RESPONSE OF ORDINARY HIGHWAY BRIDGES TO COMBINED HORIZONTAL AND VERTICAL GROUND MOTIONS

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Abstract

The effects of near-fault vertical accelerations on the overall response of ordinary highway bridges are investigated. Nonlinear simulation models with varying configurations of an existing bridge in California are considered in the analytical study. A comprehensive set of ground motions with horizontal PGA in excess of 0.5g were selected for the analytical study. The simulation models were subjected to the selected ground motion set in two stages: at first, only horizontal components of the motion were applied; while in the second stage the bridge models were subjected to both horizontal and vertical components applied simultaneously. Results of these analyses reveal that vertical ground motions can have a significant effect 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 first two issues are found to be less of a concern in the present study since the axial capacity of the columns and the moment capacity of the girders at the face of the bent cap are generally adequate to resist the increase in the respective demands due to vertical effects. On the other hand, the amplification of negative moments in the mid-span section is identified as the primary issue that should be addressed in the context of existing seismic guidelines in SDC-2006.

Introduction

For ordinary standard bridges constructed on sites where the peak rock acceleration is expected to be more than 0.6g, the Seismic Design Criteria (SDC) used by the California Department of Transportation requires consideration of vertical effects but does not require analysis of the structure under combined horizontal and vertical components of the ground motion. Instead, the provisions of SDC call for a separate equivalent static vertical load analysis under a uniformly distributed vertical load of 25% of the dead load applied in the upward and downward directions, respectively (CalTrans 2006).

This research was undertaken in light of recent renewed interest in near-field motions and the realization that the ratio of vertical to horizontal peak ground acceleration can be larger in near-fault records than far-fault records. The effect of vertical ground motions on bridges has been investigated in the past (Saadeghvaziri and Foutch 1991; Broekhuizen 1996; Yu et al. 1997; Gloyd 1997; Button et al. 2002). Findings from these

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studies indicate, among other facts, that (1) the variation of axial forces due to vertical excitations can influence the shear capacity of the section; (2) vertical accelerations can significantly increase tensile stresses in the deck. Bozorgnia and Niazi (1993) found that the ratio of vertical to horizontal spectral accelerations were smaller for longer periods than for short periods. Silva (1997) showed that the vertical motion histories show a pattern in which short-period vertical motion arrived before the main horizontal motions, while the longer-period motions arrived at about the same time as the other horizontal components. Recently, Bozorgnia et al. (2004) examined the characteristics of response spectra of free-field vertical motions recorded during the 1994 Northridge earthquake and found the vertical to horizontal (V/H) response spectral ratios to be strongly dependent on period and site-to-source distance. They also concluded that the commonly assumed V/H ratio of 2/3 is exceeded for short periods but may be conservative for longer periods.

This paper presents findings from a study to investigate the validity of the design guidelines specified in SDC-2006. In this context, nonlinear dynamic analyses were carried out on several typical "ordinary standard" bridges with and without vertical effects.

<u>Analytical Model of the Camino Del Norte Median Widening Project</u>

The bridge used in this study is a part of the widening project of the Camino Del Norte Bridge located in California. It is a single bent bridge with span lengths of 30.95 and 30.52 m. Two circular columns with a diameter of 1.78 m constitute the bent. The superstructure consists of a reinforced concrete box girder. Figure 1 shows the elevation view of the bridge. Diaphragm type abutments were used at both ends of the bridge.

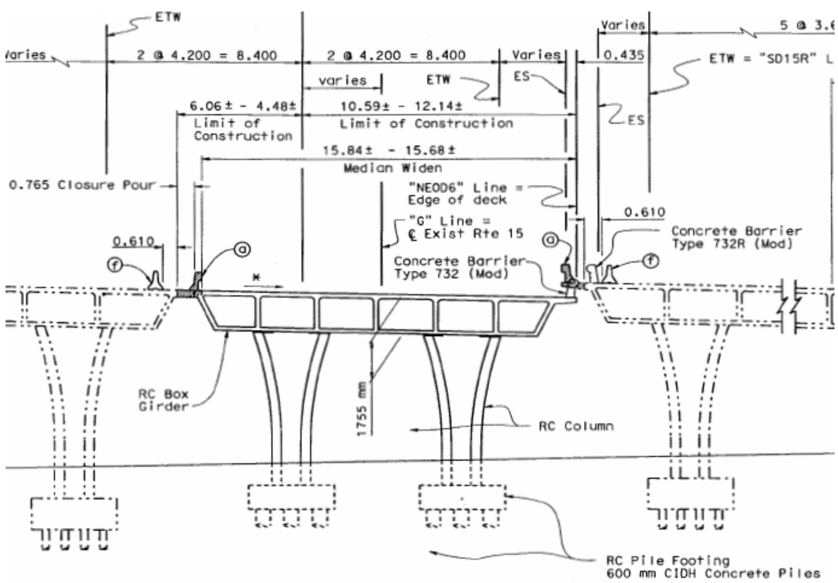

Figure 1 – Elevation view of the new segment of the Camino Del Norte Bridge

The end conditions both at the abutments and at the bottom of the columns were modeled using spring elements to simulate the flexibility of the soil-pile-foundation and abutments. The spring properties of the horizontal springs were determined using SDC-2006 guidelines. The axial rigidity of the piles and the abutments were used to compute the vertical spring properties. 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 plastic hinge regions of the columns were modeled using fiber elements with full axial force – moment interaction. Figure 2 presents the simulation model of the Camino Del Norte Bridge.

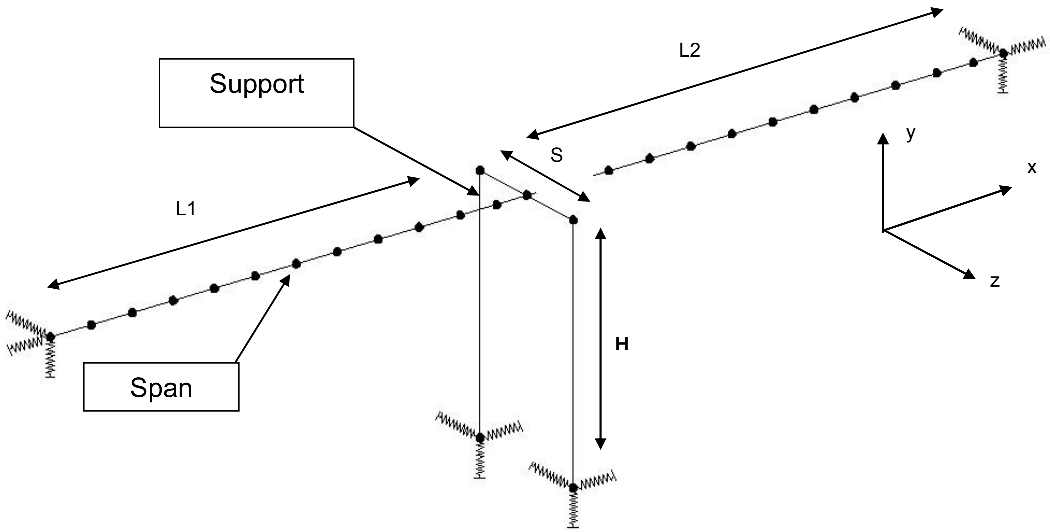

Figure 2 – Simulation model of the Camino Del Norte bridge

In order to investigate the effect of vertical accelerations on a wider frequency range, different bridge configurations were created by modifying the span lengths, L1 and L2. During this modification, care was taken to not violate the specifications of the SDC-2004 regarding the geometry of the structure. Table 1 presents the properties and the periods in the three directions of the new configurations together with the original configuration.

Table 1 – Properties and periods of bridge configurations

Configuration	L1 (m)	L2 (m)	T_L (s)	T_T (s)	T_V (s)
Original	30.95	30.52	0.32	0.55	0.19
Config 1	20.95	20.52	0.27	0.46	0.12
Config 2	40.95	40.52	0.43	0.64	0.30
Config 3	45.95	45.52	0.53	0.68	0.37
Config 4	50.95	50.52	0.62	0.75	0.45
Config 5	35.95	35.52	0.35	0.59	0.24

Ground Motions

Following a preliminary set of analyses, a reduced subset of 29 near-fault records that produced the largest demands on the bridge simulation models was selected for the detailed evaluation phase. All ground motions were scaled to match the ARS spectrum (Caltrans 2006) used in the design of Ordinary Standard Bridges 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 D together with the corresponding vertical spectra. Table 2 summarizes the properties of the ground motions used.

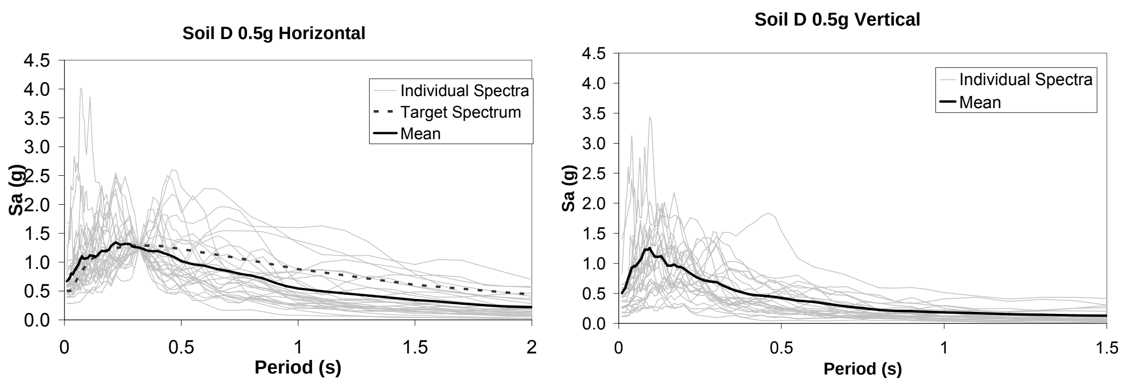

Figure 3 –Spectra of the horizontal component of ground motions scaled to match the ARS curve (Magnitude 8.0, PGA 0.5 g and site class D) at fundamental longitudinal period of base configuration, and corresponding vertical spectra

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. The amplification of the axial load in the column is not critical by itself since the nominal axial load capacity of the bridge columns is very high compared to the axial load due to the dead load effects. However, the variation in the axial force on the column may result in significant changes in the moment and shear capacity of the column.

Effect of Vertical Acceleration on Span Moment

Figure 5 shows the variation of the normalized moment demand (ratio of computed moment with all 3 ground motion components acting on the system divided by the moment demand due to dead load only) at mid-span of the left girder with 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.

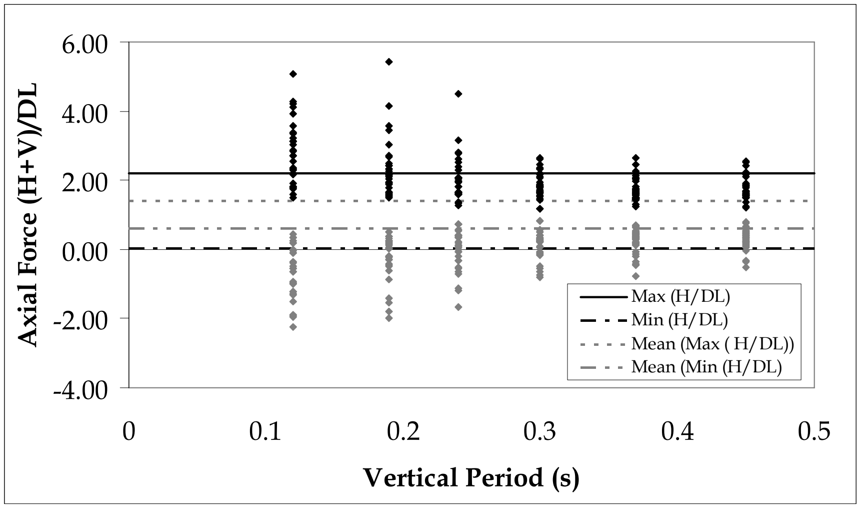

Figure 4 – Variation of column axial force demands with vertical period for unscaled ground motions

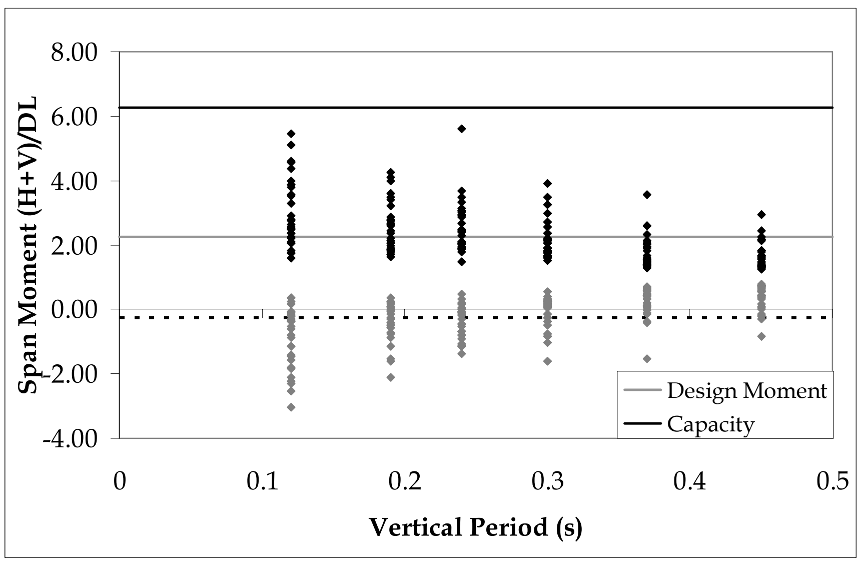

Figure 5 - Variation of moment demand at the mid-span with vertical period for unscaled ground motions

Effect of Vertical Acceleration on Column Moment and Shear

Figure 6 shows the ratio of the moment capacity of the column under the action of maximum and minimum axial forces recorded when the bridge is subjected to the ground motions including vertical effects to the moment capacity computed when the bridge is subjected to horizontal motions only. A similar plot is included to demonstrate the variation in the shear capacity of the column. As Figure 6 illustrates, both the moment and the shear capacity of the column can be reduced substantially since the axial load in the column decreases significantly when the vertical effects are included; in some cases the column may be subjected to significant axial tension. Another conclusion that can be drawn from Figure 6 is that the column moment capacity can also increase significantly. 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 end of the girder which is an undesirable situation that is supposed to be avoided by the requirements of SDC-2006 which utilizes a capacity design approach.

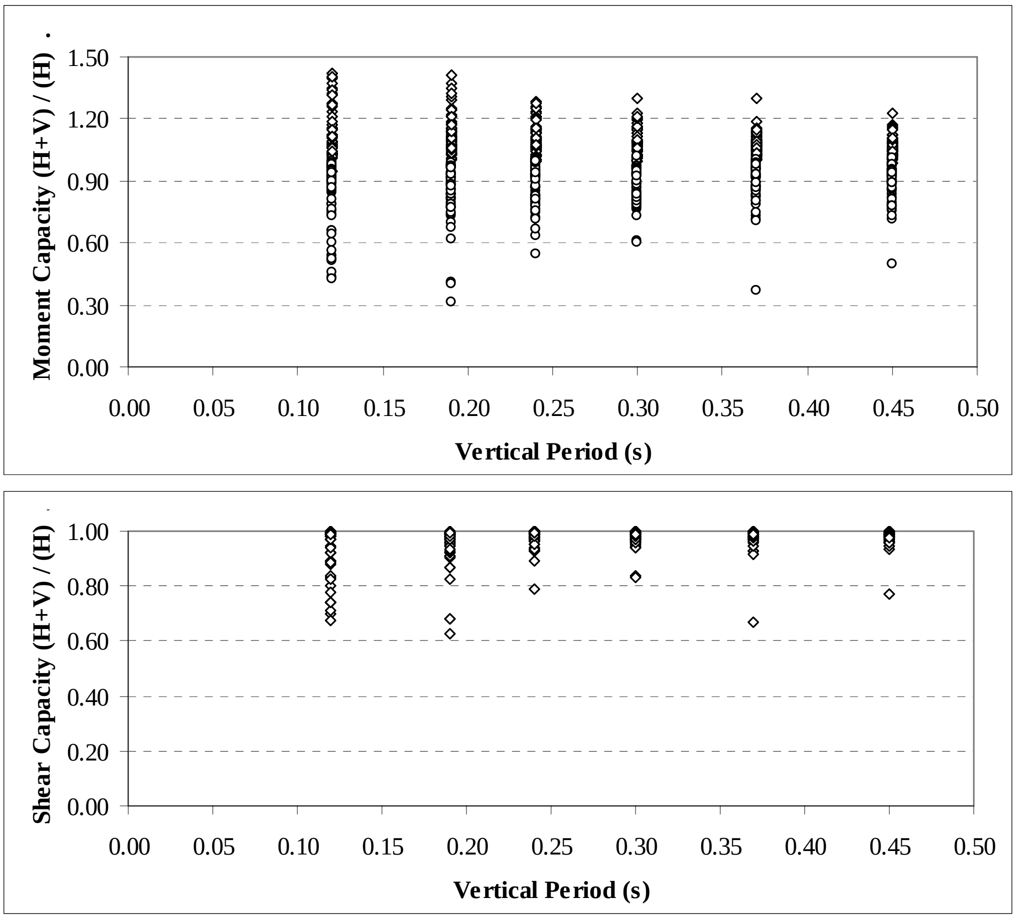

Figure 6 – Variation of column moment and shear capacity due to vertical effects

Concluding Remarks

This study was undertaken with the objective of assessing current provisions in SDC-2006 for incorporating vertical effects of ground motions in seismic evaluation and design of ordinary highway bridges. Results of the investigation suggest that highway over-crossings with relatively shorter vertical periods that are more vulnerable to vertical effects. Findings also indicate that vertical ground motions significantly affect (i) the axial force demand in columns which in turn have an effect on moment demands at the face of the bent cap and shear demands and shear capacity in the columns; and (ii) moment demands at the middle of the span. The former issue is not a matter of concern since the axial and shear capacity of the columns and the moment capacity of the girders at the face of the bent cap are generally adequate to resist these demands. On the issue of shear demand and shear capacity fluctuations, 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. The amplification of negative moments in the mid-span section is an issue that should be addressed in seismic design of ordinary short-span highway bridges. The current requirement that vertical ground motions be considered only for sites where the expected peak rock acceleration is at least 0.6g is not an adequate basis to assess the significance of vertical effects. Also, the design specification for the consideration of vertical effects by means of a static load equivalent to 25% of the dead load applied in the upward direction is an inappropriate means of considering vertical motions in strong earthquakes.

The final phase of work, not reported here, includes the development of a set of vertical spectra for use in design along with specific criteria based on system and seismological considerations which delineate the conditions that necessitate incorporation of vertical effects in the seismic design of ordinary highway bridges.

Acknowledgements

Funding for this study provided by the California Department of Transportation (Caltrans) under Contract No.59A0434 is gratefully acknowledged.

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