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Seismic response of highway bridges under multi-directional motions

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ABSTRACT

A seismic evaluation of a typical multi-span bridge is carried out to assess the suitability of linear response spectrum analysis to the combined horizontal and vertical response spectra for predicting moment demands in the bridge girder. The spectra are applied to the longitudinal and vertical direction of the bridge. The moment demands of the bridge girder are then computed from elastic response spectrum analysis considering sufficient number of modes using the longitudinal and vertical spectra. These results are compared to demands estimated with nonlinear time history simulations. It is concluded that response history analysis using the horizontal and vertical design spectra is a valid preliminary approach to estimate the effects of vertical ground motions on ordinary highway bridges.

1. INTRODUCTION

In a recent study by Kunnath et al. (2007) investigating the effect of vertical ground motions on the seismic response of ordinary highway bridges, strong vertical accelerations have been found to have significant effects on (i) the axial force demand in columns; (ii) moment demands at the face of the bent cap, and (iii) moment demands at the middle of the span. The last issue was identified as the primary issue to be considered for the analysis and design of typical short-span column supported bridge configurations. This is because, in the absence of vertical effects, the design of the mid-span section is governed by positive moments whereas strong vertical motions can cause significant negative moments in the mid-span.

The effects of vertical ground motions on structural response have also been investigated by many researchers in the past (Saadeghvaziri and Foutch 1991; Broekhuizen 1996; Papazoglou and Elnashai 1996; Elnashai and Papazoglou 1997; Yu et al. 1997; Gloyd 1997; Abrahamson et al. 1997; Collier and Elnashai 2001; Button et al. 2002; Veletzos et al. 2006). Most of these studies highlight the fact that strong vertical motions induced significant fluctuations in axial forces in vertical elements leading to a reduction of the column shear capacity. Lee (2011) carried out an experimental and analytical investigation of reinforced concrete columns subjected to

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horizontal and vertical ground motions. In the experiments conducted on the UC-Berkeley shaking table, the shear behaviour of two quarter-scale specimens was examined under combined vertical and horizontal components. The experimental results confirmed that vertical accelerations can induce tensile strains which result in shear strength degradation of RC bridge columns.

In the present study, a detailed seismic evaluation of a typical multi-span bridge is carried out to assess the suitability of linear response spectrum analysis to combined horizontal and vertical response spectra for predicting moment demands in the bridge girder.

2. MODELING OF BRIDGE SYSTEM

The selected bridge configuration is a three-bent, four span bridge with a total length of 208.8 m. The elevation view and column details are shown in Fig. 1. Additional details on the bridge configuration, including cross-sectional properties can be found in Kunnath et al. (2008). The spans of the bridge were varied to create three bridge configurations. The elastic modal properties of the three configurations are listed in Table 1. The nonlinear simulations are performed using the open-source software, OpenSees (2009).

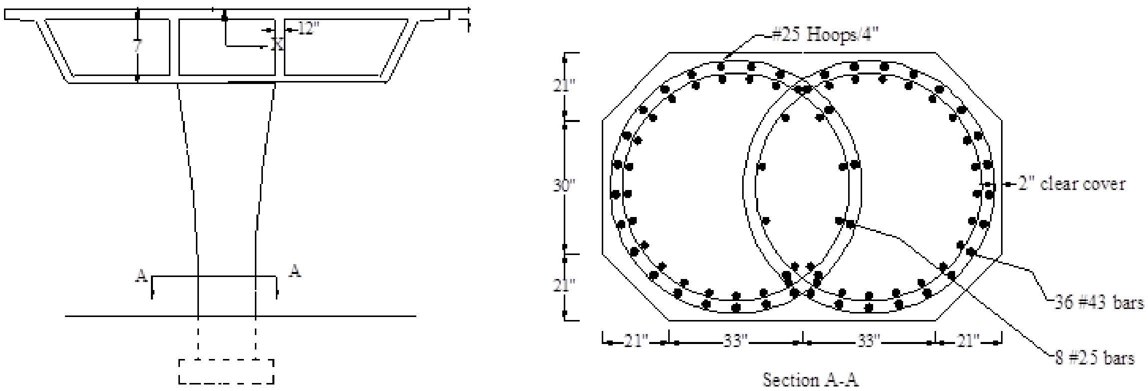


Fig. 1 Elevation view and column details of Amador Creek Bridge

Table 1 Dynamic properties of selected multi-span bridges

Configuration	**Config1**	**Config2**	**Config3**
Side span (m)	40.5	34.0	25.0
Middle span (m)	54.0	45.0	35.0
T_L (s)	2.50	2.29	1.98
T_T (s)	2.33	2.12	1.77
T_V (s)	0.52	0.37	0.23

3. NUMERICAL SIMULATIONS AND RESULTS

In order to investigate the effectiveness of simplified elastic response spectrum analysis (RSA) to estimate moment demands in the girder for the typical ordinary bridges, the response parameters of interest computed by RSA will be compared with results from nonlinear time history analysis. The moment demands at the mid-span and interior supports are identified as the main response parameters of interest. For the response spectrum analysis, the following two cases will be considered: (1) Intensity scaled (to match the spectral acceleration of the Caltrans ARS spectra at the fundamental period) response spectrum of each selected ground motion used in the nonlinear time-history (NTH) simulations, record by record, both horizontal and vertical components; (2) Mean horizontal and vertical spectrum of the response spectra of the NTH ground motion set. In addition to comparing moment demands in the bridge girder, the probability density distribution of the girder moment demands estimated by both methods will also be compared.

The design spectrum chosen is based on the USGS spectrum that corresponds to an exceedance probability of 5% in 50 years, with near fault factor applied. For the design spectrum used in this paper, the maximum magnitude (M_{max}) is 7.9 and peak rock acceleration in vertical direction is 0.58g. Hence a full 3D elastic bridge model is required for the corresponding response spectra analysis, based on SDC regulations (2006).

Twenty ground motions with peak ground acceleration (PGA) of one or both horizontal components larger than 0.25g and relatively high vertical-to-horizontal PGA ratios are selected from PEER NGA database (2011). The ground motions are scaled to match the spectrum acceleration value on the design spectrum (the Caltrans ARS spectrum) at the fundamental longitudinal period of bridge models, for each of the configurations considered in the study. For consistency, the same scale factor is applied to both horizontal and vertical directions of a ground acceleration record. The mean horizontal spectra of the twenty scaled ground motions for configuration 0 of and the model of Amador Creek Bridge are displayed in Fig. 2. The “target” spectrum – the Caltrans ARS design spectrum and the developed vertical spectrum are also plotted.

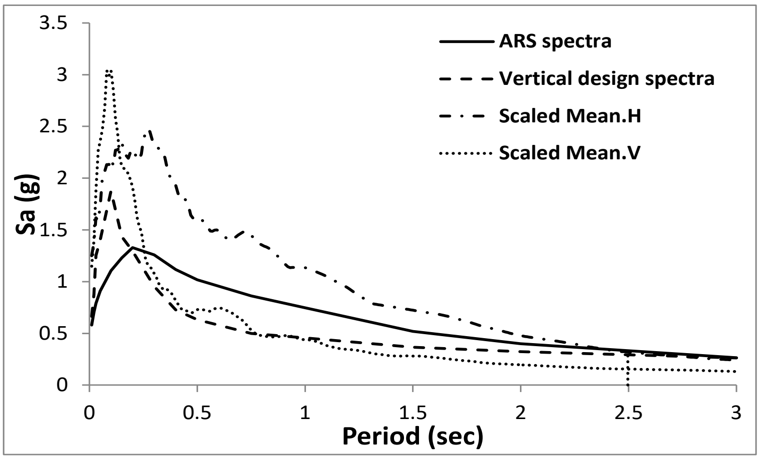
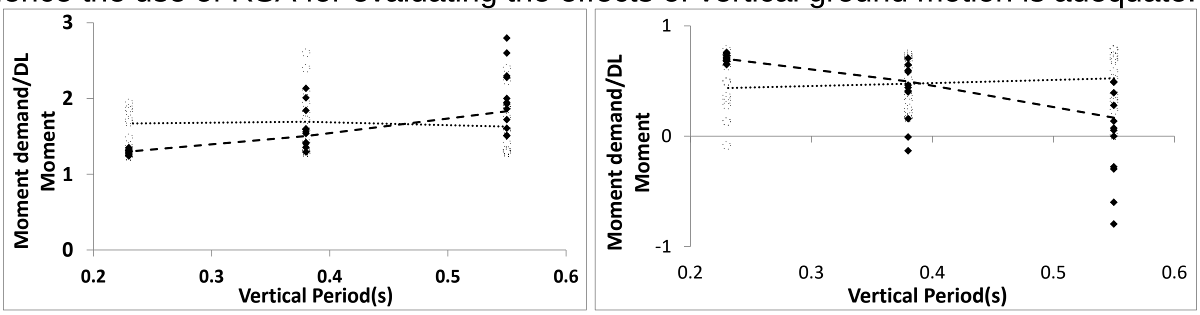


Fig. 2 Scaled spectra for base configuration of multi-span bridge

4. RESULTS OF SIMULATIONS FOR MULTI-SPAN SYSTEMS

For the exterior spans, it was found that the estimates using RSA, on average, are much higher than the predictions by NTH. This suggests that the peak demands occur during the elastic phase of response of the columns. The peak demands are compared for the interior mid-span in Fig. 3. Estimates from nonlinear time-history analysis indicate a nearly constant demand (on average) for the three configurations. The RSA results show a trend with increasing demands as the vertical period increases. In fact, the mean RSA estimates are slightly lower than NTH for a vertical period of 0.23 secs, almost the same at the intermediate period and higher than NTH for a vertical period of 0.55 seconds. This observed trend is reversed for the minimum moment demands (the critical demand parameter that induces tension in the top surface of the girder) with RSA estimates being higher than NTH at a vertical period of 0.23 seconds and lower than NTH at a vertical period of 0.55 seconds.

However, the variation in the minimum demands should be viewed with care. In most cases, the minimum values are still positive indicating that the vertical ground motions did not cause a reversal of dead load effects from positive to negative moments. Therefore, the only values of concern are the interior mid-span moments where negative demands are estimated in some cases. In all the cases where the minimum moments become negative, the estimates from RSA are higher than NTH. Hence the use of RSA for evaluating the effects of vertical ground motion is adequate.



(a) (b)

Fig. 3 Comparison of moment demands between RSA and NTH at critical sections for all configurations as a function of vertical periods: (a) Interior mid-span (maximum); (b) Interior mid-span (minimum)

The modeling of the multi-span bridges was accomplished by the use of gap springs at the abutments. A compression-only spring with a gap of 0.1 meter is provided in the longitudinal direction corresponding to realistic dimensions of the gap between the bearing pad and abutment. Once the superstructure of the bridge moves in the longitudinal direction due to the imposed ground motion, the gap is closed and significant stiffness is provided in the longitudinal direction to restrain further movement. This has an effect of decreasing the stiffness of the bridge in the direction of motion. Also, when the ground acceleration is large enough to cause longitudinal displacements that exceed the available gap, pounding of the deck with the abutment occurs. The present analysis does not have the ability to exactly simulate pounding effects, however, the large compression stiffness provided upon contact of the deck with the abutment approximately accounts for the change in system period due to contact. The large shear demands imposed on the column due to girder impact with the abutment is evident in the response. Shear yielding of the column was not explicitly modeled in the analysis because none of the columns reached their yield capacity in shear.

Fig. 4 shows the peak moment demands along the span of the girder. Figures include moment demands at the supports and at mid-spans of the girder. The values are normalized with respect to the moments resulting from dead load only. It is observed that the estimates from RSA consistently predict higher demands than NTH. This indicates that a simple elastic response spectrum analysis (RSA) provides conservative demands estimates of girder moment demands. Results are shown for only 2 configurations but similar results were observed for Configuration 3.

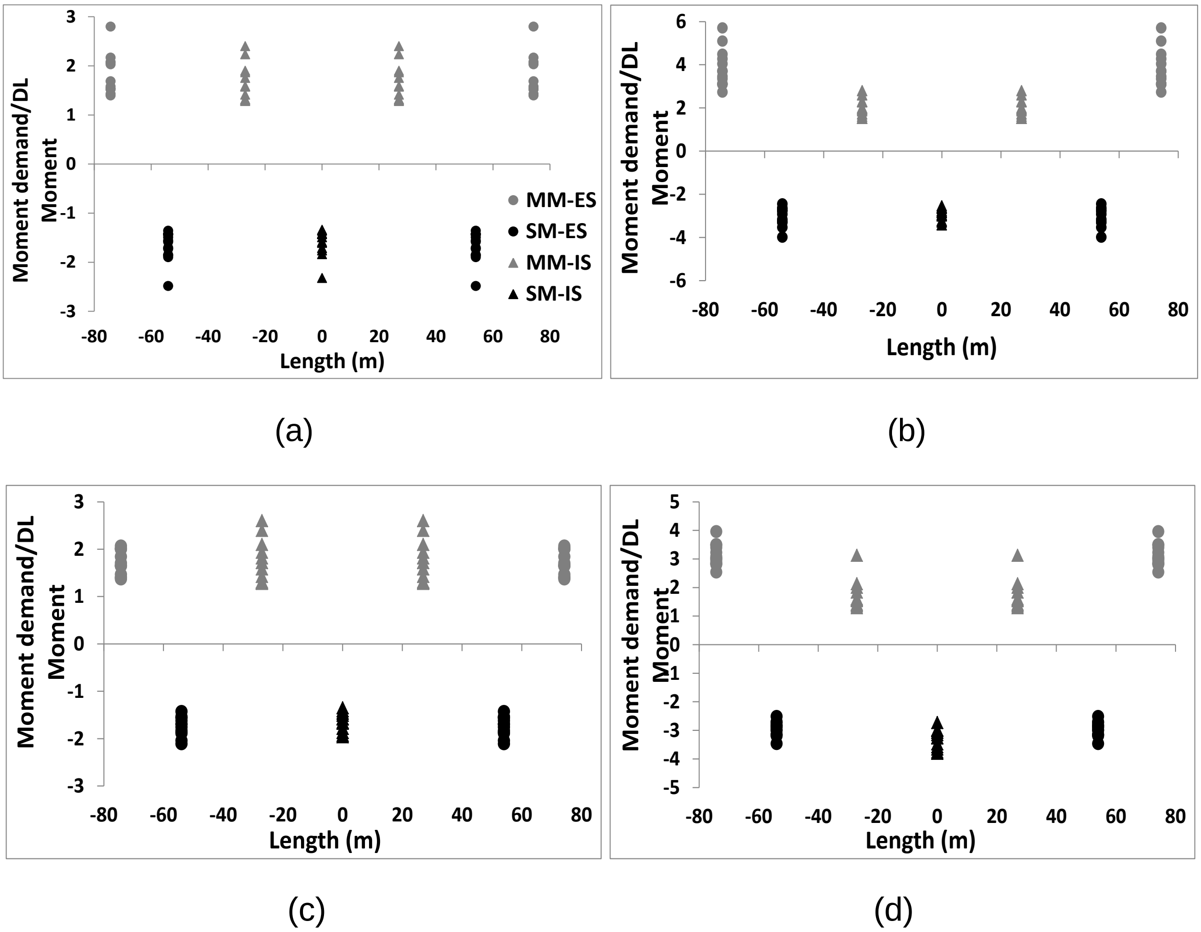


Fig. 4 Comparison of moment demands using NTH and RSA along the deck of Amador Creek Bridge: (a) Configuration 1 – NTH; (b) Configuration 1 – RSA; (c) Configuration 2 – NTH; (d) Configuration 2 – RSA.

5. CONCLUSIONS

The issue of the significance of vertical components of ground motions on structural response has continued to be a matter of debate since it is difficult to establish direct evidence of damage from vertical motions. Past research has clearly identified several potential issues that deserve attention – the moment demands in the girder that may result in inelastic behavior (this is an important consideration since highway bridges in the US are designed to keep the girder elastic and restrict inelastic action in the columns). The main objective of this study was to assess if an elastic response spectrum analysis (RSA) is sufficient to estimate critical demands in the girder. Such an analysis would only be a necessary first step to caution engineers that vertical effects should be considered and additional detailed nonlinear simulations would be necessary to determine the seriousness of the problem. Results of the analyses conducted for this study reveal that response history analysis using the horizontal and vertical design spectra is a valid preliminary approach to estimate the effects of vertical ground motions on ordinary highway bridges.

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REFERENCES

Abrahamson, N.A. and Silva, W.J. (1997), "Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes." *Seism. Soc. Am*., **68**(1), 94-127.
Broekhuizen, D. S. (1996). “Effects of vertical acceleration on prestressed concrete bridges.” MS thesis, Univ. 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.
California Department of Transportation (Caltrans) (2006), “Seismic design criteria”, SDC-2006, Sacramento, CA
Caltrans ARS Online, http://dap3.dot.ca.gov/shake_stable/v2/index.php.
Collier C. J. and Elnashai A. S. (2001), “A procedure for combining vertical and horizontal seismic action effects.” *Journal of Earthquake Engineering*, **5**(4), 521-539.
Elnashai, A. S. and Papazoglou, A. J. [1997] “Procedure and Spectra for Analysis of RC Structures Subjected to Strong Vertical Earthquake Loads," *Journal of Earthquake Engineering* **1**, 121-155.
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, NY, 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.
Kunnath, S.K., Abrahamson, N., Chai, Y.H., Erduran, E. and Yilmaz, Z. (2008), “*Development of Guidelines for Incorporation of Vertical Ground Motion Effects in Seismic Design of Highway Bridges*”, Technical Report, California Department of Transportation, Sacramento, CA.
Lee, H. (2011), “*Experimental and Analytical Investigation of Reinforced Concrete Columns Subjected to Horizontal and Vertical Ground Motions*”, Ph.D. Dissertation, University of California, Berkeley.
OpenSees (2009), Open System for Earthquake Engineering Simulation, http://opensees.berkeley.edu/
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*, **25**, 1109-1137
PEER-NGA Database (2011), http://peer.berkeley.edu/nga/
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*, **20**, 535–549.
Veletzos M. J, Restrepo, J. I, Seible F. (2006). “Seismic response of precast segmental bridge superstructures” Report submitted to Caltrans – SSRP-06/18, University of California, San Diego
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, NY, pp.249–263.