012) found the characteristics of the Jindo Bridge interesting to carry out an asynchronous analysis, taking into account the soil structure interaction, by adding the three asynchronous patterns separately and in combination. The patters that affect more, if the soil-structure interaction is taken into account, is the local site effect, increasing the demand on the deck and the towers (see Figure 12, where F, M and S represent the stable, average and soft soils, respectively on each of the four supports of the bridge).
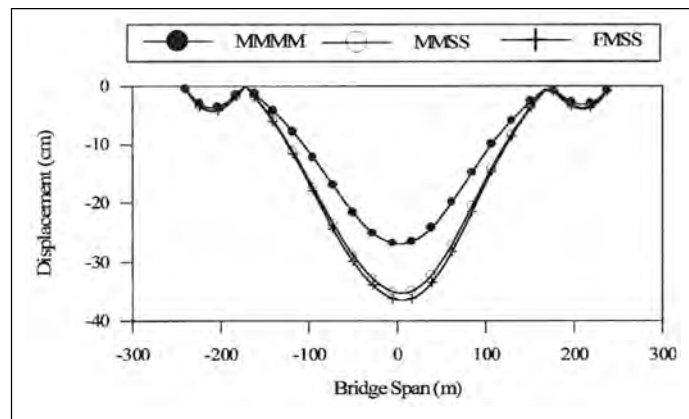
Figure 12. *Maximum vertical displacements of the dynamic component in the deck of the Jindo*

Bridge (Dumanogluid and Soyluk, 2003)

On the other hand, (Valdebenito and Aparicio, 2005) and (Soyluk and Dumanoglu, 2000) also studied the Jindo Bridge, and based on the results they determined that for cable-stayed bridges with big spans, the pattern that affects the response more is the wave passage effect since when increasing the apparent wave velocity, the temporary lag between seismic forces applied to the supports of the bridge increases. This directly affects the structural response (see

Figure 13 and Figure 14). However, the wave passage is not the only important variable, so are the span length, the structural stiffness, the static redundancy, the incidence angle of the wave and the tower/deck inertia ratio, which makes difficult to establish in a general manner whether the detrimental case for cable-stayed bridges is the asynchronous seismic excitation.
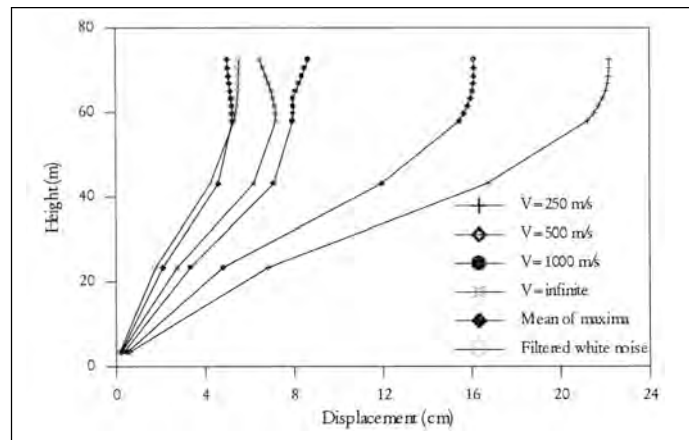
Figure 13. *Horizontal displacement of the tower found on the island varying the apparent wave velocity in the JindoBridge*

(Soyluk and Dumanoglu, 2000)
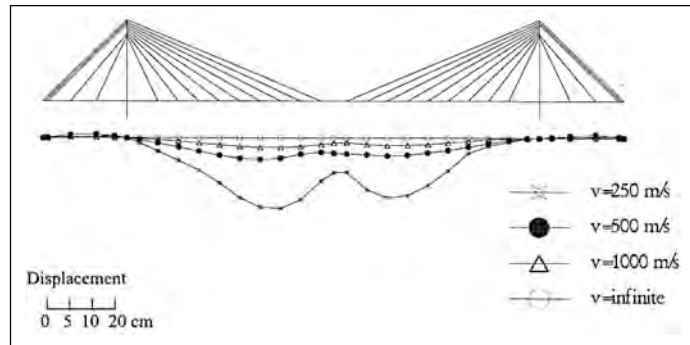
Figure 14. *Pseudostatic displacement component in the deck of the Jindo Bridge varying the apparent wave velocity*

(Soyluk and Dumanoglu, 2000)

(Karakostas et al., 2011) used a three-dimensional model of finite elements of the Evripos Bridge (Figure 15), to which actual records of the Athens earthquake (1999) were assigned. From the results they determined that: the asynchronous seismic excitation is beneficial for the bending moments in the piers and for the displacements in the central span of the deck. With regard to the bending moments outside the plane and the displacements in the top of the piers, the asynchronous moment is clearly critical and the increase of the displacements vary in accordance with the change in the amplitude of the Fourier spectrum, that is to say, it depends on the peak acceleration values contained in the range of frequencies of high modes.

According to (Abdel et al., 2011), the higher modes are a key tool to understand the role of asynchronism is the seismic response of bridges. Since these modes are mainly asymmetrical, the implementation of control systems under asynchronous seismic excitation is difficult, thus reducing the effectiveness of the energy dissipation devices, being these active, semi-active or passive.
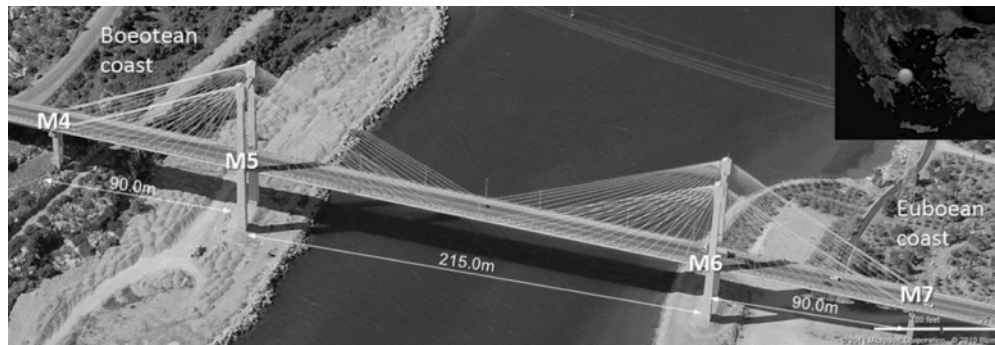
Figure 15. *Evripos cable-stayed bridge, Greece (Karakostas et al., 2011)*

7.5 Suspended bridges

(Harichandran, Hawwari and Sweidan, 1996) carried out the first asynchronous analysis on the Golden Gate Bridge (USA). In this analysis, the authors found out that the major influence component is the dynamic component. However, the pseudo-static component and the covariance component contribute significantly to the total displacement at the center of the main span. Therefore, in the case of the asynchronous seismic excitation, the response is critical at the center of the main span, but in the rest of the structure, the response is underestimated in relation to the uniform seismic excitation. On the other hand, the covariance component is greater than the pseudo-static component in the case of structures with low-frequency modes. In addition, the authors mention that the wave passage effect produces critical effects transversely since the asynchronism excites the asymmetrical modes of the structure.

The Golden Gate Bridge was also studied by (Ahmed and Lawrence, 1982), who claim that only considering the wave passage effect underestimates the structural response since in some cases the tension in the cables greatly increases

SPANISH VERSION..

when considering the incoherence, giving importance to the stiffness and the local soil conditions. That is to say, the greater the rigidity in the structure, the greater is the response under asynchronous seismic excitation. Therefore, the three patterns must be taken into account separately and in combination for the asynchronous analysis of suspended bridges.

(Nurdan et al., 2016) carried out an asynchronous analysis on the suspended bridge Fatih Sultan Mehmet in Turkey, which has a central span of 1090 m in length and two lateral spans of 210 m each. In the aforementioned analysis, the authors found an increase of 21% and 18% in the axial forces of tension in the main cable and the vertical cables, respectively. The reason for this increase is associated with opposing movements of the towers as a result of the asynchronous seismic excitation (see Figure 16), also increasing the shearing forces at the base of the towers.

In 1999, (Wang et al., 1999) analyzed the Jiangyin Yangtse Bridge (China) (see Figure 17) only considering the

wave passage effect, assuming in advance that this pattern would be most critical and emphasized the importance of taking into account the geological differences that could be present in the supports of bridges with large spans. According to Wang and Wei, the error produced by disregarding the coherence effect is approximately 15%. Therefore, for practical purposes, it is acceptable to disregard this effect. In the aforementioned study, the authors detected intervals of critical apparent wave velocity affecting the bridge response as follows: velocities under 3000 m/s and 6000 m/s could affect the relative displacements up to 15% and 5% at the top of the north and south towers, respectively. Moreover, velocities under 2500 m/s could affect up to 5% of the shearings and the bending moment at the base of the north pier. Apart from that, for velocities less than 1500 m/s or over 3000 m/s, the shearings and bending moments at the base of the south pier could increase up to 2%.

(a)

(b)
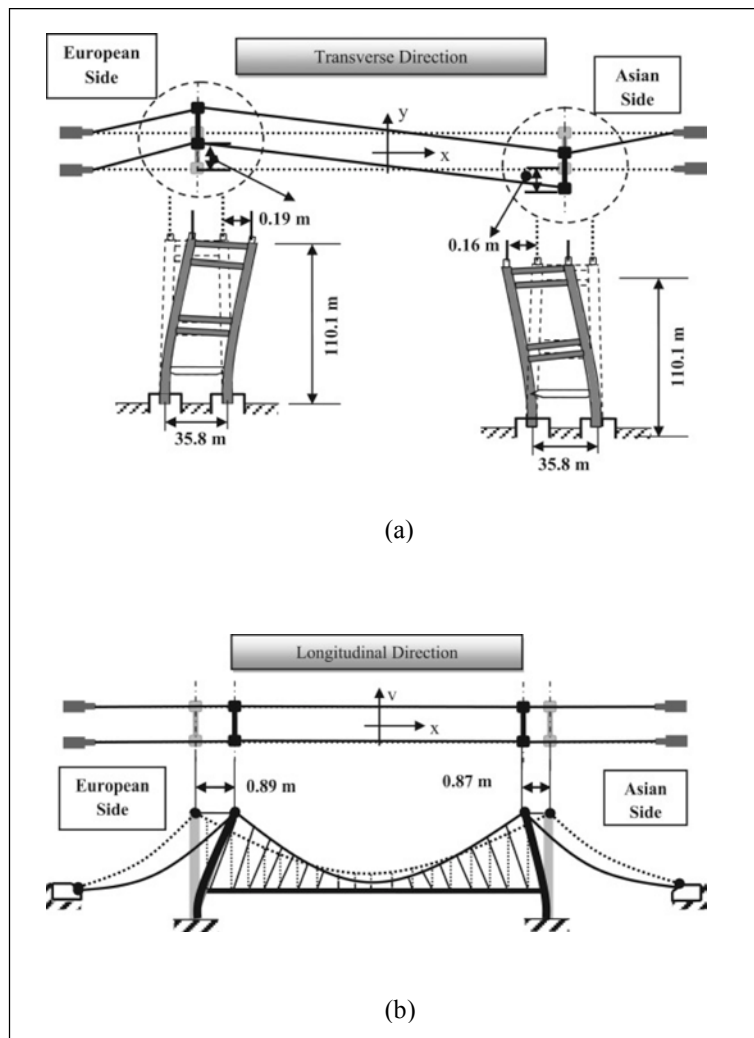
Figure 16. *Deformations of the Fatih Sultan Mehmet Bridge: (a) transverse displacement of the towers for the asynchronous case,*

(b) longitudinal displacement of the towers for the asynchronous case (Nurdan et al., 2016)
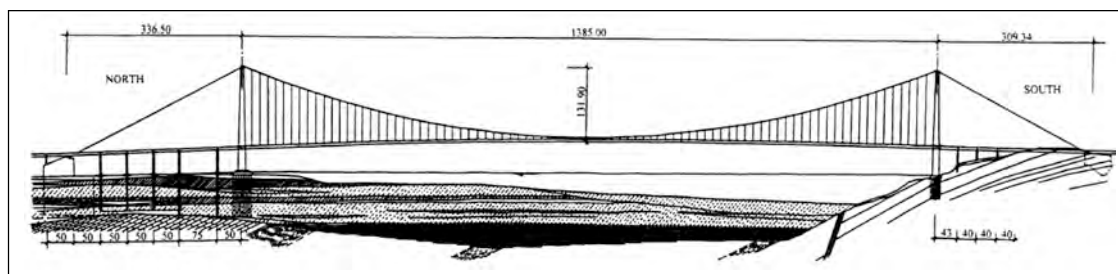
Figure 17. *Plan view of the Jiangyin Yangtse Bridge (Wang et al.,1999)*

(Karmakar et al., 2012) proposed a simulation technique to carry out a nonlinear asynchronous analysis with historical records in time in the Vincent Thomas Bridge in the USA. The validation of the model was performed through the comparison of synthetic accelerograms generated with information collected from environmental vibrations and the records of the earthquake of Chino Hills (2008). Three scenarios were considered:

i) Asynchronous seismic excitation, considering the three asynchronous patterns.

ii) The worse uniform case, the synthetic accelerogram that produces the greatest maximum peak displacement values.

iii) The best uniform case, the synthetic accelerogram that produces the lowest maximum peak displacement values.

Although the greatest demand of forces was dominated by the worst uniform case, in some sections of the deck, the asynchronous seismic excitation exceeded the response of the worse uniform case.

8. Conclusions

In this work, a state of the art on the study of asynchronous seismic excitation applied to bridges was carried out. The main conclusions obtained can be summarized as follows:

1) It is not possible to generalize the structural behavior of bridges subjected to asynchronous seismic excitation. Therefore, an asynchronous analysis is required when it is probable that the site conditions (topography, geology, the presence of faults, etc.) and the structural characteristics (stiffness, main span length, multiple supports, etc.) magnify the structural response.

2) There are analysis methods, such as random vibrations, that present a very elaborate and a not very practical approach from the engineering point of view to study the asynchronism phenomenon in bridges. Therefore, the linear and nonlinear dynamic analyses based on direct integration are a more attractive option.

3) Even though the regulations and bridge design guidelines present limits and conditions under which an asynchronous analysis must be carried out, they have been evolving and presenting improvements not only in the restrictions but also in the analysis methods in order to broaden such limits and conditions that provide safety and structural functionality. In general, different authors emphasize the importance of introducing the asynchronous analysis in regulations and design guidelines in zones with high seismic activity, when there is an increasing demand for long bridges with large and medium spans, which could present abrupt changes in their supporting conditions (variable type of soil), topography or when near faults exist.

4) In general, three asynchronous patterns are accepted to carry out the asynchronous analysis: the loss of correlation, the wave passage, and the local site effect. However, several authors recommend taking into account these three patterns separately and in combination in order to have a clearer view of the structural behavior of the analyzed bridge.

9. Funding

10. References

AASHTO (1996), *American Association of State Highway and Transpor. Interim revisions to the AASHTO standard specifications for highway bridges: division I-A, Seismic Design. Washington, 1996.*

Abdel Raheem, Shehata E.; Hayashikawa, Toshiro; Dorka, Uwe (2011), *Ground Motion Spatial Variability Effects on Seismic Response Control of Cablestayed Bridges.Earthquake Engineering And Engineering Vibration 10, no. 1 (2011): 37-49. DOI: 10.1007/s11803-011-0045-5*

Abrahamson , Norman A. (2007), *Hard-Rock Coherency Functions Based on the Pinyon Flat Array Data. Piedmont: EPRI, http://pbadupws.nrc.gov/docs/ML0721/ML072190359.pdf*

Ahmed M. , Abdel-Ghaffar, Rubin Lawrence I.. (1982), *Suspension Bridge Response to Multiple-Support Excitations. Engineering Mechanics Division 108, no. 2: 419-435.http://cedb.asce.org/CEDBsearch/record.jsp?dockey=0034014*

SPANISH VERSION..

Álvarez, J. J.; Aparicio, A. C. ; Jara, J. M. ; Jara, M.   (2012), *Seismic Assessment of a Long-Span Arch Bridge Considering the Variation in Axial Forces Induced by Earthquakes.Engineering Structures 34 (2012): 69-80. http://dx.doi.org/10.1016/j.engstruct.2011.09.013*

Álvarez Sereno, José de Jesús; Bengoechea, Ángel Carlos Aparicio (2003), *Comportamiento Sísmico de Puentes Arco. Un Panorama del Estado del Conocimiento. Revista de Ingeniería Sísmica, no. 68: 21-53. http://www.redalyc.org/comocitar.oa?id=61806802*

Álvarez, José de Jesús ; Jara, Manuel; Hernández, Hugo; Bengoechea, Ángel Carlos Aparicio. (2006), *Evaluación de la Respuesta de Grandes Puentes en Arco ante Movimientos Sísmicos Fuertes. Revista de Ingeniería Sísmica, no. 75 (2006): 23-46.*

Alvarez Sereno, José de Jesús; Parra, Nicolás G.; Bengoechea, Angel C. Aparicio (2002), *Comportamiento Estructural de Puentes en Arco Sometidos a Movimiento de Fuente Cercana. Puebla, México: XIII Congreso Nacional de Ingeniería Estructural, 2002. http://www.smie.org.mx/SMIE_Articulos/co/co_12/te_04/ar_14.pdf*

Apaydin, Nurdan Memisoglu; Bas, Selcuk; Harmandar, Ebru. (2016), *Response of the Fatih Sultan Mehmet Suspension Bridge Under Spatilly Varying Multi-Point Earthquake Excitations. Soil Dynamics and Earthquake Engineering 84 (2016): 44-54. http://dx.doi.org/10.1016/j.soildyn.2016.01.018*

Applied Technology (1996). *Council. Improved Seismic Design Criteria for California Bridges. Redwood City, California, 1996.*

Applied Technology (2003), *Council and Multidisciplinary Center for Earthquake Engineering Research. Recommended LRFD guidelines for the seismic design of highway bridges. California, 2003.*

Bayraktar, A.; Dumanoğlu, A. A.; and Calayir, Y. (1996), *Asynchronous Dynamic Analysis of Dam-Reservoir-Foundation Systems by the Lagrangian Approach. Computers & Structures 58, no. 5 (1996): 925-935. DOI:10.1016/0045-7949(95)00211-X*

Burdette N.J.; Elnashai, Amr S.; Lupoi, A.; Sextos, A.G. (2008),. *Effect of Asynchronous Earthquake Motion on Complex Bridges I : Methodology and Input Motion. Journal of Bridge Engineering 13, no. 2 (2008): 158-165. http://dx.doi.org/10.1061/(ASCE)1084-0702(2008)13:2(158)*

Burdette N.J.; Elnashai, Amr S.; Lupoi, A.; Sextos, A.G. (2008),. *Effect of Asynchronous Earthquake Motion on Complex Bridges. II- Results and Implications on Assessment.Journal of Bridge Engineering 13, no. 2 (2008): 166-172. http://dx.doi.org/10.1061/(ASCE)1084-0702(2008)13:2(166)*

Burdette N.J.; Elnashai, Amr S.; Lupoi, A.; Sextos, A.G. (2006), *The Effect of Asynchronous Earthquake Motion on Complex Bridges. Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Illinois: Mid-America Earthquake Center, 2006, 28. https://www.ideals.illinois.edu/bitstream/handle/2142/8935/Report06-03.pdf?sequence=2*

Cacciola, Pierfrancesco; Deodatis, George (2011),. *A Method for Generating Fully Non-Stationary and Spectrum-Compatible Ground Motion Vector Processes. Soil Dynamics and Earthquake Engineering 31, no. 3 (2011): 351-360.mhttp://dx.doi.org/10.1016/j.soildyn.2010.09.003*

Caltrans Seismic (1999), *Soil-foundation-structure interaction.En:Bridge Engineering Handbook, 2 ed. California, 1999.*

Chopra, Anil K.(2012), *Dinámica de estructuras. Cuarta edición. Naucalpan de Juárez: Pearson, 2014.*

Comité Europeo de Normalización (2012), *Eurocódigo 8: Proyecto de estructuras sismoresistentes. Parte 2: Puentes. Madrid, España: AENOR, 2012.*

Deodatis, G. (1996), *Simulation of Ergodic Multivariate Stochastic Processes. Journal of Engineering Mechanics 122, no. 8 (1996): 778-787. http://dx.doi.org/10.1061/(ASCE)0733-9399(1996)122:8(778)*

Deodatis, George. (1996), *Non Stationary Stochastic Vector Processes- Seismic Ground Motion Applications. Probabilistic Engineering Mechanics 11, no. 3 (1996): 149-167.DOI:10.1016/0266-8920(96)00007-0*

Der Kiureghian, Armen; Neuenhofer, Ansgar. (1992), *Response Spectrum Method for Multi-Support Seismic Excitations. Earthquake Engineering & Structural Dynamics 21, no. 8 (1992): 713-740. DOI: 10.1002/eqe.4290210805*

Dumanogluid, A. A.; Soyluk, K.(2003), *A Stochastic Analysis of Long Span Structures Subjected to Spatially Varying Ground Motions Including the Site-Response Effect.Engineering Structures 25, no. 10 (2003): 1301-1310. http://dx.doi.org/10.1016/S0141-0296(03)00080-4*

Feng, Maria Q.; Kim, Sang-Hoon (2003), *Fragility Analysis of Bridges Under Ground Motion with Spatial Variation. International Journal of Non-Linear Mechanics 38, no. 5 (2003): 705-721. http://dx.doi.org/10.1016/S0020-7462(01)00128-7*

Fernandez Sola, Luciano; Sánchez García, Raúl; Suárez López, Martha (2013), *Respuesta Dinámica de Puentes Simples Sometidos a Excitación Multisoporte Debida a la Topografía. Edited by Sociedad Mexicana de Ingeniería Sísmica. Boca del Río Veracruz: XIX Congreso Nacional de Ingeniería Sísmica, 2013.*

Ghobarah, A., Aziz, T. S.; El-Attar, M. (1996), *Response of Transmission Lines to Multiple Support Excitation. Engineering Structures 18, no. 12 (1996): 936-946.DOI:10.1016/S0141-0296(96)00020-X*

Hao, Hong. (1997), *Torsional Response of Building Structures to Spatial Random Ground Excitations. Engineering Structures 19, no. 2 (1997): 105-112. DOI:10.1016/S0141-0296(96)00029-6*

Harichandran, R.; Hawwari, A. Sweidan, B. (1996), *Response of Long-Span Bridges to Spatially Varying Ground Motion. Journal of Structural Engineering 122, no. 5 (1996): 476-484. http://dx.doi.org/10.1061/(ASCE)0733-9445(1996)122:5(476)*

Harichandran, R.; Vanmarcke, E. (1986), *Stochastic Variation of Earthquake Ground Motion in Space and Time. Journal of Engineering Mechanics 112, no. 2 (1986): 154–174.http://dx.doi.org/10.1061/(ASCE)0733-9399(1986)112:2(154)*

Japan Road Association. (2000), *Design Specifications of Highway Bridges, Part V. Japan, Tokyo: Seismic Design, Tokyo Japan Society of Civil Engineers, 2000.*

Kaiming, Bi; Hao, Hong; Ren Wei-Xin. (2013), *Seismic Response of a Concrete Filled Steel Tubular Arch Bridge to Spatially Varying Ground Motions Including Local Site Effect.Advances in Structural Engineering 16, no. 10 (2013): 1799. DOI: 10.1260/1369-4332.16.10.1799*

Karakostas, Christos; Sextos, Anastasios; Lekidis, Vassilios; Papadopoulos, Savvas (2011), *Investigation of the Dynamic Response of the Evripos Cable-Stayed Bridge in Greece, Under Asynchronous Ground Motion Records. Corfu, Greece: 3rd ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, 2011. http://congress.cimne.com/eccomas/proceedings/compdyn2011/compdyn2011_full/486.pdf*

Karmakar, Debasis; Ray-Chaudhuri, Samit; Shinozuka, Masanobu. (2012), *Seismic Response Evaluation of Retrofitted Vincent Thomas Bridge Under Spatially Variable Ground Motions. Soil Dynamics and Earthquake Engineering 42 (2012): 119-127. http://dx.doi.org/10.1016/j.soildyn.2012.06.008*

Kassawara, R.; Sandell, L. (2006), *Spatial Coherency Models for Soil-Structure Interaction. Final Report, U. S. Departmen of Energy, Electric Power Research Institute, Palo Alto, California, 2006. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001014101*

Kleoniki Fontara, Ioanna; Titirla, Magdalini; Wuttke, Frank; Athanatopoulou, Asimina; Manolis, George; Sextos, Anastasios. (2015), *Multiple Support Excitation of a Bridge Based on Bem Analysis of the Subsoil-Structure-Interaction Phenomenon. Edited by 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering. Crete Island, Greece,*

2015. http://www.bristol.ac.uk/engineering/people/anastasios-sextos/pub/55866507

Konakli, Katerina; Der Kiureghian, Armen. (2012), *Simulation of Spatially Varying Ground Motions Including Incoherence, Wave-Passage and Differential Site-Response Effects.Earthquake Engineering & Structural Dynamics 41, no. 3 (2012): 495-513. DOI: 10.1002/eqe.1141*

Konakli, Katerina; Der Kiureghian, Armen. (2011), *Stochastic Dynamic Analysis of Bridges Subjected to Spatially Varying Ground Motions. Berkeley, California: PEER, 2011.http://peer.berkeley.edu/publications/peer_reports/reports_2011/webPEER-2011-105-Konakli.pdf*

Lou, L.; 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, no. 7 (2005): 729–740. http://dx.doi.org/10.1016/j.soildyn.2004.11.016*

Luco, J. E.;Wong, H. L.(1986), *Response of a Rigid Foundation to a Spatially Random Ground Motion. Earthquake Engineering & Structural Dynamics 14, no. 6 (1986): 891–908. DOI: 10.1002/eqe.4290140606*

Mehanny, S. S. F.; Ramadan, O. M. O.;Elhowary, H. A. (2014), *Assessment of Bridge Vulnerability Due to Seismic Excitations Considering Wave Passage Effects. Engineering Structures 70, no. 1 (2014): 197-207. http://dx.doi.org/10.1016/j.engstruct.2014.04.010*

Mezouer, Nourredine; Silhadi, Kamel; Afra, Hamid. (2010), *Importance of Spatial Variability of Seismic Ground Motion Effects on Long Beams Response. Journal of Civil Engineering and Construction Technology 1, no. 1 (2010): 1-13. http://www.academicjournals.org/journal/JCECT/article-full-text-pdf/44675822575*

Nazmy A. S., Konidaris E. G. (1994), *Nonlinear Seismic Behavior of Steel Deck-Type Arch Bridges. Illinois, Chicago: US National Conference on Earthquake Engineering.*

Nuti, Camilo; Vanzi, Ivo. (2005), *Influence of Earthquake Spatial Variability on Differential Soil Displacements and SDF System Response. Earthquake Engineering & Structural Dynamics 34 (2005): 1353-1374. DOI: 10.1002/eqe.483*

Price E.; Thomas, E.; Marc O. (1998), *Effects of Spatially Varying Ground Motions on Short Bridges. Journal of Structural Engineering 124, no. 8: 948-955.http://dx.doi.org/10.1061/(ASCE)0733-9445(1998)124:8(948)*

Ramadam, O. M. O.; Mehanny, S. S. F.; Elhowary, H. A. (2015), *Seismic Vulnerability of Box Girder Continuous Bridges Under Spatially Variable Ground Motions. Bulletin of Earthquake Engineering 13, no. 6 (2015): 1727-1748. DOI: 10.1007/s10518-014-9683-0*

Ramadam, O.; Novak, M. (1993), *Simulation of Spatially Incoherent Random Ground Motions. Journal of Engineering Mechanics 119, no. 5 (1993): 997-1016.http://dx.doi.org/10.1061/(ASCE)0733-9399(1993)119:5(997)*

Saxena, Vinita; Deodatis, George; Shinozuka, Masanobu. (2000), *Effect of Spatial Variation of Earthquake Ground Motion on the Nonlinear Dynamic Response of Highway Bridges. 12th World Conference on Earthquake Engineering. Auckland, New Zealand: New Zealand Society for Earthquake Engineering, 2000. http://www.iitk.ac.in/nicee/wcee/article/2227.pdf*

Sextos, G. (2009), *Anastasios, and Andreas J. Kappos. Evaluation of Seismic Response of Bridges Under Asynchronous Excitation and Comparisons with Eurocode 8-2 Provisions. Bulletin of Earthquake Engineering 7, no. 2 (2009): 519-545. DOI: 10.1007/s10518-008-9090-5*

Sextos, Anastasios, Kappos, Andreas J.; Mergos, Panayiotis (2004), *Effect of Soil-Structure Interaction and Spatial Variability of Ground Motion on Irregular Bridges- the Case of The Krystallopigi Bridge. Vancouver, B.C., Canada: 13th World Conference on Earthquake Engineering, 2004. http://www.iitk.ac.in/nicee/wcee/article/13_2298.pdf*

Sextos, Anastasios; Karakostas, Christos; Lekidis, Vassilios; Papadopoulos, Savvas. (2015), *Multiple Support Seismic Excitation of the Evripos Bridge Based on Free-Field and on-Structure Recordings. Structure and Infrastructure Engineering 11, no. 11 (2015): 1510-1523. http://dx.doi.org/10.1080/15732479.2014.977302*

Sgambi, L.; Garavaglia, E.; Basso, N.;Bontempi, F. (2014), *Monte Carlo Simulation for Seismic Analysis of a Long Span Suspension Bridge. Engineering Structures 78 (2014): 100-111. http://dx.doi.org/10.1016/j.engstruct.2014.08.051*

Snaebjornsson, J.; Sigbjornsson, R. (2008), *The Spatial Variability of Ground Motion and its Effects on Multi-Supported Structures. Beijing, China: The 14th World Conference on Earthquake Engineering, 2008. http://www.iitk.ac.in/nicee/wcee/article/14_06-0079.PDF*

Soyluk, K. (2004), *Comparison of Random Vibration Methods for Multi-Support Seismic Excitation Analysis of Long-Span Bridges. Engineering Structures 26, no. 11 (2004): 1573-1583. http://dx.doi.org/10.1016/j.engstruct.2004.05.016*

Soyluk, K.; Dumanoglu, A. A. (2000), *Comparison of Asynchronous and Stochastic Dynamic Responses of a Cable-Stayed Bridge. Engineering Structures 22, no. 5 (2000): 435-445. http://dx.doi.org/10.1016/S0141-0296(98)00126-6*

Soyluk, K.; Dumanoglu, A. A. (2004), *Spatial Variability Effects of Ground Motions on Cable-Stayed Bridges. Soil Dynamics and Earthquake Engineering 24, no. 3 (2004): 241–250. http://dx.doi.org/10.1016/j.soildyn.2003.11.005*

Soyluk, Kurtulus; Sicacik, Eda Avanoglu (2012), *Soil–Structure Interaction Analysis of Cable-Stayed Bridges for Spatially Varying Ground Motion Components. Soil Dynamics and Earthquake Engineering 35 (2012): 80-90. http://dx.doi.org/10.1016/j.soildyn.2011.11.003*

Tecchio, G.; Grendene, M. ; Modena, C. (2012), *Pounding Effects in Simply Supported Bridges Accounting for Spatial Variability of Groundmotion: a Case Study. Advances in Civil Engineering 2012 (2012): 10. http://dx.doi.org/10.1155/2012/267584*

Valdebenito, Galo E.; Aparicio, Ángel C. (2005), *Comportamiento Sísmico de Puentes Atirantados y Disipación de Energía Adicional: Un Estado del Conocimiento, Edited by A. H. Barbat. Barcelona: Monografías de Ingeniería Sísmica, 2005. http://hdl.handle.net/2117/28373*

Wang, H.; Harada, T.; Nonaka, T.; Nakamura, M. (2008), *Spatial Variability of Near Field Ground Motions and its Design Implication of Long Extended Lifeline Structures Nearby a Fault. Beijing, China: The 14th World Conference on Earthquake Engineering, 2008. http://www.iitk.ac.in/nicee/wcee/article/14_02-0025.PDF*

Wang, J.; Carr, A.; Cooke, N.; Moss, P. (2003), *Wave-Passage Effect on the Seismic Response of Long Bridges. Christchurch, New Zealand: 2003 Pacific conference on earthquake engineering, 2003. http://www.nzsee.org.nz/db/2003/View/Paper050s.pdf*

Wang, Junjie; Hu, Shide; Wei, Xiao (1999), *Effects of Engineering Geological Condition on Response of Suspension Bridges. Soil Dynamics and Earthquake Engineering 18, no. 4 (1999): 297-304. http://dx.doi.org/10.1016/S0267-7261(99)00002-0*

Zhang, Y. H.;Li, Q.S.; Lin, J. H.; Williams,F. W. (2009), *Random Vibration Analysis of Long-Span Structures Subjected to Spatially Varying Ground Motions. Soil Dynamics and Earthquake Engineering 29, no. 4 (2009): 620-629. http://dx.doi.org/10.1016/j.soildyn.2008.06.007*