The Effect of Asynchronous Earthquake Motion on Complex Bridges

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SUMMARY

Based on observed damage patterns from previous earthquakes and a rich history of analytical studies, asynchronous input motion has been identified as a major source of unfavorable response for long span structures, such as bridges. This study is aimed at quantifying the effect of geometric incoherence and wave arrival delay on complex straight and curved bridges using state-of-the-art methodologies and tools. Using fully parameterized computer codes combining expert geotechnical and earthquake structural engineering knowledge, suites of asynchronous accelerograms are produced for use in inelastic dynamic analysis of the bridge model. Two multi-degree-of-freedom (MDOF) analytical models are analyzed using 2,000 unique synthetic accelerograms. Results from this study indicate that response for the 344 meter study structure is amplified significantly by non-synchronous excitation, with displacement amplification factors between 1.6 and 3.4 for all levels of incoherence. This amplification was not constant or easily predicable, demonstrating the importance of inelastic dynamic analysis using asynchronous motion for assessment and design of this class of structure. Additionally, deck stiffness is shown to significantly affect response amplification, through response comparison between the curved and an equivalent straight bridge. Study results are used to suggest an appropriate domain for consideration of asynchronous excitation as well as an efficient methodology for analysis.

INTRODUCTION

Because irregular elevated transportation structures are becoming a common solution to complex transportation problems, it is important that a commensurate breadth and depth of research are invested in understanding these complex structures. Natural disasters of the past few decades have provided numerous examples of bridge damage and collapse for bridges that were designed for seismic forces (Elnashai *et al.,* 1999). To better protect bridges from future earthquakes, researchers must aid bridge designers by utilizing field observations and expanding on past investigations to include representative bridges of all types and alignments, striving to make inelastic dynamic analyses as realistic as possible. With advances in computing power, structural and seismological features previously simplified can be fully included in analysis.

Utilizing advanced analysis tools, this study seeks to include two complicating factors not often considered in seismic analysis: (i) bridge irregularity, including varied pier heights, abutment end conditions, and a curved horizontal alignment and (ii) spatially varied seismic input with a range of incoherence cases. Inclusion of the first factor recognizes that actual bridges must often be irregular due to site limitations or alignment requirements. The second factor is included due to increased understanding of the seismological characteristics of earthquakes and the higher displacement demand possible from asynchronous input, demonstrated in recent studies (Sextos *et al.*, 2004, Lupoi *et al*., 2005).

To consider the effect of bridge irregularity, equivalent curved and straight concrete bridge models were subjected to asynchronous earthquake motion and their responses compared at the end of this report. Because the vast majority of previous analytical studies have been performed on straight bridges, this comparison will determine whether asynchronous response amplification can be expected to be similar for curved versions of previous bridges studied. Additionally, the effect of various levels of earthquake incoherence will be determined using synthetic accelerograms generated by means of two specifically developed, state-of-the-art asynchronous record generation software programs.

SPATIALLY ASYNCHRONOUS EARTHQUAKE MOTION

Sources of Asynchronous Motion

Consideration of spatially varied seismic input motion is challenging due to its complexity. Wave travel speed, reflection and refraction, and heterogeneous soil conditions all cause deviations from synchronous excitation for distributed foundation structures such as bridges. For simplification, asynchronous motion is commonly divided into three components: (i) a wave passage effect, (ii) geometric incoherence of the input and (iii) local site conditions. The first component is due to the finite travel speed of seismic waves, resulting in progressive excitation of each support point as a wave front passes. The second component accounts for the reflection and refraction of seismic waves as they pass through the ground, changing their signal content between support points. The final component accounts for situations where structures are founded on different soil types, such as a bridge that spans a geologic divide. Though the asynchronous motion observed during earthquakes is a complex interaction of all three components, for analytical simplicity, researches have divided the phenomenon into these three sources.

Observations from Previous Earthquakes

In recent earthquakes there are numerous examples of bridge failures that may have been caused or aided by differential support motion. During the Northridge earthquake of 1994, a number of spans of the Gavin Canyon undercrossing fell off of their supports, resulting in the total collapse of substantial portions of the structure (Tzanetos *et al*., 2000). The spans became unseated and collapsed, despite being retrofitted with restraining devices following the San Fernando earthquake. While shifting and pounding of deck slabs from synchronous motion could cause unseating, differential support motion is a more likely cause of the large displacements resulting in failure of this retrofitted structure.

The Kobe earthquake of 1995 provides further examples of deck unseating where differential support movement was likely involved. The city of Kobe has many kilometers of elevated highways where single spans supported on rollers bridge the gaps between piers. Many of these single spans fell off of their supports at expansion joints during this earthquake because of large longitudinal displacements between piers (Elnashai *et al.*, 1995). Again, it is difficult to fully attribute these failures to asynchronous earthquake motion, but such motion is known to cause large differential movement of neighboring supports. As discussed in greater detail below, several studies have shown that spatially varied ground motion can exact higher demands on a bridge structure than synchronous motion.

Previous Studies

Studies on the response of extended foundation structures to differential support excitation began over 40 years ago with a study by Bodganoff *et al.* (1965) on the effect of ground transmission time on long structures. This and other early studies, such as Dumanoglu, *et al.* (1987) and Leger *et al.* (1990), focused on long bridges subjected to wave passage effects only. These studies identified isolated cases of response amplification due to asynchronous motion, but their conclusions were limited due to their simplicity. Significant advances in computing power in the early 1990s allowed larger, more involved studies to be performed. The advent of “spatial” models of asynchronous motion allowed geometric incoherence to be incorporated into studies using a stochastic field based on random vibration theory.

The majority of studies including both the wave passage effect and geometric incoherence terms use synthetic ground motion based on the Luco and Wong coherency function (Luco and Wong, 1986). This function provides a mathematical representation of coherence and consists of two terms, one which quantifies the severity of the wave passage effect, and another which represents the level of geometric incoherence. While other coherence functions have been suggested (see Oliveira *et al.*, 1991 and Der Kiureghian *et al.*, 1992, among others), the function proposed by Luco and Wong has gained the widest use for its simplicity and clarity.

One of the first studies based on the random vibration theory approach was done by Zerva (1990). In this study the structural response of beams with varied lengths were evaluated for seismic input with different degrees of incoherence, including totally synchronous excitation. The results showed that asynchronous response is very complex and a clear trend is hard to define, with incoherence either increasing or decreasing the structural response, depending on many parameters.

The first major study to include inelastic dynamic analysis was by Monti *et al.*, (1996) and involved the inelastic response of a simple, symmetric, 6-span reinforced concrete bridge to asynchronous motion. The results showed that in cases of severe incoherence, the bridge responds almost entirely pseudo-statically, though the response is still less than the synchronous case. Because the simplicity of this study structure limited the scope of the results, future researchers often introduced irregularities into simple bridge structures. Tzanetos *et al.*, (2000) varied the pier heights of a straight bridge which was analyzed using inelastic asynchronous analysis. For this irregular bridge, asynchronous motion was shown to significantly increase response for many cases, especially in the transverse direction. Tzanetos *et al.*, (2000) identified suppression of the fundamental mode and dominance of higher-mode response as a hallmark of asynchronous excitation, a finding supported in future studies.

Two recent asynchronous inelastic bridge analyses including structural irregularities are by Sextos *et al.,* (2003) and Lupoi *et al.*, (2005). The first study involved a broad parametric study of 20 bridges with different geometric and dynamic characteristics (though all straight). Results from this study showed that relative pier displacements are strongly tied to the overall length of the bridge, with these displacements increasing logarithmically for the study range (up to 600m) and exceeding synchronous displacements frequently above 400 meters. The second study by Lupoi *et al.*, (2005) involved the analysis of a straight, 200m 4-span bridge in the longitudinal direction only, with varied pier heights, deck stiffness, and coherency level of the input motion. This study showed that asynchronous motion can increase the probability of bridge failure for even relatively short structures.

The analytical study most similar to the current investigation of curved bridges under asynchronous motion is by Sextos *et al.* (2004). The study involved the inelastic response history analysis of a curved, prestressed concrete bridge in Greece, the Krystallopigi Bridge. The study structure is a 12-span, 638 m, curved bridge with varied pier heights. The bridge was analyzed with both a natural record recorded near the bridge site, and a suite of synthetic records with varied degrees of correlation. Results of this analysis support the conclusion of previous studies that asynchronous motion can excite higher dynamic modes, and cases of pier displacement demands doubling were noted. This led the authors to propose the 600 m length suggested by Eurocode 8 as a threshold for asynchronous analysis be reduced in the case of curved bridges, although the difficulty in drawing further conclusions for such a complex bridge without further study is acknowledged.

STUDY OVERVIEW

Study Parameters

The two primary parameters considered in this study are (i) bridge plan geometry and (ii) level of incoherence, described by a wave passage effect and geometric incoherence contribution. The effect of plan geometry on response was evaluated by analyzing two equivalent bridge models with straight and curved decks. In order to approach the issue of incoherent ground motion in a logical and incremental way, three levels of incoherence were studied for each of the two contributing phenomenon. These three levels of incoherence relate to the following ground motion coherency function proposed by Luco and Wong (1986):

$$\gamma(\xi,\omega) = \exp\left[-\left(\frac{\alpha\omega\xi}{v_s}\right)^2\right]\exp\left[i\frac{\omega\xi^L}{v_{app}}\right] \tag{1}$$

Where α includes the mechanical characteristics of the soil, ξ and ξ^L are the separation distance between two support points and the projected distance from the source, respectively, ν_s is the shear wave velocity and ν_{app} is the apparent surface wave velocity. The coherence level of generated time histories is controlled by this expression, which in this study is used essentially as a two-parameter function, with inputs of ν_s/α and ν_{app}. The separation distance between two bridge piers and the projected distance in the direction of propagation are determined by the geometry of the study structure.

The first variable input quantity is the lumped shear wave velocity and soil property term ν_s/α. This quantity controls the first term of the coherency function, and accounts for the geometric incoherence of the ground motion. The second input quantity, ν_{app}, is the apparent surface velocity. This parameter is associated with the second term of Equation 1, and it controls the severity of the wave-passage effect. Setting $\nu_{app} = \infty$ is equivalent to an earthquake in which the seismic waves travel with infinite speed, reaching all bridge supports simultaneously and rendering the motion coherent with regard to this parameter. In the coherency function, this is reflected by the second term becoming one, meaning any loss of coherence must be from geometric incoherence (term one). In the same manner, when $\nu_s/\alpha = \infty$, the first term of the expression becomes one and thus any incoherence is from the wave passage effect only (term two).

By performing a parametric study varying these coherency input parameters for a given earthquake, the effect of each source of incoherence can be isolated. Table 1 shows the range of coherency cases considered with their abbreviations to facilitate easy reference. The level of geometric incoherence increases from left to right in the table, while wave passage severity increases from top to bottom. Thus the upper left entry “inin” corresponds to synchronous input motion, while the bottom right “3030” represents the most incoherent case, with ν_s/α and ν_{app} values of 300 m/s.

ν_{app} value	ν_s/α value		
	Infinity	900 m/s	300 m/s
Infinity	inin	90in	30in
900 m/s	in90	9090	3090
300 m/s	in30	9030	3030

TABLE 1. Incoherence cases and their abbreviations

This range of study parameters was selected based on previous studies and observed shear wave velocities, which can be as low as 200-300 m/s in soft soil (Wilson and Jennings, 1985). It is noted that as the apparent velocity ν_{app} is generally much higher than the corresponding shear wave velocity, however the low value of 300 m/s is adopted as the extreme case of maximum wave arrival delay. To compare synchronous and asynchronous response, fully coherent (infinite ν_s/α and ν_{app}) motion was also analyzed, which could correspond to a dense rock site. The intermediate value of 900 m/s is chosen to represent moderate velocities, and geometric incoherence parameters are selected to correspond to ν_{app} values, as done in previous studies (Monti *et al.*, 1996 and Lupoi *et al.*, 2005). Though highly dependent on the individual time history records, these levels of incoherence resulted in maximum relative ground displacements of approximately 20-30mm for moderate incoherence and 100-150mm for severely incoherent records.

Structural Model

The curved, prestressed concrete bridge structure analyzed in this study was proposed as a design example for the Second International Workshop on the Seismic Design of Bridges (Priestley, 1994). This bridge was selected because all of its structural data is readily available, and because it was designed as an example structure to encourage (synchronous) seismic analyses. Like most bridges in previous asynchronous studies it has a cellular concrete deck. Because pseudo-static deflections play an important role in asynchronous response, the stiffness of the bridge deck can influence the displacement demand placed on bridge piers, and it is acknowledged that results found using this structure may not be easily transferable to a steel bridge, however it represents a common structural form for long-span bridges and a practical study structure.

The prestressed concrete study bridge is shown in Figure 1. It is supported by 8 piers and 2 abutments with a total length of 344 meters rotating 98 degrees. The piers consist of 1 meter diameter single column bents supporting a prestressed concrete twin box girder superstructure with sliding bearings, which allow rotation and longitudinal motion but are restrained transversely. The deck is fixed to abutment 1 and attached through a similar bearing to abutment 10. The abutments are supported by 6 one meter diameter reinforced concrete cast in drilled hole (CIDH) cylinders a minimum of 15 meters long. Each of the 8 bridge piers are supported by a monolithic footing and 4 similar CIDH cylinders.

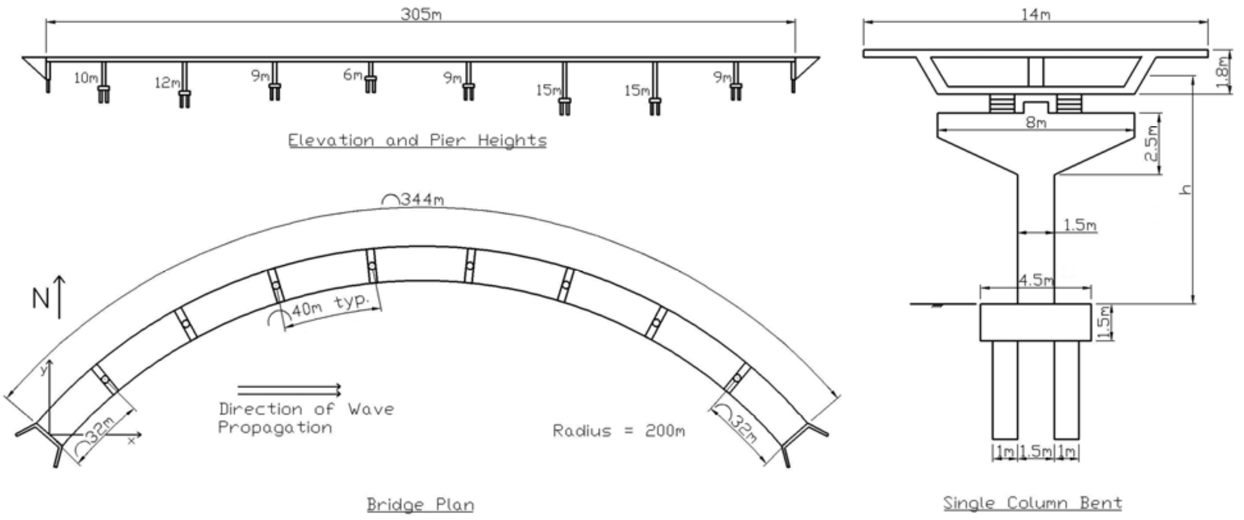


FIGURE 1. Study structure plan, elevation, and section (adapted from Priestley, 1994)

INPUT MOTION AND MODELING

Synthetic Earthquake Records

Due to the large number of correlated time history records required for such a large parametric study, synthetic records were used for analysis. These records were provided from two sources using different record generation software. A suite of 10 earthquake events for each of the 9 incoherence cases considered in Table 1 were produced using a generation model developed by Pinto (2006). Records simulating 1 earthquake event for the 9 coherency cases were produced (Pitilakis, 2006) using ASING (Asynchronous Support Input Generator) software developed by Sextos *et al.* (2003).

Both of these software models account for bridge geometry and desired coherence level to produce spatially variable earthquake ground motion based on random vibrations. Given the bridge geometry and the ν_s/α and ν_{app} terms, the software produces correlated response history records for any number of points spaced along a line. Records produced using each of these programs have been used in previous studies by the developers, with satisfactory verification of record quality (see Lupoi *et al.*, 2005 and Sextos *et al.*, 2003). Additionally, the ASING program was calibrated based on measured seismic excitation from a strong motion array in Greece, primarily with respect to the effect of local soil conditions which is one of the main modules of the program.

Because this study structure was excited in both the longitudinal and transverse directions, a total of 180 unique time histories were required for each earthquake event (20 for each coherency case). Therefore a total of 1,800 unique time histories were created using software developed at the University of Rome and 180 time histories were produced using the ASING program. All synthetic earthquake records were generated to closely match the criteria given with the design example, with a record duration of 20 seconds and PGA of 5 m/s^2. To ensure the earthquakes did not miss an important dynamic mode of the study structure, the synthetic records were generated to closely match the Eurocode 8 design spectrum.

To prevent spurious net displacements between bridge support points in the bridge structure, all generated records were baseline-corrected to zero final displacement using a linear baseline correction algorithm. This ensured that the final ground displacement of the entire bridge site is zero while allowing absolute displacements of various support points to vary during seismic excitation (resulting in pseudo-static forces). Figure 2 demonstrates the effect of baseline correction on an example accelerogram. When the original displacement record is adjusted using a linear function to produce a zero final displacement, the corrected accelerogram closely matches the original. Slight differences can be seen between the two, but the general shape, amplitude, and frequency content of the signal are preserved.

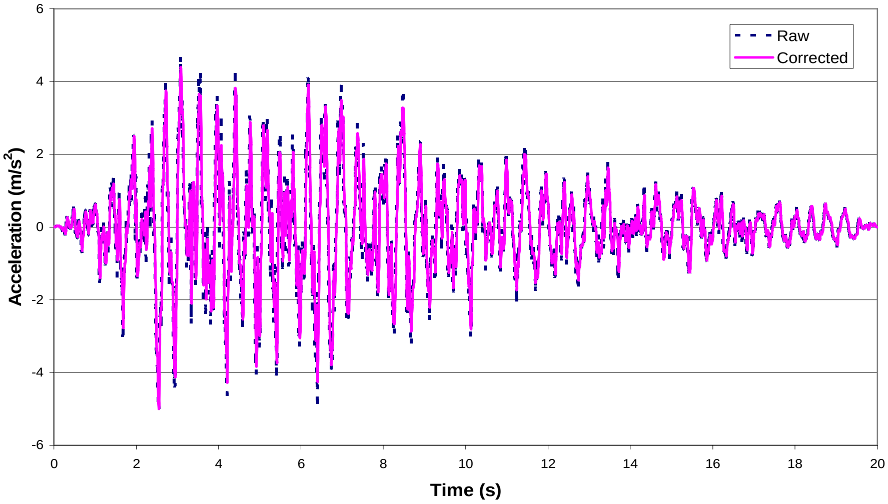


FIGURE 2. Example of accelerogram before and after baseline correction.

Figure 3 shows example time history records applied at support points 1, 5, and 10 for moderate wave passage effect and moderate geometric incoherence. The simple shift in accelerograms caused by the wave passage effect is evident in the first figure, with the finite wave travel speed causing a time delay at each support. The records showing geometric incoherence are more complex, with variations both in frequency content and signal shape at each support.

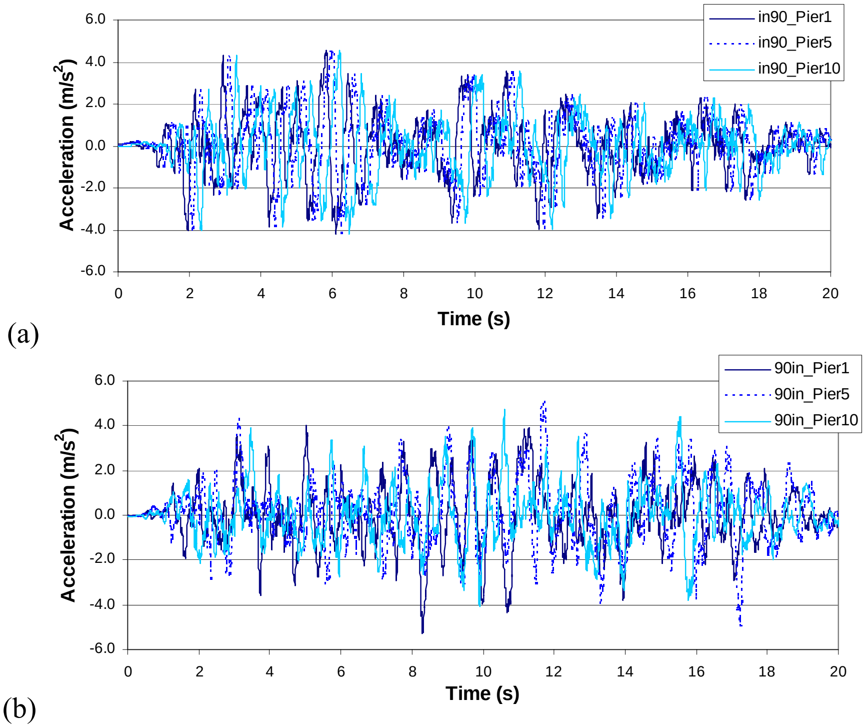


FIGURE 3. Example time history records for (a) wave passage effect and (b) geometric incoherence.

Modeling

The inelastic analysis program ZEUS-NL (Elnashai *et al*., 2002) was used to perform dynamic time history analysis of both bridge models. Due to the complexity of the models, a detailed multi-degree-of-freedom (MDOF) model was created for both the straight and curved cases (Figure 4). To accurately model geometric and material nonlinearities in these three-dimensional structures, all deck, pier, and pier cap elements are cubic elasto-plastic 3D beam-column elements. The model uses confined and unconfined concrete, which is modeled using a uniaxial constant confinement concrete model with confinement determined using a procedure developed by Mander *et al.* (1988) based on pier cross section and shear reinforcement.

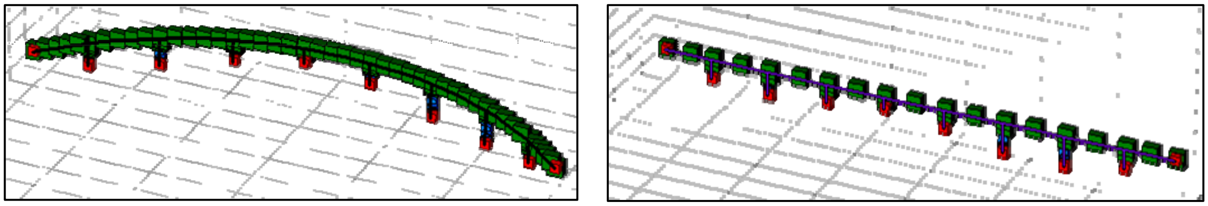


FIGURE 4. Isometric view of curved and straight bridge models in ZEUS-NL.

To reduce analysis time due to the large number of non-linear analyses performed on the study structure, foundation boundary conditions were simplified and piers considered fixed to the ground. Though this simplification ignores local soil conditions which are known to be an additional source of asynchronous motion, for clarity this site effect was not included in the study. Accelerograms were applied (in global coordinates) to the base of each pier in both the longitudinal (east-west) and transverse (north-south) directions simultaneously for each earthquake event. The software program converts these accelerograms into displacement time histories which are then applied in analysis. Deck bearing connections at all pier caps and the east abutment were modeled in ZEUS-NL using tri-linear symmetric elasto-plastic joint curves, calibrated to a sliding friction (μ) of 0.12, as specified in the design example used for this study (Priestley, 1994). The mass of the deck and pier caps was considered using lumped mass elements, shown as the large boxes at deck level in Figure 4. Finally, Rayleigh damping elements were included in the model, simulating a viscous damping value of 2%.

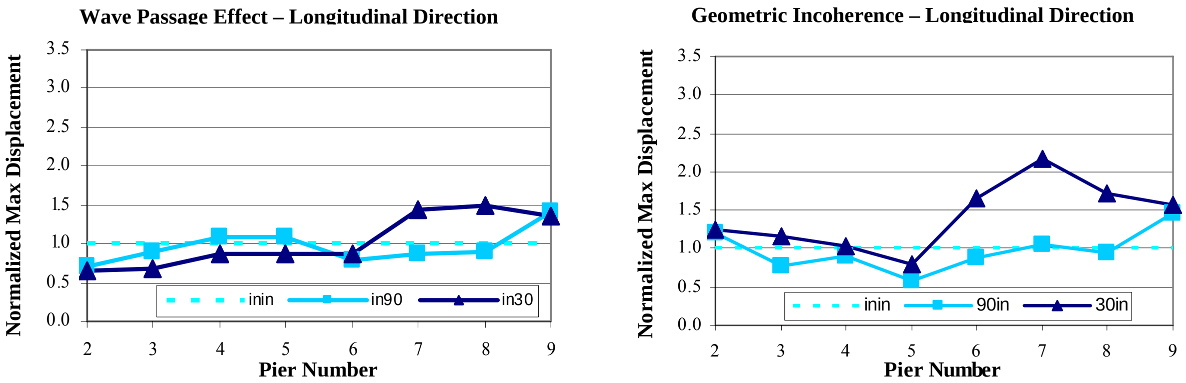
In addition to the curved bridge model, analysis was performed on an identical 344 meter long straight bridge structure to examine the effect of deck geometry on seismic response. The model was created with identical boundary conditions and material properties as the curved bridge. The same suite of synthetic earthquake records were applied to this model, isolating deck curvature as the only factor modifying bridge response.

ANALYSIS RESULTS

Both the curved and straight bridge models were analyzed using 11 uniquely generated earthquake events for each incoherence level, for a total of 99 independent analyses for each structure. Though the earthquake records for these 11 earthquake events were produced using two different software generation models, results are summarized together to simplify presentation. Because maximum structural response from asynchronous motion is typically dominated by pseudo-static displacements due to specific peculiarities of a given earthquake record, performing this large number of analyses per incoherence case provides greater opportunity for deleterious response to manifest. Additionally, using records provided from two independent sources increases the diversity of input motion and improves the credibility of analytical results.

Influence of Wave Passage Effect and Geometric Incoherence on Response

Figure 5 shows sample results comparing relative maximum pier displacements between the top and bottom of each pier for moderate (“90”) and severe (“30”) cases of wave passage delay and geometric incoherence. The vertical graph axis compares the maximum pier displacement in the global longitudinal direction (a line connecting the two abutments) of the curved bridge model to the same value for the control (synchronous) case. Values greater than 1.0 indicate amplified response from asynchronous motion. These graphs demonstrate the complexity of asynchronous response, with varied response amplification evident for each pier, as well as cases of moderate asynchronous motion producing more severe response than severely incoherent earthquake input. This irregular response is likely due to pseudo-static displacements produced by particular combinations of neighboring acceleration records, as well as higher-mode response initiated by spatially incoherent input motion.



(a) (b)

FIGURE 5. Normalized maximum pier displacement due to (a) wave passage effect and (b) geometric incoherence alone.

To identify general behavioral trends, the results from the 11 studied earthquake events are summarized for each incoherence case in Figures 6 and 7, for both the curved and straight bridges. Each graph shows the displacement amplification range from asynchronous motion observed at each pier. The horizontal axes indicate pier number, while vertical axes show maximum and minimum normalized response amplification. For each pier, the left line indicates curved bridge response, and the right line summarizes straight response. The graphs in Figures 6 and 7 are organized in the same order as Table 1, with wave passage delay increasing from top to bottom, and geometric incoherency severity increasing from left to right.

The effect of wave passage delay and geometric incoherence level on bridge response can be isolated by comparing incoherence cases in Figures 6 and 7 that have only one incoherence parameter. The left three graphs in these figures, showing increasing wave passage delay from top to bottom, demonstrate that asynchronous response amplification as high as 1.6 and 2.4 times the synchronous case is possible at some piers, for moderate and severe wave passage delay respectively. These summary figures also show that, as expected, in most cases the extreme in30 case created the greatest displacement response. The amplification in the in30 case seems to be especially high for a select number of piers, specifically piers 5, 6, and 9 in the transverse direction. The high transverse amplification for these piers corresponds to the 3rd mode shape of the curved bridge (Figure 8). This mode involves a rotation of the right half of the bridge structure, with the middle section (piers 5 and 6) moving south and the far right end of the bridge (pier 9) moving north. Significant excitation of this mode by waves with a low ν_{app} value could also explain the higher longitudinal translation of piers 6-9, since these piers are involved in the rotation of the east half of the bridge model by the 3rd mode described.

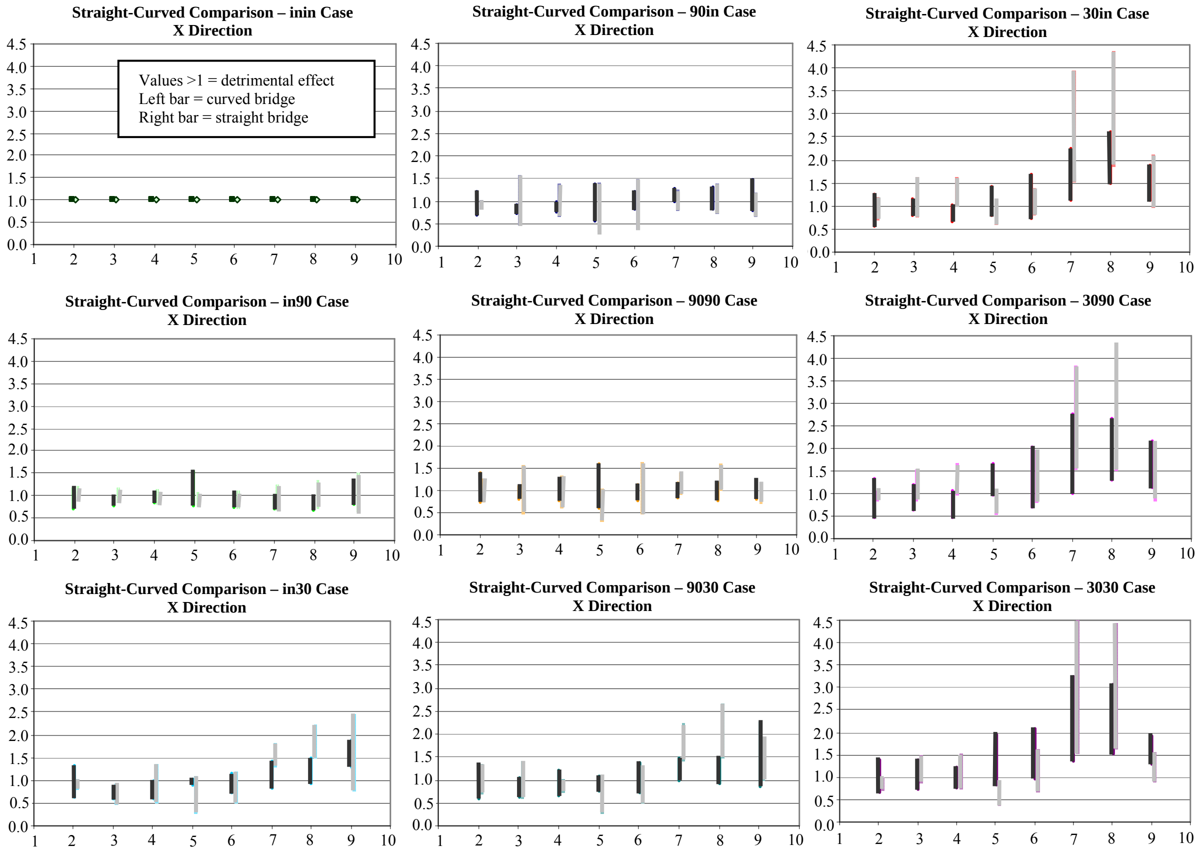


FIGURE 6. Normalized asynchronous response range for each incoherence case in the longitudinal direction.

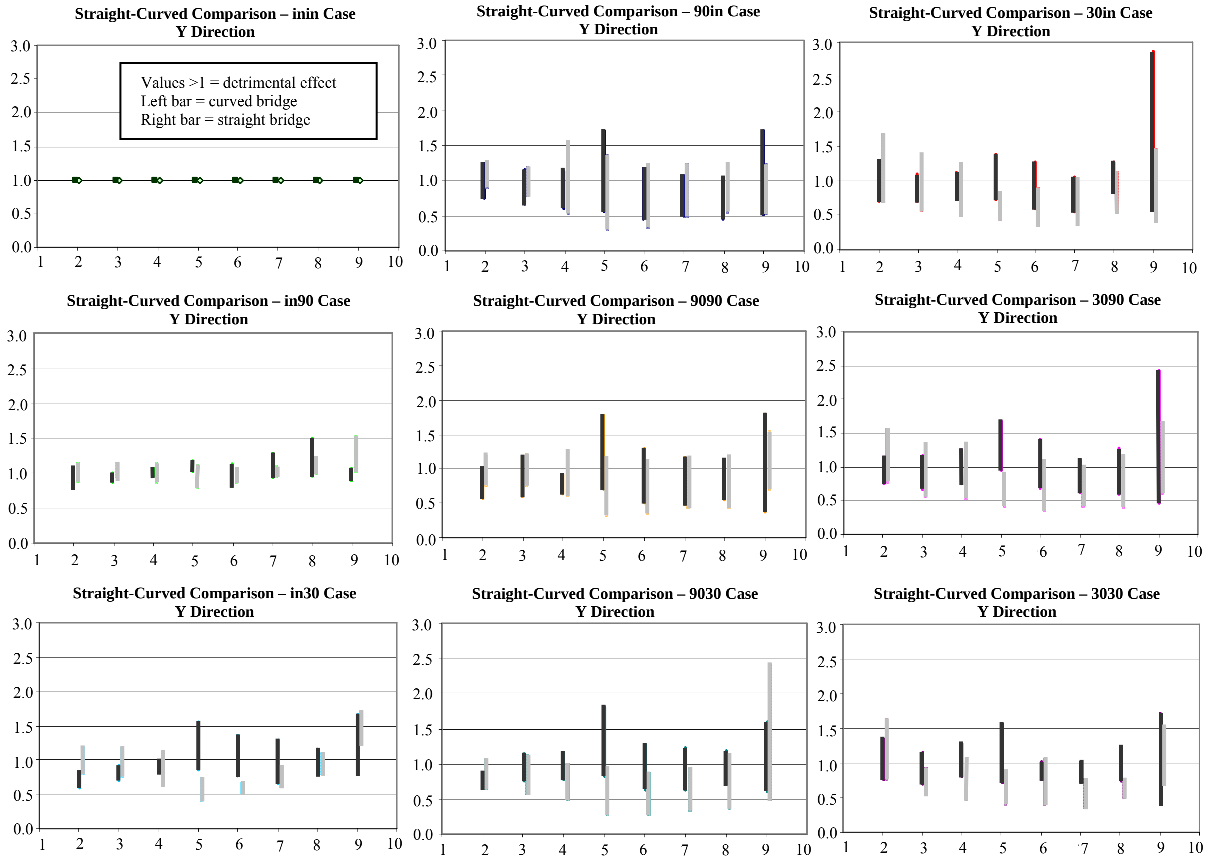


FIGURE 7. Normalized asynchronous response range for each incoherence case in the transverse direction.

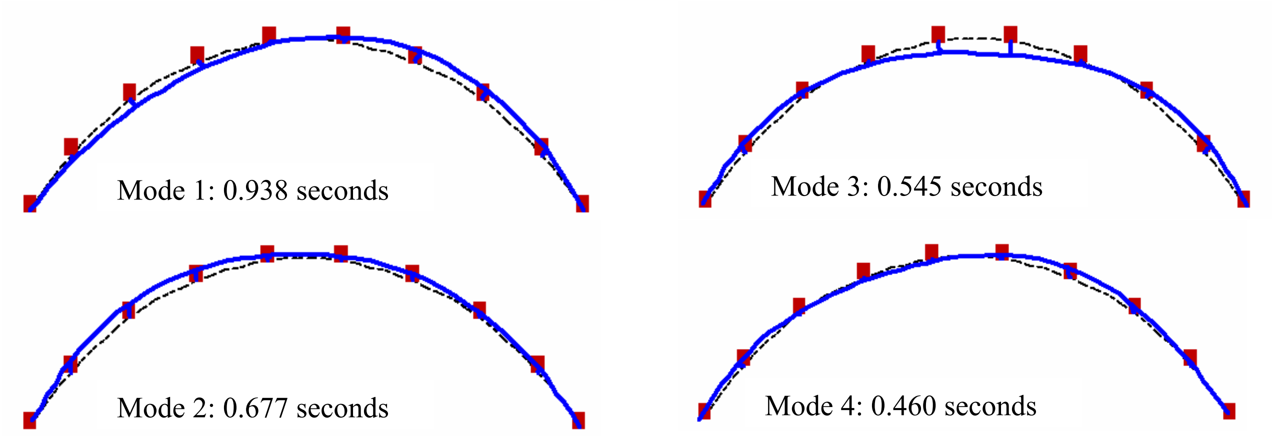


FIGURE 8. Plan view of the first four mode shapes for the curved bridge study structure.

Similar response amplification and higher-mode excitation is evident for geometric incoherence alone. The top three graphs in Figures 6 and 7, showing increasing geometric incoherence from left to right, demonstrate that asynchronous response amplification as high as 1.7 and 3.4 times the synchronous case is possible at some piers, for moderate and severe geometric incoherence respectively. As with the wave passage effect, excitation of higher modes is evident from geometric incoherence in both bridge directions. For the longitudinal response shown in Figure 6, pier 6 and the middle of the bridge in general are predominantly affected by the asynchronous excitation. These piers are targeted by mode 4 of the curved bridge, which has a significant longitudinal contribution centered on pier 6. In the transverse direction, amplification seems to consist of a triangular peak focused on pier 5 (ignoring amplification of pier 9, which is due to the deck being unrestrained transversely at abutment 10). This behavior is consistent with excitation of the 2nd and 3rd modes.

Curved Bridge Combined Response

As asynchronous motion from an actual earthquake is likely to be composed of both incoherence components, the four incoherence cases including both parameters in Figures 6 and 7 are important to understand anticipated structural response from a real event. Examination of the results for these four cases with the curved bridge shows a fairly clear superposition of the corresponding study parameter cases. For instance, the 3090 incoherence case appears to be the 30in incoherence case with some minor increases in bar range, which can be seen to occur from moderate wave passage effect in the in90 case. This seems to indicate that the interaction between geometric incoherence and delayed wave arrival time is minor and does not cause large increases in response; superposition of the two individual components produces an accurate estimate of combined response.

When the effect of increased levels of geometric incoherence is compared to increased levels of wave passage incoherence, the dominance of the former is noteworthy. As the graphs in Figures 6 and 7 progress from top to bottom (increasing wave passage delay), very little change is seen. Although there are cases of significant amplification for some piers, compared to an examination of the graphs from left to right (increasing the level of geometric incoherence), the effect is minor. For geometric incoherence, the response increase when this coherency parameter is increased from moderate to extreme (90in to 30in) is quite large for both the curved and straight bridges. This response increase is likely due to the greater pseudostatic displacement that is possible with geometric incoherence. While the only source of differential support motion with the wave passage effect is a slight shift in displacement records, resulting in one pier lagging slightly behind the motion of its neighbor, the geometric incoherence records are produced using random vibration theory and more significant deviations in local displacement time histories are possible. Because this fundamental difference in the time histories results in different levels of pseudostatic displacements, the trend of geometric incoherence dominating would likely be evident for bridges of any length, though to varying degrees.

Curved Bridge vs. Straight Bridge

Because most previous asynchronous motion studies were performed on straight bridges, a comparison between equivalent straight and curved bridges was made in Figures 6 and 7 to evaluate inherent differences (if any) between this and past studies. Ignoring details of individual bridge pier response, these comparison figures show that at a global level response amplification from asynchronous motion seems to be greater for the straight bridge in the longitudinal direction, and greater for the curved bridge in the transverse direction. Though exceptions to this trend exist at individual piers, as a general rule it is fairly consistent.

As deck plan geometry is the only difference between the two study structures, longitudinal and transverse deck properties must be the primary source of response differences. In past studies (Lupoi *et al.*, 2005) it was found that the deck stiffness significantly affects the forces and displacements that piers are subjected to, with a stiff deck providing greater restraint and thus higher demand on the bridge piers.

In the current study, when each bridge is excited in the longitudinal direction, the curved bridge resists forces by a combination of flexural and axial stiffness of the deck, while the straight bridge deck resists these forces efficiently in pure axial tension or compression. Thus the straight bridge deck is stiffer longitudinally, and bridge piers rather than the deck must deflect significantly to balance the pseudo-static deformations caused by asynchronous motion. This explains the larger demand placed by asynchronous motion on straight bridges in the longitudinal direction.

In the transverse direction, however, the opposite is true, with curved decks providing greater stiffness through arch or catenary action. The straight deck resists transverse forces in flexure, which allows more of the pseudo-static displacements to be absorbed by the bridge deck. This difference in deck stiffness provides a plausible explanation for the clear trend of heightened response amplification for straight bridges when excited longitudinally and curved bridges when exposed to transverse asynchronous motion.

CONCLUSIONS AND DISCUSSION

The volume of analysis for the two structures in the current study far surpasses the number of inelastic dynamic response history analyses performed on a single structure in past studies, providing an analysis breadth and depth that enables greater confidence in the conclusions drawn. Through the wealth of data produced by the 99 earthquake events studied, the following conclusions are made:

- In all cases of incoherence, irregular distributions of response amplification match higher mode shapes of the study structure, emphasizing the tendency of asynchronous motion to preferentially amplify higher mode response.
- For the curved bridge, higher asynchronous response compared to synchronous response occurred for all levels of incoherence, with displacement amplification factors between 1.6 and 3.4. This shows unequivocally that analysis with asynchronous excitation is needed to determine maximum

demand imposed on structures with similar length and geometry, and that synchronous analysis alone will potentially underestimate the demand.

- Though the study provides numerous cases of asynchronous amplification, Figures 6 and 7 show that in many cases non-synchronous motion can reduce pier response, often significantly. Because this is such a complex, motion-specific phenomenon, it is necessary to use a suite of ground motions in design to provide opportunities for detrimental response to manifest.
- For no case of asynchronous motion is the structural response amplified in a regular or easily predictable way. Therefore, attempts to account for asynchronous motion through scaling of synchronous response are unlikely to succeed. It does seem possible, however, to capture irregular response amplification from each of the two incoherence components alone, and superimpose these responses to determine combined response.
- Incoherence resulting from wave arrival delay has minimal effect on bridge response compared with geometric incoherence, due to the complex and random nature of geometric incoherence. Because geometric incoherence is most deleterious at similar coherency levels, it is important that future asynchronous motion studies include an adequate representation of this incoherence source in the utilized earthquake records.
- Due to pseudo-static displacements dominating bridge response to asynchronous motion, deck stiffness significantly affects response amplification. This is demonstrated by comparing the asynchronous response of a curved and equivalent straight bridge, showing directions of greater deck stiffness to also be those of greater response amplification.

The current study demonstrates clearly the importance of asynchronous analysis in the design of long and complex bridge structures. For cases of moderate incoherence that are likely to occur in practice, asynchronous response can be almost twice that of synchronous response. Due to the large number of varied analyses performed, trends and behavior useful in understanding common asynchronous response could be identified with greater confidence. Though many of these trends are valid only in broad terms, due to the innate randomness of earthquake records and resulting structural response, they still provide a guide for identifying critical regions and cases for asynchronous analysis. Through use of these general trends, the significant number of varied analysis cases needed for the current study could be reduced for cases of practical asynchronous bridge analysis during the design process. Reductions could include the following:

- Cases of incoherence from multiple sources in the current study showed that structural response similar to a superposition of the maximum structural response of each incoherence parameter individually. This indicates analysis with multiple sources of incoherence may be unnecessary, since these cases can be estimated accurately through superposition of simpler single incoherence source analyses.
- For practical design cases, analysis with multiple incoherence cases is not necessary since designers can set a maximum incoherence level expected based on site location and conditions. Analysis using this worst-case scenario should be suitable. Results show amplification of bridge response compared to synchronous input is strongly tied to incoherence level and it is unlikely lower levels of incoherence would result in greater structural response.
- Comparison between a curved and similar straight bridge in the current study shows that directions of greatest deck stiffness deserve careful consideration during bridge design. Support deflections due to pseudo-static displacements are generally highest where the deck most rigidly connects them, i.e. has the greatest axial stiffness. Analysis for design could be reduced by focusing on the direction of maximum deck stiffness, where the largest response amplification from asynchronous motion is expected.

The burden of determining the simplifications reasonable during design analysis falls on the bridge designer. Previous studies have helped to identify when asynchronous analysis might be advisable at all, with recommendations for asynchronous analysis thresholds, usually based on total bridge length. Sextos *et al.* (2003) propose the Eurocode 8 threshold of 600 meters be reduced to 400 meters. In a later paper (2004) the same authors recommend adding a provision for curved bridges, with a lower threshold for this type of structure. Results from the current study support this recommendation, especially in the transverse direction, since the response of a 344 meter long curved bridge was amplified significantly by asynchronous input motion compared to an equivalent straight structure.

These recent studies have challenged the common assumption that asynchronous motion is only significant for extremely long structures. Bridges of moderate lengths and common configurations show substantial response increase from asynchronous input, compared to synchronous excitation. As dynamic response history analysis becomes more prevalent in modern design offices, asynchronous analysis should become a design step that earthquake engineers are willing to take for major structures located in regions of significant seismic hazard. Trends found in the current study could help to reduce the resources needed for asynchronous analysis as noted above.

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