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

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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, 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
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 Evripus 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):

\[
\begin{bmatrix}
M & M_c & M_g \\
M_c^T & C_c & C_g \\
M_g^T & C_g & K_g
\end{bmatrix}
\begin{bmatrix}
\ddot{x} \\
\dot{\ddot{u}}
\end{bmatrix} +
\begin{bmatrix}
C & C_c & C_g \\
C_c^T & K_c & K_g \\
C_g^T & K_g & K_g
\end{bmatrix}
\begin{bmatrix}
\dot{x} \\
\dot{\ddot{u}}
\end{bmatrix} +
\begin{bmatrix}
F \\
0 \\
0
\end{bmatrix} = 0
\]  

(1)

Where, 

\( M \) and \( C \) are respectively the matrices of mass and damping, and \( K \) the stiffness, associated with the unrestricted degrees of freedom.

\( M_g \), \( C_g \) and \( K_g \) are respectively the matrices of mass, damping and stiffness, associated with the degrees of freedom from the supports.

\( M_c \), \( C_c \) and \( K_c \) are respectively the 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, Dumanoglu and Calayir, 1996), (Hao, 1997), (Konakli and Kureghian, 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:

\[
\begin{bmatrix}
x \\
u \end{bmatrix} = \begin{bmatrix}
x_{ps} \\
u \end{bmatrix} + \begin{bmatrix}
x_d \\
0 \end{bmatrix}
\]

(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:

\[
\begin{bmatrix}
K & K_c \\
K_c^T & K_g
\end{bmatrix}
\begin{bmatrix}
x \\
u
\end{bmatrix} = \begin{bmatrix}
0 \\
F_s
\end{bmatrix}
\]

(3)

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

\[
M \dddot{x} + M_c \dddot{u} + C \dddot{x} + C_c \dddot{u} + K \dddot{u} + K_c \dddot{u} = 0
\]

(4)

Replacing equation 2 in equation 4, we obtain:

\[
M \dddot{x}_d + C \dddot{x}_d + K \dddot{x}_d = F_{ef}(t)
\]

(5)

Where the effective seismic force vector will be given by:

\[
F_{ef}(t) = -(M \dddot{x}_{ps} + M_c \dddot{u}) - (C \dddot{x}_{ps} + C_c \dddot{u}) - (K \dddot{x}_{ps} + K_c \dddot{u})
\]

(6)

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

$$\gamma_{kl}^{(w)}(\omega) = \exp \left[ -\frac{\text{iod}_{kl}}{V_{app}} \right]$$

Where,

- $d_{kl}$ 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:

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

Where,

- $d_{kl}$ is the horizontal spacing between supports $k$ and $l$, and
- $\alpha$ and $\beta$ are angles depending on $d_{kl}$ and $\omega$.

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:

$$\gamma_{kl}^{(\xi)}(\omega) = \exp[\theta_{kl}^{(\xi)}(\omega)]$$

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

Where,

- $\xi_k$ and $\xi_l$ are soil damping ratios in points $k$ and $l$, respectively.
- $\omega_k$ and $\omega_l$ 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 ($\gamma_{kl}$):
\[ \gamma_{kl}(\omega) = \gamma_{kl}^{(i)}(\omega) \gamma_{kl}^{(w)}(\omega) \gamma_{kl}^{(s)}(\omega) \tag{15} \]

Where,

\( \omega \) is the angular frequency, and \( \gamma_{kl} \) is the coherence function between the supports \( k \) and \( l \), in accordance with the angular frequency \( \omega \).

Subscripts \( k \) and \( l \) indicate points \( k \) and \( l \) of the structure with \( k, l = 1, 2, \ldots, N \) 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)](image)
In 2003, (Dumanoglu 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 \( S_{u_k u_l} \) in accordance with the angular frequency. See equation 7.

\[
S_{u_k u_l}(\omega) = \gamma_{k l}(\omega)[S_{u_k u_k}(\omega)S_{u_l u_l}(\omega)]
\]  

Where,
\( S_{u_k u_k}(\omega) \) is the white noise amplitude of acceleration in bedrock.
\( \omega_0 \) and \( \zeta_0 \) are the angular frequency and the damping coefficient of the first filter, respectively.
\( \omega_f \) and \( \zeta_f \) are the angular frequency and the damping coefficient of the second filter, respectively.
\( \gamma_{k l} \) 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.

\[
S_{u_k u_l}(\omega) = S_0 \left[ \frac{\omega^4 + 4\zeta_0^2 \omega^2 \omega^2}{(\omega_0^2 - \omega^2)^2 + 4\zeta_0^2 \omega^2 \omega^2} \right] \left[ \frac{\omega^4}{(\omega_f^2 - \omega^2)^2 + 4\zeta_f^2 \omega_f^2 \omega^2} \right]
\]  

\[(17)\]

**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)
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:

\[ u_{rn}(t) = u_r(t) \cdot \text{sen}\left(\frac{nt}{T}\right) \]  

(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 arch bridges with a span greater than 400 m. Following the same line, (Álvarez et al., 2012) found out that in the case of concrete arch 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

(Álvarez 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).
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 and 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.
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.

(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 seismic, being more critical for high-frequency ranges in order not to underestimate the probability of structural failure.

![Figure 6. Elevated view of the arched bridge of the Yeshan river in China. Units: mm (Kaiming et al., 2013)](image)

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

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

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

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 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.

$$C_p = \frac{T_p V_{app}}{L_s}$$

(19)

Where,
$T_p$ 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 El-Nasha, 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 1.85 s, 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.

(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°.
(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 TYOH 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 patterns 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).

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.
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.

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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...
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%.

![Figure 16](image_url)

*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)*
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 asynchronous 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.

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10. References


