EFFECTS OF NEAR-FAULT VERTICAL ACCELERATIONS ON HIGHWAY BRIDGE COLUMNS

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Abstract

The effects of vertical ground motions on the seismic response of ordinary highway bridges are investigated. Nonlinear simulation models with varying configurations of an existing bridge in California are developed for use in a detailed parametric study. The models are subjected to earthquake motions with and without vertical accelerations. Results indicate that vertical effects lead to significant variations in axial force demand in columns which can result in: fluctuations in moment demands at the face of the bent cap, amplification of moment demands at the girder mid-span, and changes to moment and shear capacity of the column. In the second phase, the effect of vertical motions on shear demand and capacity of bridge columns are examined.

Introduction

The Seismic Design Criteria (SDC) used by the California Department of Transportation for ordinary standard bridges states that vertical effects should be considered on sites where the peak rock acceleration is expected to be more than 0.6g. However, the procedure to evaluate vertical effects is rather simplistic: a separate equivalent static vertical load analysis should be carried out under a uniformly distributed vertical load of 25% of the dead load applied in the upward and downward directions, respectively (CalTrans 2006).

Recent earthquakes have revealed that the ratio of vertical to horizontal peak ground acceleration can be larger in near-fault records than far-fault records. Hence it has become necessary to reexamine the consequences of vertical motions on typical highway bridges. The characteristics of vertical motions and the effect of vertical accelerations on bridge structures have been investigated by several researchers (Saadeghvaziri and Foutch 1991; Bozorgnia and Niazi 1993; Broekhuizen 1996; Papazoglou and Elnashai 1996; Yu et al. 1997; Gloyd 1997; Collier and Elnashai 2001; Button et al. 2002). Among other findings, these studies conclude that the variation of axial forces due to vertical excitations can influence both the moment and shear capacity of the section and also increase tensile stresses in the deck. An evaluation of the characteristics of response spectra of free-field vertical motions recorded during the 1994 Northridge earthquake by Bozorgnia et al. (2004) found the vertical to horizontal (V/H) response spectral ratios to be strongly dependent on period and site-to-source distance.

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Important Characteristics of Vertical Accelerations

A preliminary study of 65 near-fault earthquake records with horizontal PGA greater than 0.5g indicates that:

- The predominant period of the vertical ground motions are smaller than the corresponding horizontal component (Figure 1).
- The ratio of vertical-to-horizontal PGA decreases gradually with increasing fault distance, therefore, the vertical component of ground motions will be more severe for near fault ground motions.

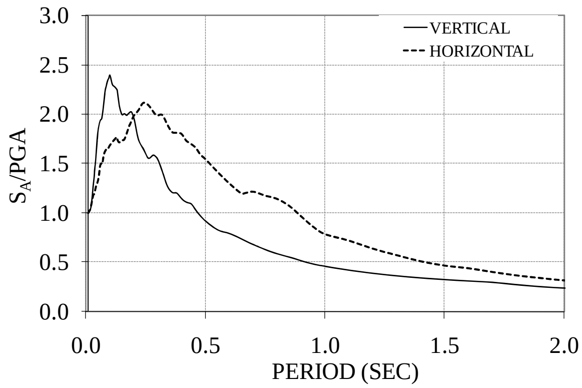


Figure 1: Characteristics of near-fault horizontal and vertical motions

Summary of Phase I Study

An existing two-span overcrossing was selected to represent a typical ordinary highway bridge in California. The computer model used in the simulations is shown in Figure 2. The superstructure consists of a reinforced concrete box girder supported by two circular columns with a diameter of 1.78 m. The width of the girder was unchanged at S = 8.8 m and the column height was fixed at H = 8.5 m.

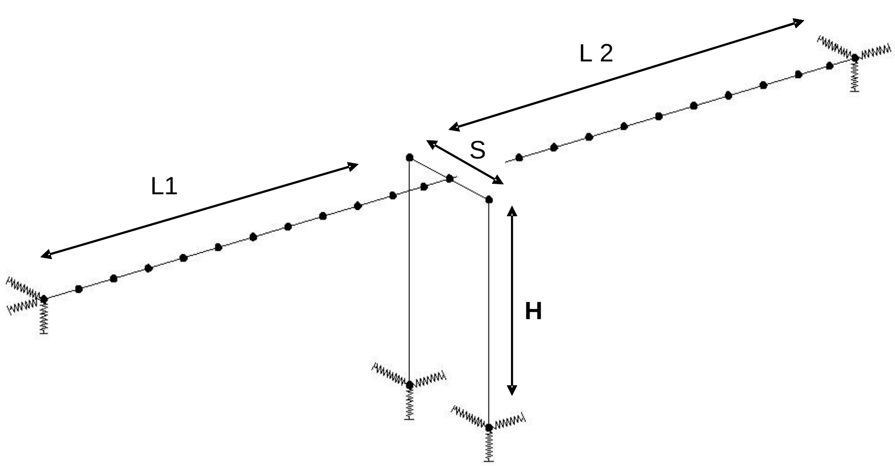


Figure 2 – Simulation model of typical two-span bridge

The end conditions both at the abutments and at the bottom of the columns were modeled using spring elements whose properties were determined using SDC (CalTrans 2006) guidelines. The superstructure was modeled both as elastic elements in the initial phase of the study and later as inelastic elements to examine the effects of inelasticity on reinforcement yielding. Potential inelastic regions of the columns were modeled using fiber hinge elements with prescribed plastic hinge lengths. Axial force – moment interaction was therefore included in the simulations. Additional details of the bridge and the simulation models are reported in Kunnath et al. (2007). In order to investigate the effect of vertical accelerations on a wider range of vertical frequencies, different bridge configurations were created by modifying the span lengths, L1 and L2. Table 1 presents the fundamental dynamic properties of the selected configurations.

Table 1 – Properties and periods of bridge configurations

Simulation Model #	T_V (s)	T_L (s)	T_T (s)
1	0.19	0.32	0.55
2	0.12	0.27	0.46
3	0.30	0.43	0.64
4	0.37	0.53	0.68
5	0.45	0.62	0.75
6	0.24	0.35	0.59

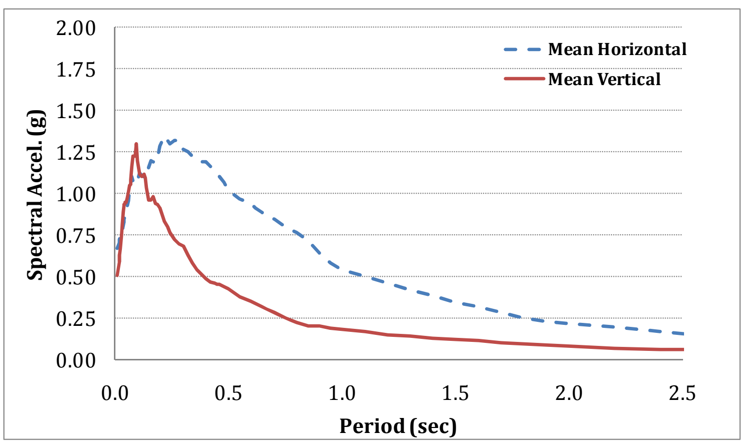


Figure 3 –Spectra of the horizontal component of ground motions scaled to match the ARS curve (Magnitude 8.0, PGA 0.5 g and site class D) at fundamental longitudinal period of base configuration, and corresponding vertical spectra

Ground Motions

Following a preliminary set of analyses, a reduced subset of 29 near-fault records that produced the largest demands on the bridge was selected for detailed evaluation. All ground motions were scaled to match the ARS spectrum (CalTrans 2006) at the longitudinal period of each bridge configuration. Figure 3 displays typical spectra of the horizontal component of the ground motions scaled to match the ARS curve for ground motions with a PGA 0.5g and site class C together with the corresponding vertical spectra.

Effect of Vertical Acceleration on Column Axial Force

Figure 4 summarizes the variation of the normalized axial load as a function of the vertical fundamental period. Both the maximum and minimum axial force experienced by the column in each simulation is recorded. The amplification of the axial load in the column is not a source for concern since the nominal axial load capacity of the columns is adequate to resist these forces without damage. However, the variation in the axial force on the column may result in significant changes in the moment and shear capacity of the column.

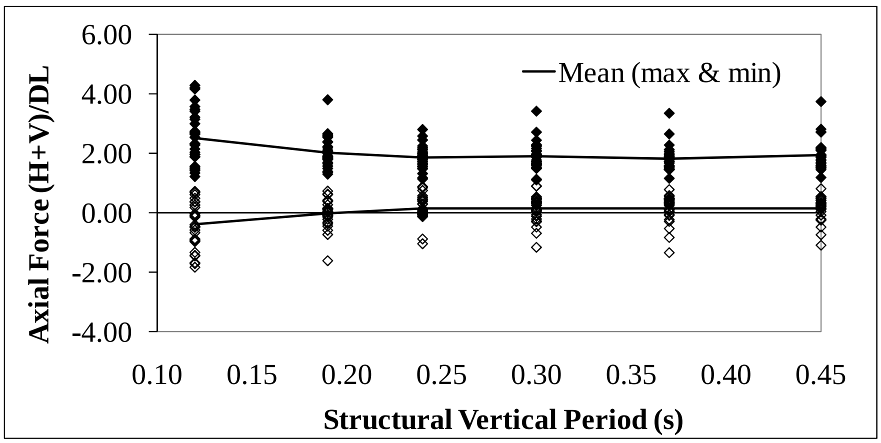


Figure 4 – Variation of column axial force demands with vertical period for unscaled ground motions

Effect of Vertical Acceleration on Span Moment

Figure 5 shows the variation of the normalized moment demand (ratio of moment demand to the moment demand due to dead load only) at mid-span of the left girder as a function of the fundamental vertical period. The results highlight the significant effects of vertical motions on the moment demands in the longitudinal girders. It should be pointed out that the girders were modeled as elastic elements in these simulations. Since the negative moments far exceed the available capacity, the simulations were repeated using inelastic elements for the girder. Peak strains were found to vary up to 12 times the yield strain.

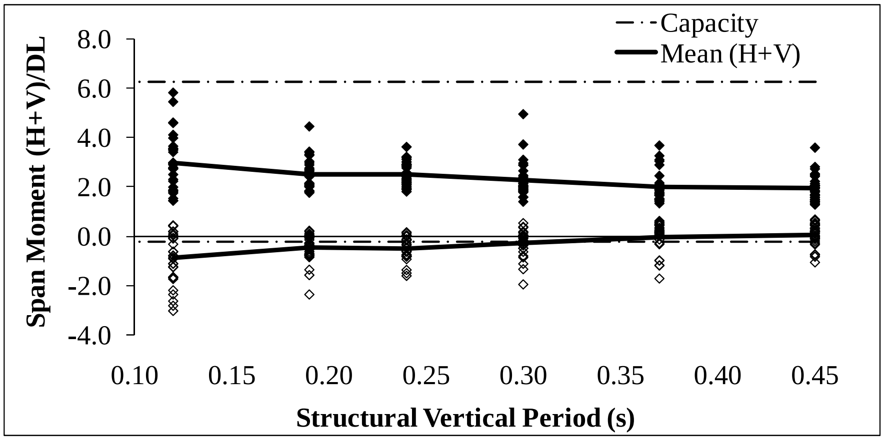


Figure 5 - Variation of moment demand at the mid-span with vertical period for unscaled ground motions

Effect of Vertical Acceleration on Column Moment

The large increases in the axial compression in columns due to vertical accelerations (Figure 4) can lead to significant increases in the column moment capacity. Although this may suggest conservatism in the design, it may result in the shifting of the potential plastic hinge zone from the top of the column to the girder which is an undesirable situation that is supposed to be avoided by the requirements of SDC-2006.

Phase II Results

In reviewing some of the earlier work on the effects of vertical motions on structures, some investigators have raised the issue of shear demand and capacity in bridge columns due to changes in the axial force demands. Since the bridge configurations used in the Phase I study consisted of two-column bents and single columns with very large shear span ratios, shear demands were generally not critical. Hence a new study was initiated to identify critical bridge configurations that might be prone to shear damage due to vertical effects.

The typical configuration selected for this phase of the work is the Plumas Bridge in California which is a three-span bridge with span lengths of 40.5m, 58.0m and 40.5m. The heights of the as-built columns are approx 9 m each. In order to study shear demands under strong near-fault motions, the column heights were varied to generate a range of aspect ratios. A nonlinear simulation model, as displayed in Figure 6, was developed in OpenSees (2009). To ensure proper modeling of the torsional properties of the deck, a three dimensional shell model of the bridge was created in SAP-2000 and a series of elastic modal analyses were carried out on both systems to calibrate the inertial properties of the superstructure of the line model.

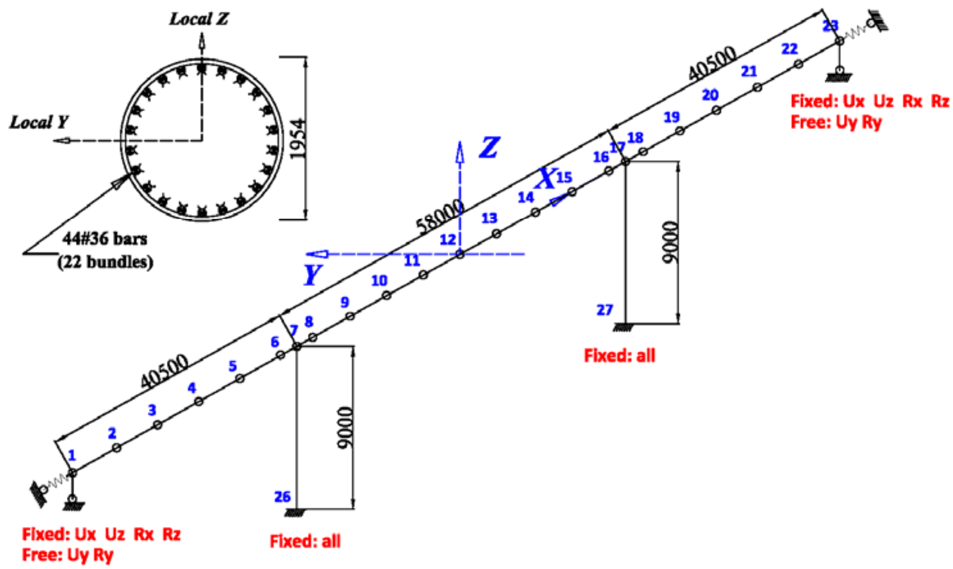


Figure 6 – Simulation model of the Plumas Bridge used in Phase II Study

The model was subjected to a series of combined horizontal and vertical near-fault motions. The earthquake records used in the simulations are listed in Table 2. Each set of records was scaled to match the SDC-ARS spectra (corresponding to a magnitude 8 event with PGA of 0.6g) at the fundamental transverse period of the bridge (which was estimated at 0.8 seconds). Scale factors were established for the larger of the two horizontal components and this factor was used to scale the remaining two components. A plot showing the mean spectra for all scaled records is summarized in Figure 7.

Table 2 – Characteristics of selected near-fault records

Earthquake	Year	Station	Distance* (km)	PGA-H_{MAX} (g)	PGA-H_{MIN} (g)	PGA-Vert (g)
1. Gazli (USSR)	1976	Karakyr	5.46	0.718	0.608	1.264
2. Imperial Valley	1979	Bonds Corner	2.68	0.755	0.588	0.425
3. Morgan Hill	1984	Coyote Lake Dam	0.30	1.298	0.711	0.388
4. Erzican (Turkey)	1992	Erzincan	4.38	0.515	0.496	0.248
5. Landers	1992	Lucerne	2.19	0.785	0.721	0.818
6. Northridge	1994	Rinaldi Rec Stn	6.50	0.838	0.472	0.852
7. Kobe (Japan)	1995	KJMA	0.96	0.821	0.599	0.343

* Closest fault distance

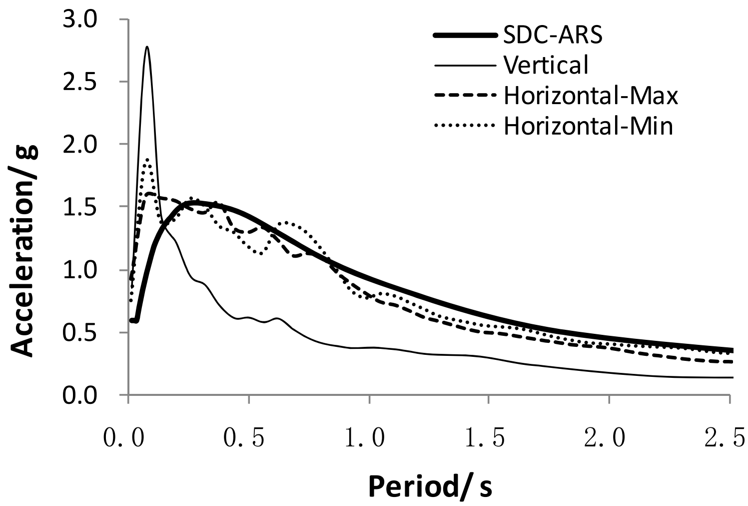


Figure 7 – Spectra of ground motions used in Phase II study

For each simulation, the axial force, shear demand and shear capacity in the column was monitored. Shear capacity at any instant in time was evaluated using ACI-318 (2007) expressions:

$$V_n = V_c + V_s \tag{1}$$

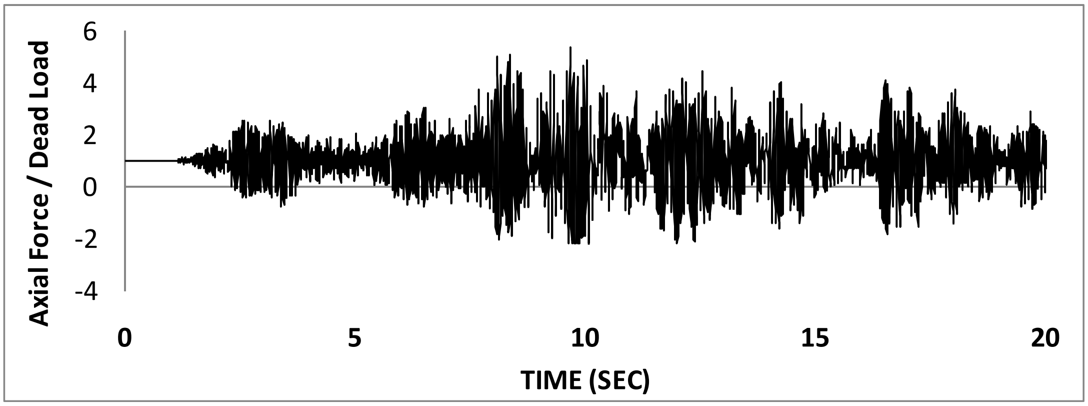
In the above equation, V_c is shear strength provided by concrete, and V_s is shear strength provided by shear reinforcement.

$$V_c = \begin{cases} 2\left(1+\dfrac{N_u}{2000A_g}\right)\sqrt{f_c'}\,b_w d, & \text{when } N_u > 0 \text{ (axial compression)} \\ 2\left(1+\dfrac{N_u}{500A_g}\right)\sqrt{f_c'}\,b_w d, & \text{when} N_u \le 0 \text{ (tension)} \end{cases} \tag{2}$$

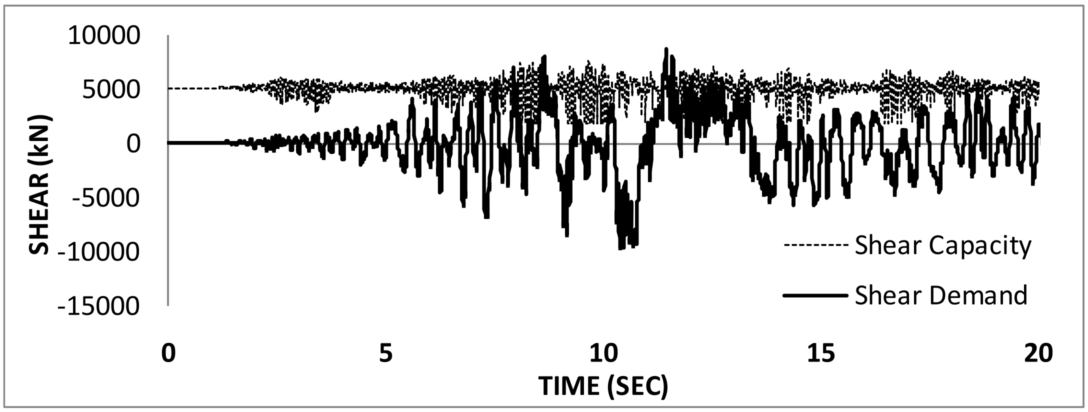
$$V_s = \frac{A_v f_{yt} d}{s} \tag{3}$$

N_u : factored axial force normal to the cross section

Figure 8 shows a typical response of the bridge column. The computed axial force is normalized by the dead load which means that values below 1.0 indicate a state of axial tension in the column. The shear capacity (which is a function of the axial force) is superimposed on the demand plot so that the demand to capacity ratio (DCR) can be ascertained. The particular case study presented in Figure 8 is for the Landers record set which provided the maximum DCR among all ground motions considered.



(a)



(b)

Figure 8 – Response of the bridge column with aspect ratio of 3.0 subjected to the Landers (1992) record: (a) Axial force variation; (b) Shear demand vs. available shear capacity.

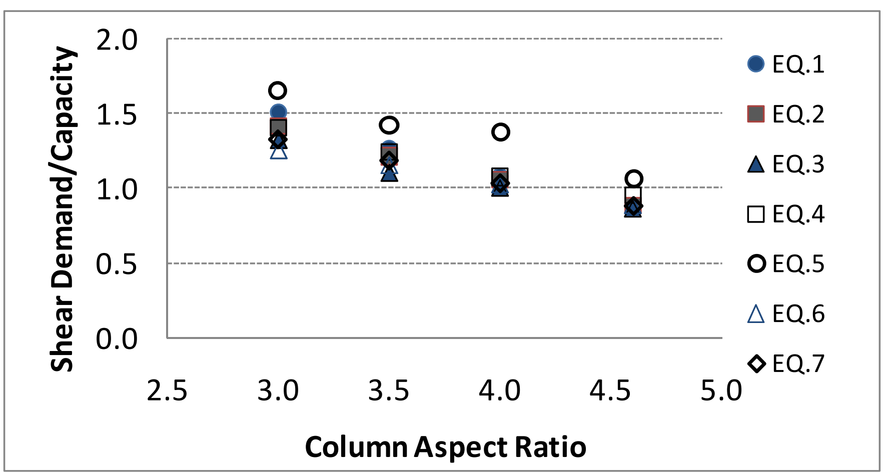


Figure 9 – Effect of aspect ratio (column height/diameter) on shear DCR

Finally, a summary of the shear DCR for all simulations is presented in Figure 9. The record numbers correspond to the list identified in Table 2. It is evident that shear damage is likely only for aspect ratios below 4.5. Given the fact that the expressions used to estimate shear capacity are generally conservative, it is reasonable to conclude that only columns with aspect ratios below 4.0 need further investigation.

Concluding Remarks

The main objective of the present study is to assess current provisions in SDC-2006 for incorporating vertical effects of ground motions in seismic design of ordinary highway bridges. Results of the investigation suggest that highway over-crossings with vertical periods close to the predominant period of the vertical component of the motion are more vulnerable to vertical effects.

Findings also indicate that vertical ground motions significantly affect the axial force demand in columns which in turn have an effect on moment demands at the middle of the span. A separate study on the effects of vertical motions on shear demands and shear capacity in the columns reveal that the aspect ratio (column height to diameter) is a significant parameter that influences potential shear damage to the column. It should also be noted that axial forces vary at much higher frequencies than lateral forces. Hence the sudden shifts in shear capacity as the column goes from compression to tension may require further investigation. A shaking table test program on this issue is the subject of an ongoing investigation funded by Caltrans and being carried out collaboratively between UC Berkeley and UC Davis.

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References

Bozorgnia, Y., M. Niazi. (1993). "Distance Scaling of Vertical and Horizontal Response Spectra of the Loma Prieta Earthquake." *Earthquake Engineering and Structural Dynamics*, Vol 22, pp.695-707.

Bozorgnia, Y. M. and Campbell, K. W. (2004). The vertical-to-horizontal response spectral ratio and tentative procedures for developing simplified V/H and vertical design spectra, *J. Earthquake Engineering*, Vol. 8, pp. 175-207.

Broekhuizen, D. S. (1996). “Effects of vertical acceleration on prestressed concrete bridges.” MS Thesis, University of Texas at Austin, Texas.

Button, M.R., Cronin, C.J. and Mayes, R.L. (2002). “Effect of Vertical Motions on Seismic Response of Bridges.” *ASCE Journal of Structural Engineering*, Vol.128 (12), 1551-1564.

CalTrans (2006), “Seismic Design Criteria”, California Department of Transportation Sacramento, CA.

Collier, C.J. and Elnashai, A.S. (2001). “A Procedure for Combining Vertical and Horizontal Seismic Action Effects.” *Journal of Earthquake Engineering*, Vol. 5, No. 4, 521-539.

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., pp.277–290.

Kunnath, S.K., Erduran, E., Chai, Y.H. and Yashinsky, M. (2007). “Near-Fault Vertical Ground Motions on Seismic Response of Highway Overcrossings.” ASCE *Journal of Bridge Engineering*, Vol.13, No.3, 282-290.

Papazoglou, A.J. and Elnashai, A.S. (1996). “Analytical and Field Evidence of the Damaging Effect of Vertical Earthquake Ground Motion.” *Earthquake Engineering and Structural Dynamics*, Vol. 25, No.10, 1109 – 1137.

Saadeghvaziri, M. A., and Foutch, D. A. (1991). “Dynamic behavior of R/C highway bridges under the combined effect of vertical and horizontal earthquake motions.” *Earthquake Engineering and Structural Dynamics*,Vol 20, pp.535–549.

Silva, W. J. (1997). “Characteristics of vertical ground motions for applications to engineering design.” *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., pp.205–252.

Yu, C-P., Broekhuizen, D. S., Roesset, J. M., Breen, J. E., and Kreger, M. E. (1997). “Effect of vertical ground motion on bridge deck response.” *Proc., Workshop on Earthquake Engineering Frontiers in Transportation Facilities, Tech. Rep. No. NCEER-97-0005*, National Center for Earthquake Engineering Research, State Univ. of New York at Buffalo, N.Y., pp.249–263.