EFFECTS OF VERTICAL GROUND MOTIONS ON SEISMIC RESPONSE OF HIGHWAY BRIDGES

Sashi Kunnath, Norm Abrahamson, Y.H. Chai, Zhiyu Zong and Zeynep Yilmaz
University of California, Davis, CA.

ABSTRACT

Preliminary findings from an ongoing research study that systematically characterizes ground motion parameters and investigates the effects of vertical acceleration on the overall response of typical highway bridges will be presented. Nonlinear simulation models of an existing bridge designed to Caltrans specifications is considered in the analytical study. Sixty ground motions with horizontal PGA in excess of 0.5g were selected from the PEER NGA (Next Generation Attenuation) project. The selected ground motions are classified by source mechanism, fault distance, vertical to horizontal acceleration ratios, and other relevant ground motion measures. The simulation models will be subjected to the selected ground motion set in two stages: at first, only horizontal components of the motion will be applied; while in the second stage both horizontal and vertical components will be applied simultaneously. Important response measures will be monitored to gain an insight into the effects of vertical acceleration on the inelastic response of the bridge structures. The analytical simulations will provide a basis for investigating features of the ground motion that most significantly contribute to adverse effects from vertical accelerations. Findings from the study will provide the basis for developing revised guidelines to address vertical ground motion effects in the seismic design of highway bridges.

INTRODUCTION

The effects of vertical ground motions on the response of highway bridges are not well understood. This is evident from the fact that current CALTRANS criteria for considering vertical accelerations is extremely simplistic and does not account for seismic source, geology, ground motion characteristics, structural configuration or method of analysis. Even though the CALTRANS specifications call for a case-by-case evaluation of non-standard bridges, no guidelines exist to assist engineers in the design process. Research on this topic is also very limited leading to significant uncertainty in the design process about the consequences of vertical ground motions on the response of bridge structures.

This paper will present preliminary findings from an ongoing research study that systematically characterizes ground motion parameters and investigates the effects of vertical acceleration on the overall response of typical highway bridges. Selected ground motions, which are classified by source mechanism, fault distance, vertical to horizontal acceleration ratios, and other relevant ground motion measures, are utilized in a detailed and systematic analytical study of the seismic response of a selected highway bridge in this initial phase of the study. Results from this phase

will provide a basis for identifying additional configurations for the comprehensive evaluation in the next phase. Findings from the overall study are expected to provide the basis for developing revised guidelines to address vertical ground motion effects in the seismic design of highway bridges.

GROUND MOTIONS

A preliminary subset of 65 earthquake records with horizontal PGA greater than 0.5g was selected from the PEER (Pacific Earthquake Engineering Research) NGA (Next Generation Attenuation) project database. Based on initial studies to characterize the selected ground motions, the following observations were made:

a) The predominant period of the vertical ground motions are smaller than the corresponding horizontal component for both firm and soft soils (see Figure 1). The predominant periods of soft soil records tend to be larger than that of motions recorded on firmer soil.

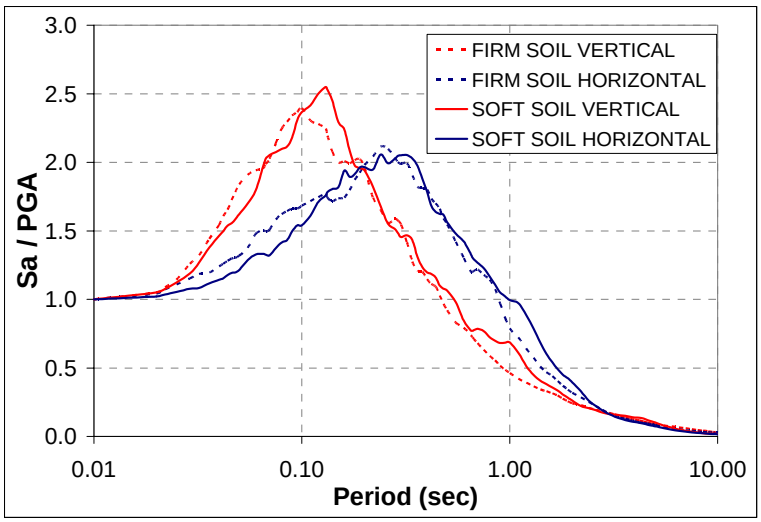

Figure 1: Mean spectral characteristics of selected ground motions.

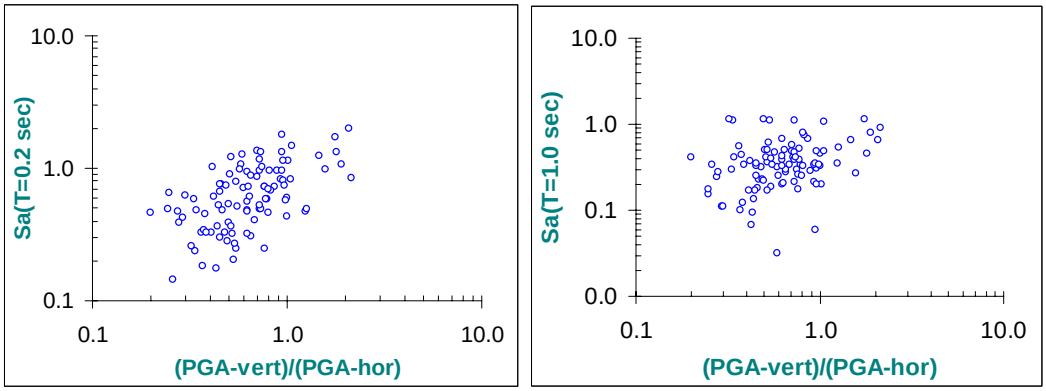

Figure 2: Correlation between spectral demands and vertical to horizontal PGA ratio

b) Some correlation exists between the peak vertical to horizontal PGA ratio and the spectral demands at both short (T=0.2 seconds) and long periods (T = 1.0 seconds) as shown in Figure 2.

c) The ratio of vertical-to-horizontal PGA decreases gradually with increasing fault distance indicating that vertical component of ground motions will be more severe for near fault ground motions (see Figure 3). Hence, all the earthquakes considered in this phase of the study are near fault records (within 15 km from the site).

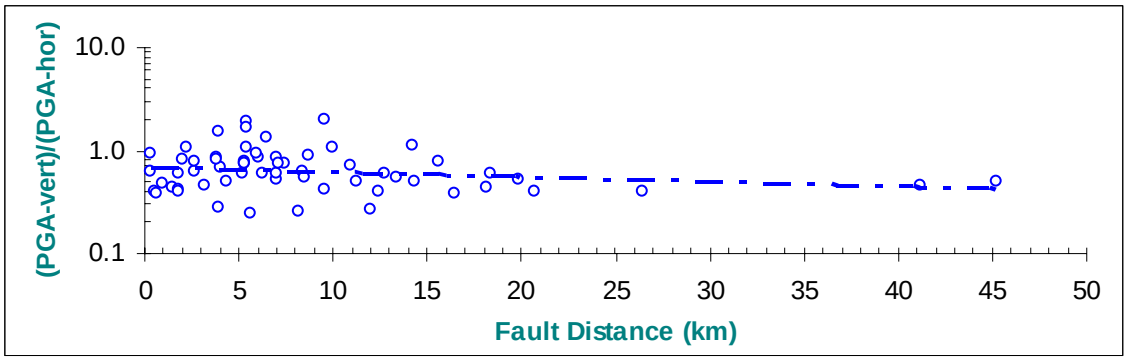

Figure 3: Effect of fault distance on ratio of peak vertical to horizontal acceleration magnitude.

BRIDGE CONFIGURATION FOR PRELIMINARY STUDY

After a review of the drawings of several bridge configurations designed to current SDC specifications, the new segment of the Camino Del Norte Bridge widening project was selected for the preliminary analytical study. The elevation of the bridge is shown in Figure 4.

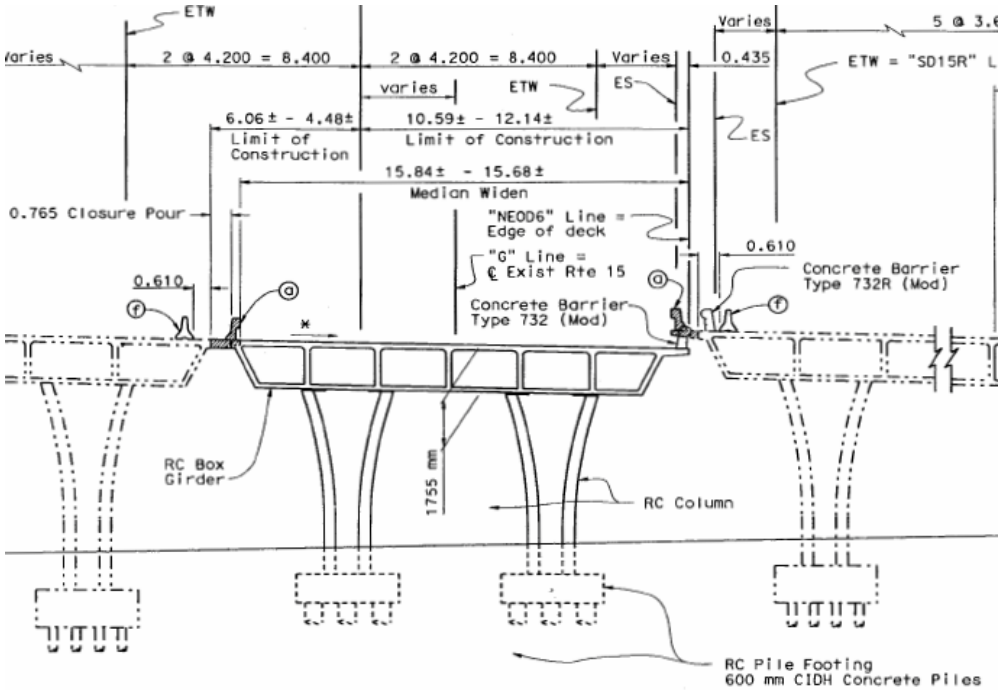

Figure 4: Elevation view of the new segment of the Camino Del Norte Bridge.

The simulation model used of the bridge is shown in Figure 5. Springs are introduced both at the base of the columns to incorporate soil-foundation flexibility and at the abutments to simulate the

restraints provided by the diaphragm walls at the abutment. However, in this preliminary study the foundation is assumed to be fixed and the restraints at the abutments are ignored. The columns are modeled as nonlinear beam-columns with fiber-beam discretization at the integration points. The box-girder superstructure is presently modeled as an elastic beam and sufficient elements are incorporated to capture the moment history in the deck.

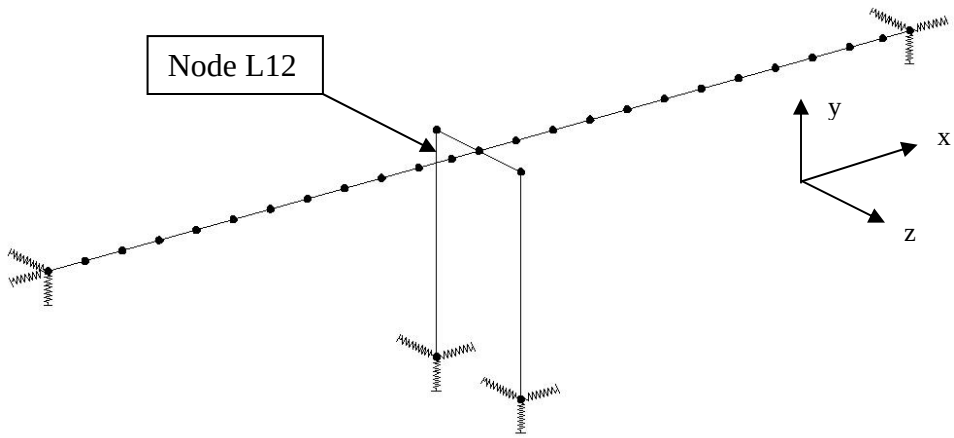

Figure 5: Simulation model of the Camino Del Norte Bridge

Figure 6 shows the effect of including vertical ground motions on the lateral response of the bridge. The vertical axis shows the ratio of the maximum lateral deck displacement with and without incorporating vertical ground motions. A ratio of 1.0 suggests that vertical accelerations have no effect while ratios less than 1.0 suggests a beneficial effect. Ratios greater than 1.0 indicate that the vertical component is magnifying the lateral displacements. Only cases where the system experienced displacements larger than the yield displacement of the bent are included in the plot. As is evident from the figure, approximately half the cases showed that the vertical motions produced beneficial effects while the remaining responses indicated a marginal increase in the computed lateral displacements.

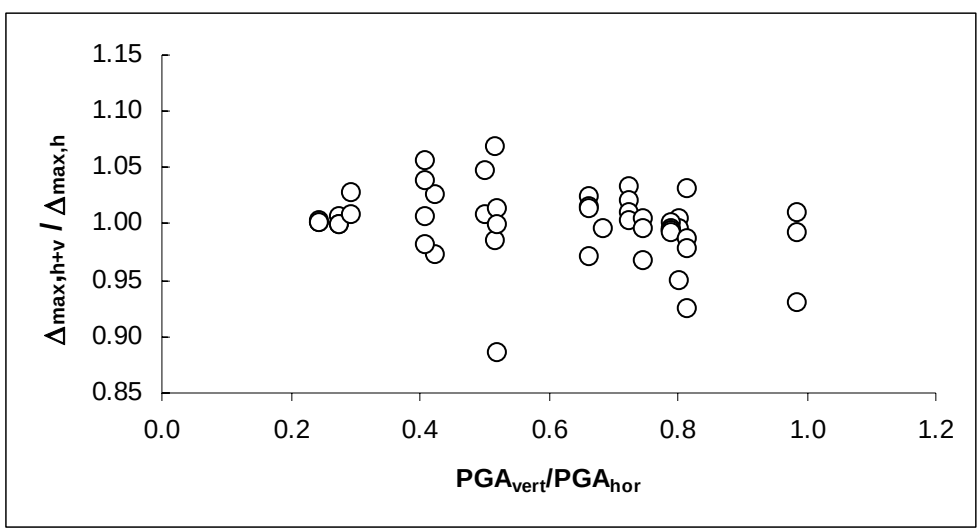

Figure 6: Effect of vertical ground motions on peak lateral displacement

Effect of Scaling Records

Results presented in Figure 6 are based on simulations using unscaled records. In an effort to investigate the influence of vertical ground motions at higher intensities, selected records that produced the largest demands were scaled uniformly in both the lateral and vertical directions. The scaling process consisted of factoring only the lateral component, only the vertical component, and both the lateral and vertical component uniformly by factors ranging from 1.2 to 1.5. Scaling vertical motions generally resulted in larger demands than scaling the horizontal motions. For example, scaling only the vertical motion by a factor of 1.5 increased the lateral demand by about 5% in one case. However, in most cases, the increase was negligible and in some cases, the demands were found to decrease indicating that axial compression led to an increase in the column capacity.

Effect of Vertical Motions on Moment Demand in Longitudinal Girder

Another aspect of behavior that was investigated was the moment demand in the longitudinal girder. Results are summarized in Table 1 for four critical earthquakes. Significant increase in the moment demand is observed. This finding is consistent with the study by Gloyd (1997) who evaluated 60 prestressed box-girder bridges and concluded that the dynamic response due the effects of vertical acceleration was larger than dead load effects, and that a reversal of flexure in the deck can occur in both the positive and negative moment areas.

Table 1. Ratio of peak moment demand due to vertical effects

*Earthquake (*Station)	*Peak Ratio At Node 4*	*Peak Ratio At Node 6*
Chi-Chi (CHY-028)	1.585	1.581
Chi-Chi (TCU-071)	1.912	1.902
Coalinga (H-PVV)	1.744	1.736
Sylmar (Conver-East)	2.139	2.127

Figure 7 shows the time history response in the girder section at Node L12 (see Figure 5) for the cases when the vertical component of the ground motion was included and excluded. Gravity moments are applied prior to application of the ground motions. The increased moment demands due to the effects of vertical accelerations amplify the girder moments significantly and the response has a pronounced high frequency component. Note that the girder element in the current simulation model is elastic.

STUDY OF GROUND MOTION CHARACTERISTICS

In this phase of the study, a careful and comprehensive investigation of the characteristics of vertical ground motions that most significantly influence the response of bridge systems is underway. The measures of response that are being used to identify the adverse effects of vertical shaking include lateral displacement of the superstructure, moments in the longitudinal girder and shear demands in the piers. Results from the ongoing analytical study will provide a basis for identifying ground motion pairs (horizontal + vertical) where vertical effects were pronounced and significant.

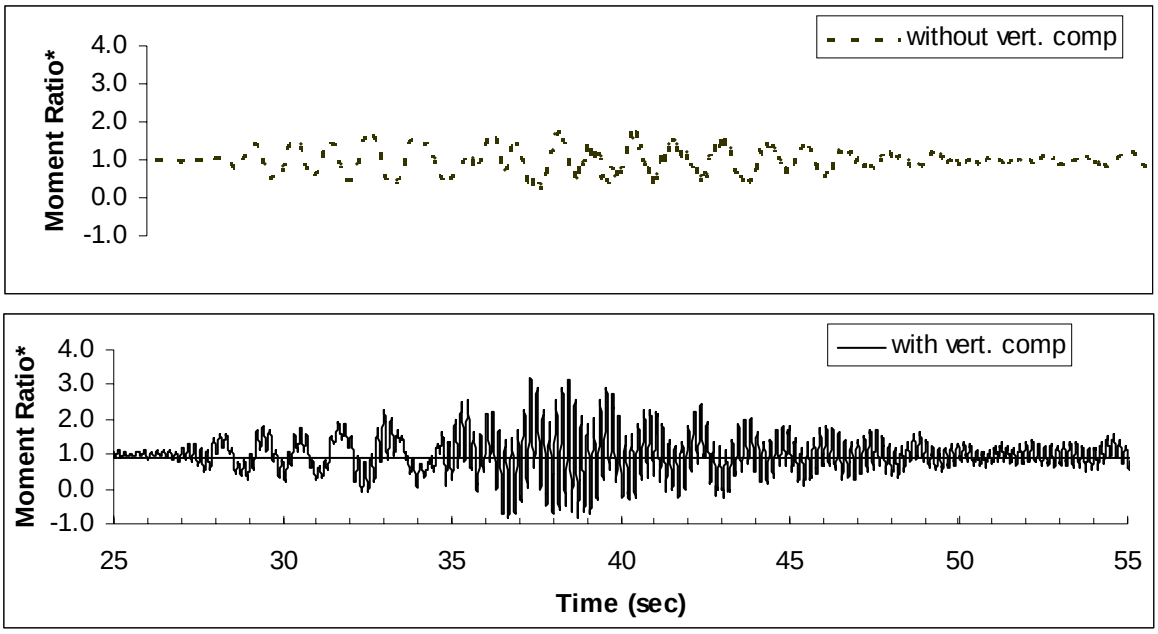

Figure 7: Increased moment demand in longitudinal girder section adjacent to bent due to vertical ground motions (*Moment/Dead Load Moment)

Contribution of P- and S- Waves to Vertical Motions

The relative contribution of compressional and shear waves to vertical motions, as a function of frequency, can be determined by the analysis of the spectra of surface motions in respective time windows (Beresnev et al., 2002). Since geologic materials are stiffest in compression, P-waves travel faster than other seismic waves and are therefore the first to arrive at a particular site. If surface waves are present, they typically arrive after body waves. The length of the P-wave window, ending at the arrival of the S-wave, is characteristic for each record and will be determined using the Arias Intensity of the horizontal component of the record within the context of this study. Figure 8 shows the normalized arias intensity vs. time plot of both horizontal components of two typical earthquake records. The arias intensity curve starts with a mild slope in the p-wave zone. There is a steep increase in the slope between 0.05 I(t) and 0.80 to 0.90 I(t) indicating the large amount of energy carried by the S-waves. Therefore the p-wave window of the vertical component of the record can be determined by finding the time corresponding to 0.05 I(t) of the horizontal components. In examining the two records shown in Figure 8, it is seen that the arrival of the S-wave varies from record-to-record and the variation of the Arias Intensity for the two horizontal components may be similar (Earthquake 1) or different (Earthquake 2).

In order to compare the contribution of p-waves to the response, two different response spectra are constructed for each record. A sample set of spectra plots are shown in Figure 9a. The “full spectra” plot is the normal spectrum of the entire record while the “Post S-wave” response contains only the response after the arrival of the S-wave. Differences in the spectral magnitude are clearly evident in the high-frequency (low period) range of the response.

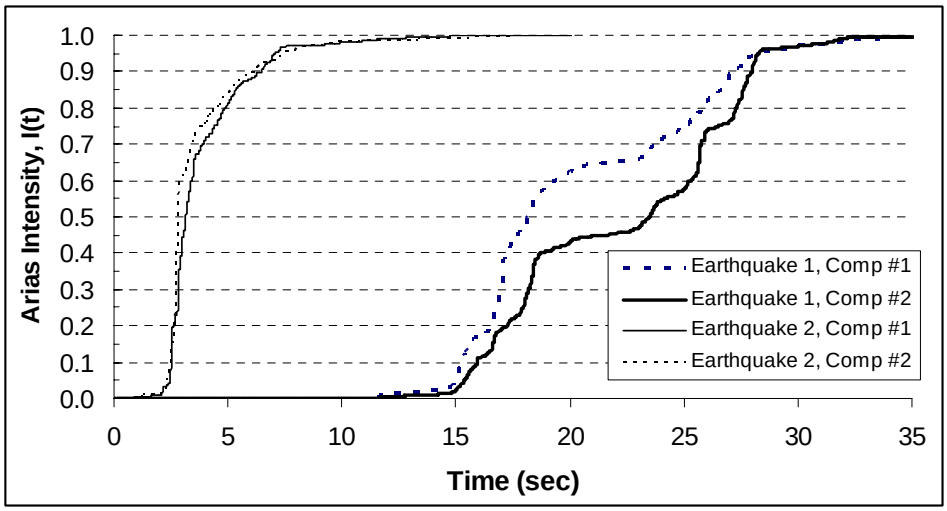

Figure 8: Normalized Arias intensity curves for horizontal components of earthquakes.

Next, we examine the ratio of the horizontal to vertical spectra for a typical set of earthquakes when the P-wave window is removed from the record. Figure 9b compares the ratio of the vertical spectral acceleration to the horizontal spectral acceleration for the full record and the reduced record after the arrival of the S-waves. The ratios are significantly different in the very low period range but an increase in the ratio for the post S-wave record is evident in some regions. These features of selected records in the NGA database are being investigated.

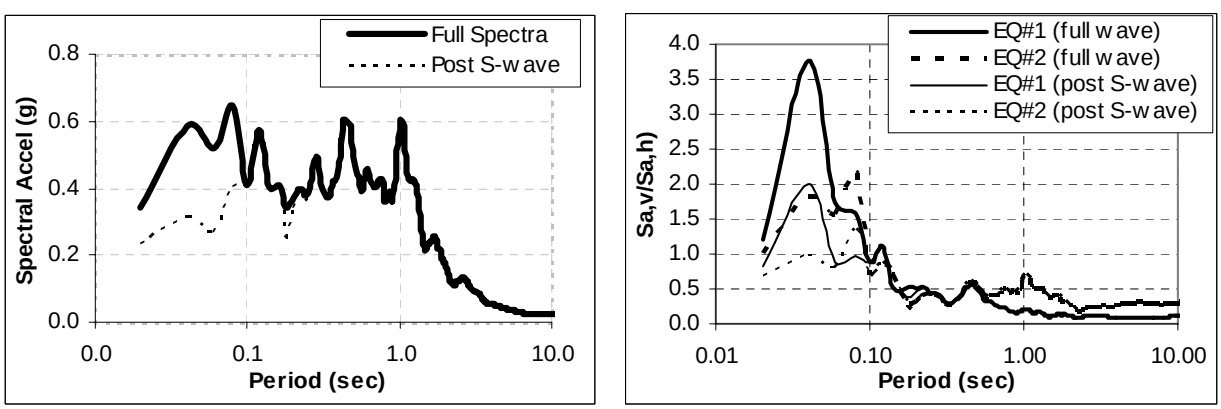

Figure 9: Full response spectrum and S-wave response spectrum plots
(a) Vertical spectra for a typical earthquake
(b) Ratio of vertical to horizontal spectra for two typical records

CONCLUDING REMARKS

Preliminary findings from this study indicate that the most significant influence of vertical ground motions is the amplification and potential for reversal of bending moments in the longitudinal girder. A more comprehensive study of this effect is being investigated for generic bridge configuration with varying column height, cap beam length and girder spans. Those records that produce the most adverse effects will be analyzed by the seismological team to identify spectral and related seismological characteristics of these earthquakes. Some of the

initial parameters being examined concurrently with the analytical study were presented in the previous section. A more complete set of records with similar ground motion characteristics will be identified in the NGA database and these records will be used in the next phase of the study.

REFERENCES

Gloyd, S. (1997). "Design of ordinary bridges for vertical seismic acceleration." *Proc., FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities, Tech. Rep. No. NCEER-97-0010*, National Center for Earthquake Engineering Research, State Univ. of New York at Buffalo, N.Y., 277–290.

Beresnev, I. A., Nightengale, A. M., and Silva, W. J. (2002). Properties of Vertical Ground Motions, Bull. Seism. Soc. Am., Vol. 92, No. 88, pp. 3152-3164.

Key Words

Bridges; near-fault effects; nonlinear analysis; vertical ground motion