EFFECT OF SPATIAL VARIATION OF EARTHQUAKE GROUND MOTION ON THE NONLINEAR DYNAMIC RESPONSE OF HIGHWAY BRIDGES

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SUMMARY

The effect of spatial variability of earthquake ground motion can be mainly attributed to the wave passage, loss of coherence and different local soil conditions. This paper estimates the relative significance of these three effects on the seismic response of long multi-span reinforced concrete highway bridges. Since the bridge response under strong ground motion that can cause damage is essentially non-linear, non-linear dynamic analyses including multi-support excitation are carried out for two example reinforced concrete highway bridges of different span lengths and structural configurations. The statistics of the maximum response are obtained in terms of the ductility demand at the piers. Two types of differential support excitations are considered: 1) all structural supports on same local soil conditions, and 2) different structural supports on different local soil conditions. For comparison purposes, each bridge is also subjected to identical support ground motion. One of the most important conclusions for the two bridges considered is that for the case of different local soil conditions, the ductility demand could be twice as large as the corresponding value for the case of same local soil conditions. For the bridges considered in this study, the incoherence effect appears to be more significant than the wave passage effect, with the exception of the longer bridge subjected to relatively low apparent velocities of wave propagation. Finally, the identical ground motion assumption, commonly used in engineering practice, almost always provides an unconservative value of the ductility demand for the bridges analyzed.

INTRODUCTION

Spatial variability of seismic ground motion can be mainly attributed to the following three mechanisms: 1) difference in arrival times of seismic waves at different locations, commonly known as the "wave passage effect," 2) loss of coherence of seismic waves due to multiple reflection and refraction as they propagate through the highly inhomogeneous soil medium, referred to as the "incoherence effect," and 3) change in the amplitude and frequency content of seismic ground motion due to different local soil conditions, known as the "local soil effect".

Past research studies have demonstrated that seismic ground motion can vary significantly over distances comparable to the length of highway bridges on multiple supports. In several cases, these differential (asynchronous) motions at the bridge supports can induce additional internal forces in the structure compared to the case where all supports are subjected to identical support ground motion. This in turn might have a potentially detrimental effect on the safety of a bridge during a severe earthquake event. It is very common in engineering practice to determine the structural response by performing an equivalent linear static or a linear dynamic analysis of the bridge. For the case of a linear dynamic analysis, it is more common to perform a response spectrum analysis rather than doing a time history analysis. Furthermore, when deciding to perform a time history analysis, it is customary to assume that all of the bridge supports experience identical ground motion time histories, even for multi-span bridges of considerable overall length.

Several researchers have investigated the response of long span structures to differential (asynchronous) support excitations (e.g. Zerva [16,17,18], Harichandran and Wang [6,7,8]). Most of these studies have used relatively simple linear models to describe the structure (e.g. simple or continuous beams) and have followed a linear

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random vibration approach to determine the response, focussing on the wave passage and incoherence effects with comparisons made to the case of identical support ground motion. Der Kiureghian suggested a model incorporating the wave passage, incoherence and local soil effects [4] and used it to analyze the response of multiple-span bridges modeled as frames using a linear random vibration approach [5]. Monti et al. [13] examined the inelastic response of multiple-span bridges using a Monte Carlo simulation approach and the spectral representation method (Shinozuka and Deodatis [15]) and examined the relative importance of the incoherence and wave passage effects. However, the local soil effect was not taken into account in this study and all supports of the bridge were assumed to be on the same local soil conditions.

This study takes into account all three spatial variability effects and estimates the response of the bridge structure to asynchronous input ground motions by performing a nonlinear time history analysis. The "wave passage effect" is characterized by the apparent velocity of wave propagation and the "incoherence effect" is characterized by a coherence function, while the "local soil effect" is characterized by defining different response spectra at different locations corresponding to their local soil conditions. A nonlinear two-dimensional finite element model is created for each example bridge and the SAP2000 computer program is used to perform the non-linear dynamic time history analyses. The spatially varying ground motion time histories at the bridge supports are generated using a recently developed variation of the spectral representation method (Deodatis [3]). Several samples of earthquake ground motions are generated in the framework of a Monte Carlo simulation procedure and the statistics of the corresponding maximum responses (provided in terms of ductility demand) are finally estimated.

EXAMPLE BRIDGES

Two bridge models are considered in this study:

I) TY0H BRIDGE: - Five spans, pier height 65 ft, largest span 175 ft.
II) SANTA CLARA BRIDGE: - Twelve spans, pier height 39.35 ft., largest span 143 ft.

The geometry and boundary conditions of the two bridge models are shown in Figs. 1 and 2. The details of the material and cross-sectional properties can be found in [14].

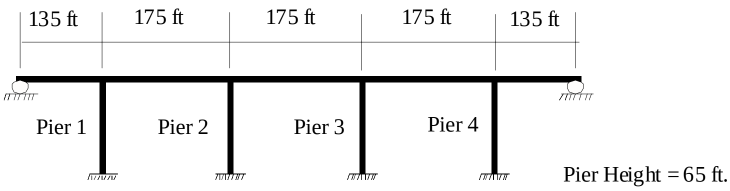


Fig. 1: Elevation of TY0H Bridge

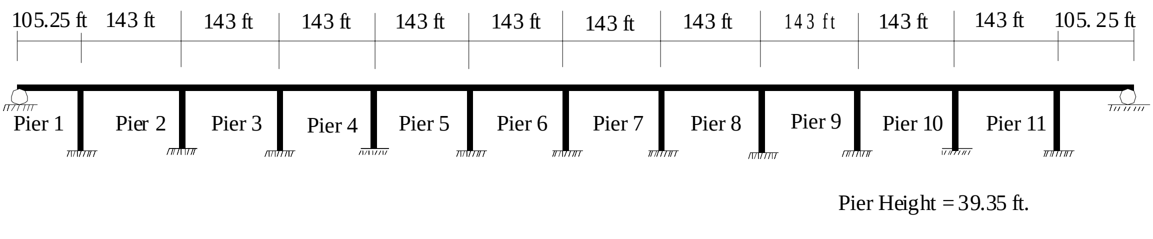


Fig. 2: Elevation of Santa Clara Bridge

The bridges were modeled with the SAP2000 finite element program [2]. A two-dimensional model consisting of a series of frame elements was used for the bridge deck as well as the piers. The pier bases were assumed fixed while the two abutments were modeled as roller supports.

NONLINEAR DYNAMIC ANALYSIS

In order to capture the essence of the nonlinear behavior, a relatively simple model is used to perform the nonlinear dynamic analysis. This appears quite appropriate in face of various types of approximations, randomness and uncertainty involved in specifying the input ground motion and the structural system.
The model used to describe the potentially nonlinear behavior of the piers of the bridges (the only members considered to exhibit nonlinear behavior in this study) is depicted in Fig. 3a. According to this model, a pier is modeled as an elastic column of length $2H_e$, with a pair of plastic zones of length L_p at each end of the column, as shown in Fig. 3a. The total height H of the pier from the ground to the soffit of the girder is therefore equal to $2(H_e + L_p)$. Each plastic zone is then modeled to consist of a nonlinear rotational spring and a rigid element of length L_p as shown in Fig. 3b. The typical moment-rotation relationship used in this study for the nonlinear springs is a bilinear one as shown in Fig. 3c. Its specific parameters are established using the *Column Ductility Program* COLx (Caltrans [1]).

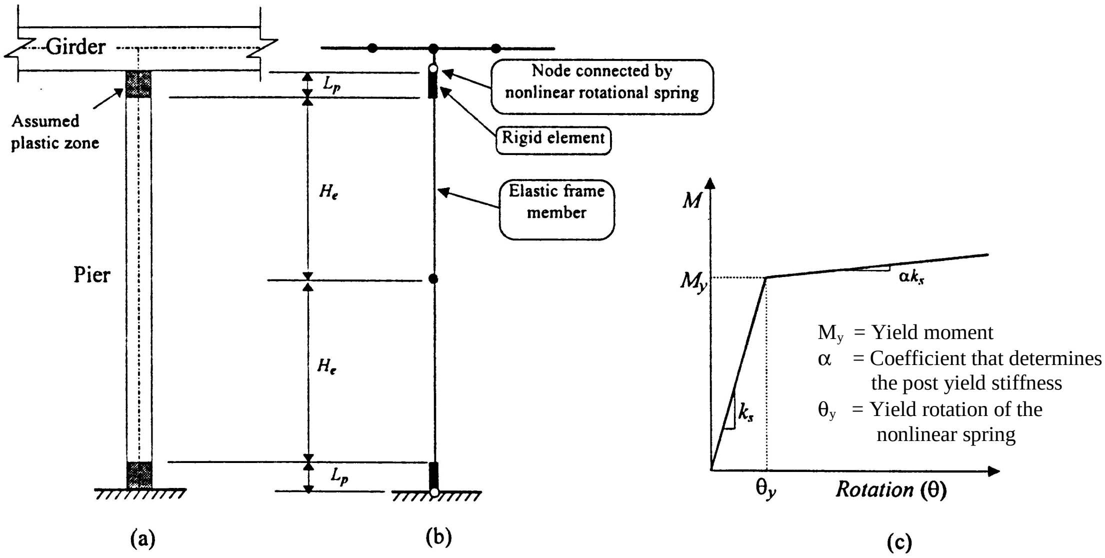


Fig. 3: Modeling of a pier by an elastic column and nonlinear rotational springs at both ends

GROUND MOTION CHARACTERISTICS

In order to study the effect of spatial variation of earthquake ground motion on highway bridges, it is necessary to establish a methodology to generate acceleration and displacement time histories at several prescribed locations on the ground surface corresponding to the bridge supports. These time histories can then be used as input excitations at the bridge supports to perform their nonlinear dynamic time history analysis. In this study seismic ground motion time histories are generated using a variation of the spectral representation method (Deodatis [3]). The generated time histories are compatible with prescribed response spectra and duration of strong ground motion, and reflect the wave passage and loss of coherence effects. According to this methodology [3], a particular apparent velocity of wave propagation can be prescribed and the duration of ground motion can be controlled by an envelope function. The local site effect is described by assigning different response spectra at locations with different local soil conditions. The Uniform Building Code [11] acceleration response spectrum for Type II soil, 5% damping, and 0.5g peak ground acceleration is selected to describe the ground motion at piers on medium soil, and the UBC acceleration response spectrum for Type III soil, 5% damping, and 0.5g peak ground acceleration is used to describe the ground motion at piers on soft soils. The Jennings–Housner-Tsai [12] envelope with a build up time of 2 seconds, a flat part of 7 seconds and decay time of 11 seconds is used to describe the duration of strong ground motion. The Harichandran and Vanmarcke model [6,10] is chosen to model the coherence loss between pair of bridge supports.

The generated acceleration time histories are integrated to obtain the corresponding displacement time histories. For each set of differential (asynchronous) support ground motion time histories, the corresponding set of identical support ground motion time histories are obtained by considering that the displacement time history at the first support of the bridge is applied at all the other supports. A number of samples of such spatially varying ground motion time histories are generated at the bridge supports and dynamic time history analyses of every bridge are carried out along the lines of a Monte Carlo simulation procedure. It should be pointed out that as a two-dimensional model was considered for each bridge, only the horizontal component of ground motion parallel to the axis of the bridge has been generated.

NONLINEAR RESPONSE OF BRIDGES TO MULTI-SUPPORT EXCITATION

In order to determine the relative importance of the wave passage and incoherence effects to the nonlinear dynamic structural response, the following three cases were considered:

Table 1: Detailed description of cases considered

SPATIAL VARIABILITY EFFFECTS CONSIDERED	CONDITIONS AT SUPPORTS AND INFORMATION ABOUT APPARENT VELOCITY OF WAVE PROPAGATION
CASE 1 **Both the wave passage and incoherence effects considered**	1) All supports on same local soil conditions with velocity of 1000 m/s 2) All supports on same local soil conditions with velocity of 300 m/s 3) Different supports on different local soil conditions with velocity of 1000 m/s
CASE 2 **Only the incoherence effect considered. (loss of coherence but no wave propagation considered)**	1) All supports on same local soil conditions with velocity approaching infinity 2) Different supports on different local soil conditions with velocity approaching infinity
CASE 3 **Only the wave passage effect considered. (wave propagation considered, but seismic waves are perfectly coherent – no loss of coherence)**	1) All supports on same local soil conditions with velocity of 1000 m/s 2) All supports on same local soil conditions with velocity of 300 m/s 3) Different supports on different local soil conditions with velocity of 1000 m/s

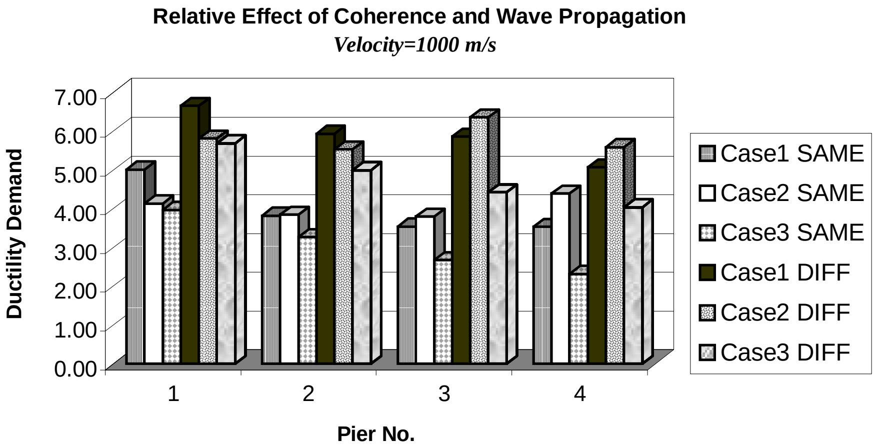
For comparison purposes, cases with identical support ground motion have also been considered.

In order to study the local soil effect (i.e. bridges with supports on different local soil conditions), certain supports of each bridge were assumed to be on different (softer) local soil conditions than the rest. Such cases can be encountered in practice in bridges over small (or large) valleys where the abutments and some of the supports close to the abutments can be in harder soil conditions, while some of the supports around the center of the bridge can be on softer local soil conditions. Table 2 describes the different local soil conditions assumed for the piers of each one of the two bridges considered.

Table 2: Description of different local soil conditions

Bridge	Total No. of Spans	Total No. of Piers	Soil at Left Abutment	UBC Soil Type II (medium) at Piers	UBC Soil Type III (soft) at Piers	Soil at Right Abutment
TY0H BRIDGE	5	4	medium	Pier 1 , Pier 4	Pier 2, Pier 3	medium
SANTA CLARA	12	11	medium	Pier 1-4 , Pier 8-11	Pier 5-7	medium

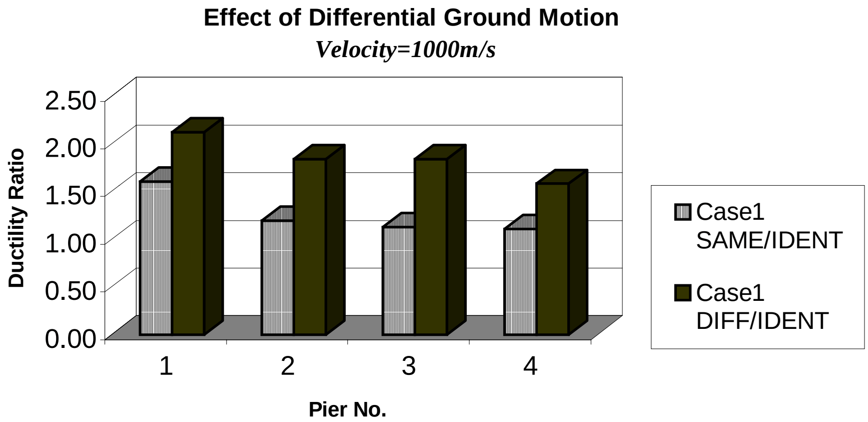
From the above, it is obvious that there is a large number of different cases of seismic ground motions that have been considered for each bridge. The parameter used to describe the (nonlinear) structural response is the *ductility demand*. The ductility demand is defined as follows: denoting by θ the rotation of the nonlinear spring used to model the plastic zone at each end of every pier, and by θ_y the corresponding rotation at the yield point, the ratio θ/θ_y is defined as the *ductility demand* of the plastic zone. Finally, it has to be pointed out that for each one of the cases, the mean value of the peak ductility demand at each of the piers was obtained by ensemble averaging from twenty nonlinear dynamic time history analyses.



SAME denotes all supports on same local soil conditions

DIFF denotes supports on different local soil conditions

(a)

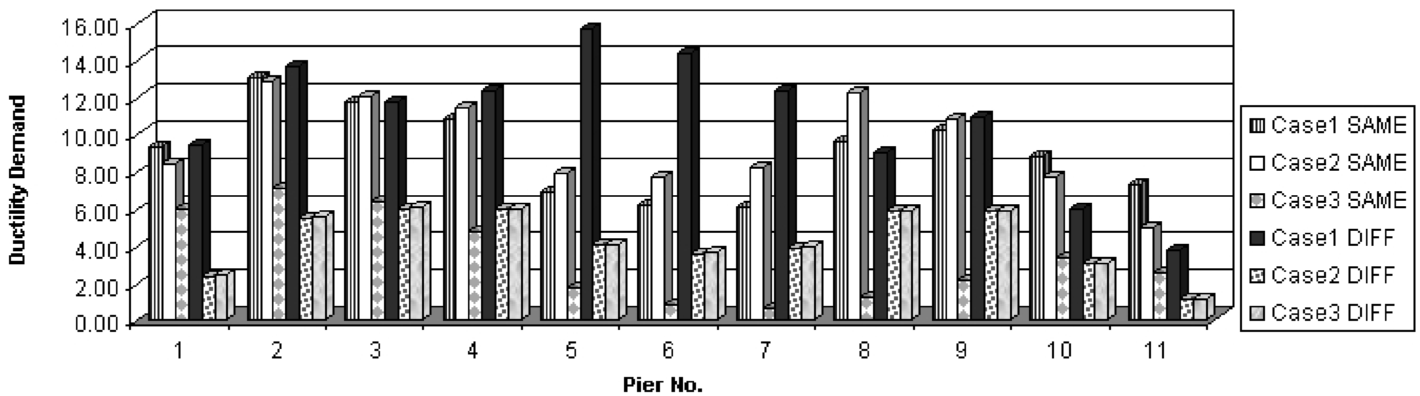


(b)

SAME/IDENT denotes the ratio of the peak ductility demand computed using differential support ground motion and same local soil conditions over the peak ductility demand computed using identical support ground motion.

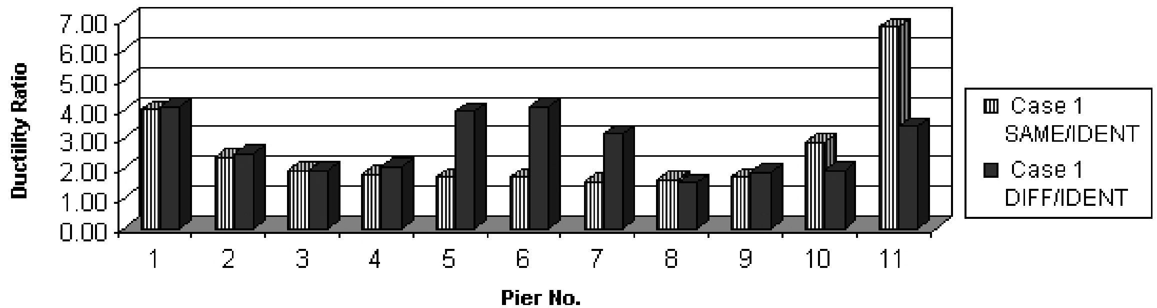
DIFF/IDENT denotes the ratio of the peak ductility demand computed using differential support ground motion and different local soil conditions over the peak ductility demand computed using identical support ground motion.

Fig. 4 Bar charts depicting mean values for the peak ductility demand of the various piers of the TY0H bridge, obtained by ensemble averaging from 20 nonlinear time history analyses. (a) Mean values for the peak ductility demand for the various cases considered. (b) Ratios of the mean values for the peak ductility demand at the piers.



SAME denotes all supports on same local soil conditions
DIFF denotes supports on different local soil conditions.

(a)



(b)

SAME/IDENT denotes the ratio of the peak ductility demand computed using differential ground motion and same local soil conditions over the peak ductility demand computed using identical support ground motion.

DIFF/IDENT denotes the ratio of the peak ductility demand computed using differential support ground motion and different local soil conditions over the peak ductility demand computed using identical support ground motion.

Fig. 5 **Bar charts depicting mean values for the peak ductility demand of the various piers of the Santa Clara bridge , obtained by ensemble averaging from 20 nonlinear time history analyses. (a) Mean values for the peak ductility demand for the various cases considered, (b) Ratios of the mean values for the peak ductility demand at the piers.**

RESULTS AND CONCLUSIONS

Figs. 4a and 5a present comparisons of the mean values for the peak ductility demand at the piers of the TY0H bridge and the Santa Clara bridge for the different cases examined. Results from Cases 1, 2, and 3 are compared to estimate the relative effect of loss of coherence and wave passage. In addition, the cases of different and same local soil conditions can be easily compared.

Figs. 4b and 5b present information in the form of ratios rather than direct values for the means of the peak ductility demand at the piers. The ratios are defined in the captions of Figs. 4 and 5. It should be noted that Figs. 4 and 5 make it easy to assess the differences in the mean values for the peak ductility demand between the two cases of differential support ground motion: different versus same local soil conditions. In addition, direct comparisons can be done with the reference case of identical support ground motion.

Based on the results displayed in Figs. 4 and 5, the following conclusions can be drawn:

1. The peak ductility demand at the piers can increase substantially when the bridge is analyzed using differential support ground motion and considering that different supports of the bridge are on different local soil conditions, compared to the case of identical support ground motion.
2. The peak ductility demand at the piers can increase by a smaller amount when the bridge is analyzed using differential support ground motion and considering that all supports of the bridge are on the same local soil conditions, compared to the case of identical support ground motion.
3. Low apparent velocity of wave propagation might reduce in some cases the peak ductility demand of some of the piers, for the general case where both the wave propagation and loss of coherence effects are considered and all supports of the bridge are on the same type of local soil conditions. Further, a low value of the velocity might change the relative contribution of the wave passage and the incoherence effects in some of the piers.
4. The incoherence effect is in general more important than the wave passage effect. The wave passage effect becomes more important than the incoherence effect only for the relatively longer Santa Clara Bridge and for low velocities of wave propagation. But even in the majority of the cases where the incoherence effect is more important, the wave passage effect is still substantial and its interaction with the incoherence effect cannot be predicted a priori. Therefore neglecting either one of these two effects might produce inaccurate results.
5. The relative contribution of the wave passage and incoherence effects to the peak ductility demand of the piers does not seem to be affected to any considerable degree by the assumption of different versus same local soil conditions at the supports of the bridge.
6. The identical support ground motion assumption seems to be generally unconservative, but much more so in the case of different local soil conditions.

It should be pointed out that the above conclusions hold for the two bridges considered (and for bridges of similar configuration), but cannot be generalized to bridges of different types. The only general conclusion is that the effect of spatial variability of ground motion on the response of a bridge is a very complex one, and depends on various parameters describing the structure and the characteristics of the seismic ground motion.

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