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CHARACTERISTICS OF VERTICAL SPECTRUM IN NEAR-FIELD REGION AND INVESTIGATION OF ITS EFFECTS ON THE DYNAMIC RESPONSE OF BRIDGES

Morteza ZAHEDI [1], Gholamreza GHODRATI AMIRI [2], Masoud AKBARZADEH[3]

ABSTRACT

Recently, the characteristics of horizontal ground motions in near field regions have been widely studied and it is time for the vertical excitations to be considered as well. Excluding the vertical component of motion in the analysis of structures, especially bridges, in current design practice was the major reason to investigate the vertical spectrum in near field and their effects on dynamic responses of bridges in this paper. The average and total average spectra for each earthquake are obtained in determined boundaries. In order to make a comparison between vertical and horizontal spectra, the same process is carried out to obtain the horizontal spectra. In addition, the ratio of vertical to horizontal spectra is computed and compared to the assumed value of 2/3 in some code provisions. Moreover, the vertical average spectra are compared to Uniform Building Code's vertical specification and Eurocode's vertical spectrum. Finally, the results of the response spectrum analyses of six different bridges subjected to vertical excitations are presented.

Keywords: vertical spectrum, near field, bridge, UBC97, Eurocode 8.

INTRODUCTION

In the last few decades, the characteristics of lateral earthquake ground excitation have been studied extensively. This is evidenced by the large body of available literature devoted to the characteristics of lateral excitation (e.g., Boore et al., 1997; Frankle et al., 2000). Recently, researchers drew attention to the significance of studying vertical ground motion and its damaging effects on structures. The importance of earthquake vertical motion to structures and the inadequacy of related studies especially in near-field regions have motivated researchers to further investigate the characteristics of vertical ground motion. On account of rarely including the effects of vertical accelerations in design of bridges for seismic loads, the objective of this study is to examine the characteristics of vertical spectrum and its effect on dynamic responses of bridges based on the available data in near-field regions. The significance of several earthquakes in recent researches was the basis of their selection in this study. Accordingly, the distance from fault was divided into six boundaries; <5, 5-10, 10-15, 15-20, 20-30 and 30-40 km from surface projection of fault rupture, and the recorded information of earthquakes was classified based on this category. Through the further steps of present study, because of the probability of soil type effects on characteristics of vertical component in near field regions, records with similar soil type (soil type C based on USGS classification (1997), Average shear wave velocity to a depth of 30m 180 to 360 m/s) were included in this investigation alone. It should be mentioned that the abundance of the data in soil type C was the only reason for choosing the mentioned soil type in this investigation.

[1] Assistant Professor, College of Civil Engineering, Iran University of Science & Technology, Narmak, Tehran 16846, IRAN
[2] Associate Professor, Center of Excellence for Fundamental Studies in Structural Engineering, College of Civil Engineering, Iran University of Science & Technology, Narmak, Tehran 16846, IRAN, Email: ghodrati@iust.ac.ir
[3] Graduate student, College of Civil Engineering, Iran University of Science & Technology, Narmak, Tehran 16846, IRAN, Email: makbarzadeh@civileng.iust.ac.ir

VERTICAL GROUND MOTION DATA

Obtained from the Pacific Earthquake Engineering Strong-motion Databases (http://peer.berkeley.edu/smact/index.html), all the employed earthquakes in this study is shown in Table 1. In the table, Records are presented based on their magnitude and distance to the source.

CHARACTERISTICS OF RECORDED VERTICAL MOTIONS
VARIATION OF PVA WITH DISTANCE

Peak Vertical Acceleration is one of the most commonly used parameters to characterize ground motion (Silva, 1997; Elgamal and He, 2004). In order to find the relationship between PVA and distance to fault, it is essential for the records to be presented with respect to distance from fault (Figure 1). Based on Figure 1, the closer the distance of station to fault, the higher level of PVA its record contains. With the help of SeismoSignal (2006) program, the time-history acceleration of these records was converted to response spectra with 5 percent damping. Consequently, the elastic response of structure was considered in this study alone.

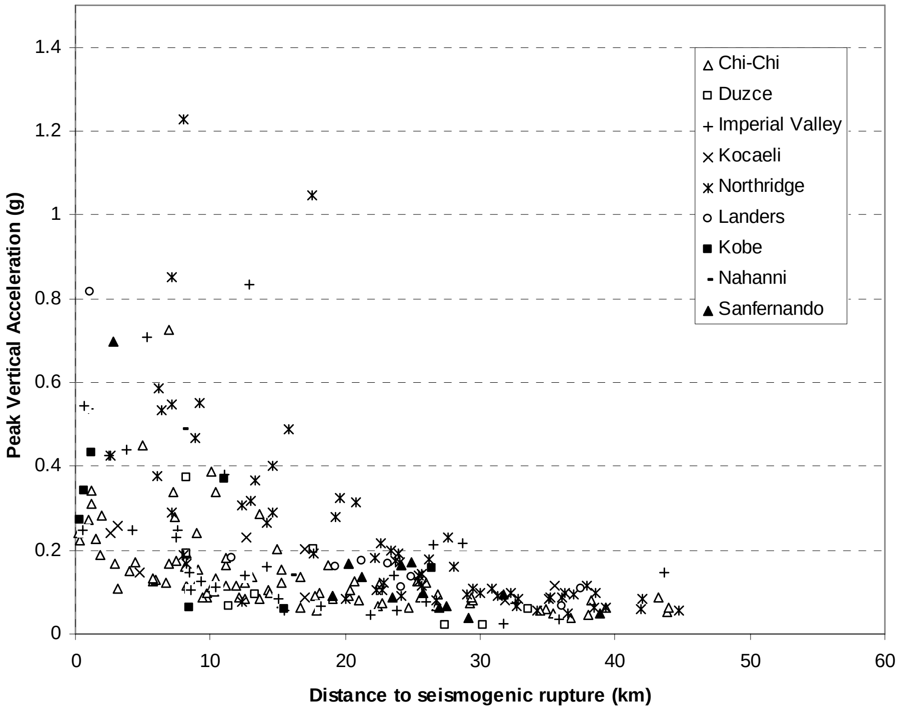

Figure 1. Variation of Peak Vertical Acceleration with respect to distance

AVERAGE AND TOTAL AVERAGE SPECTRUM THROUGH CLASSIFIED DISTANCES

In order to examine the content of records with respect to their shape, quantity and distance from fault, the average spectrum for each earthquake was separately and respectively computed in classified boundaries. Finally, the total average spectrum was calculated from average spectra obtained in previous section for all earthquakes in each boundary. The Juxtaposition of the total average spectra reveals the following observations; 1) the maximum content of energy in graphs occurs between 0.03s and 0.6 s (Figure 2). 2) With increase in distance from fault, the maximum level of acceleration in total average spectra diminishes. This process has been shown in Figure 3.

Table 1. Earthquakes from the Pacific Earthquake Engineering Research Center

Event Name	Magnitude	Number of Available Records, by closest distance from fault (km)						
		<5	5-10	10-15	15-20	20-30	30-40	0 – 40
Landers, USA 1992/06/28	7.4	1	-	1	1	5	2	10
Chi-Chi, Taiwan 1999/09/20	7.6	18	18	17	12	18	14	97
Duzçe, Turkey 1999/11/12	7.1	1	3	2	2	1	2	11
Imperial Valley, USA 1979/10/15	6.9	8	9	7	3	5	3	35
Kocaeli, Turkey 1999/08/17	7.4	3	-	1	2	-	2	8
Northridge, USA 1994/01/17	6.7	9	9	6	8	22	21	75
Kobe, Japan 1995/01/16	6.9	3	1	1	1	1	-	7
Nahanni, Canada 1985/12/23	6.9	2	-	-	1	-	-	3
Sanfernando, USA 1978/09/16	6.6	1	-	-	3	10	2	16

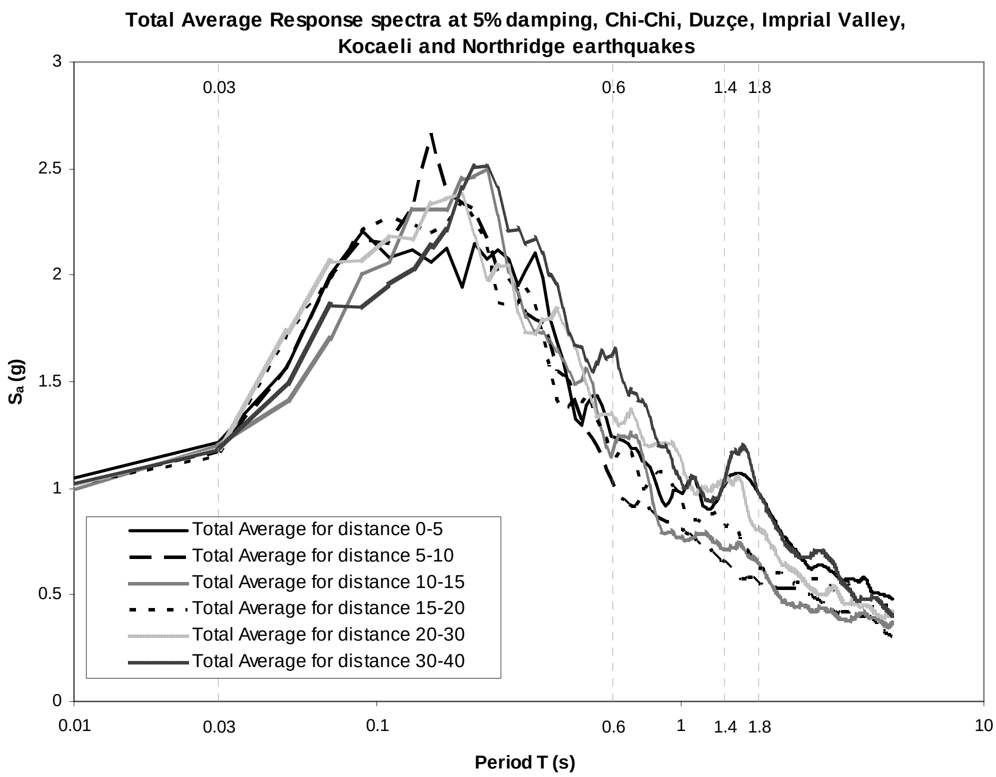

Figure 2. Maximum content of energy in vertical spectra

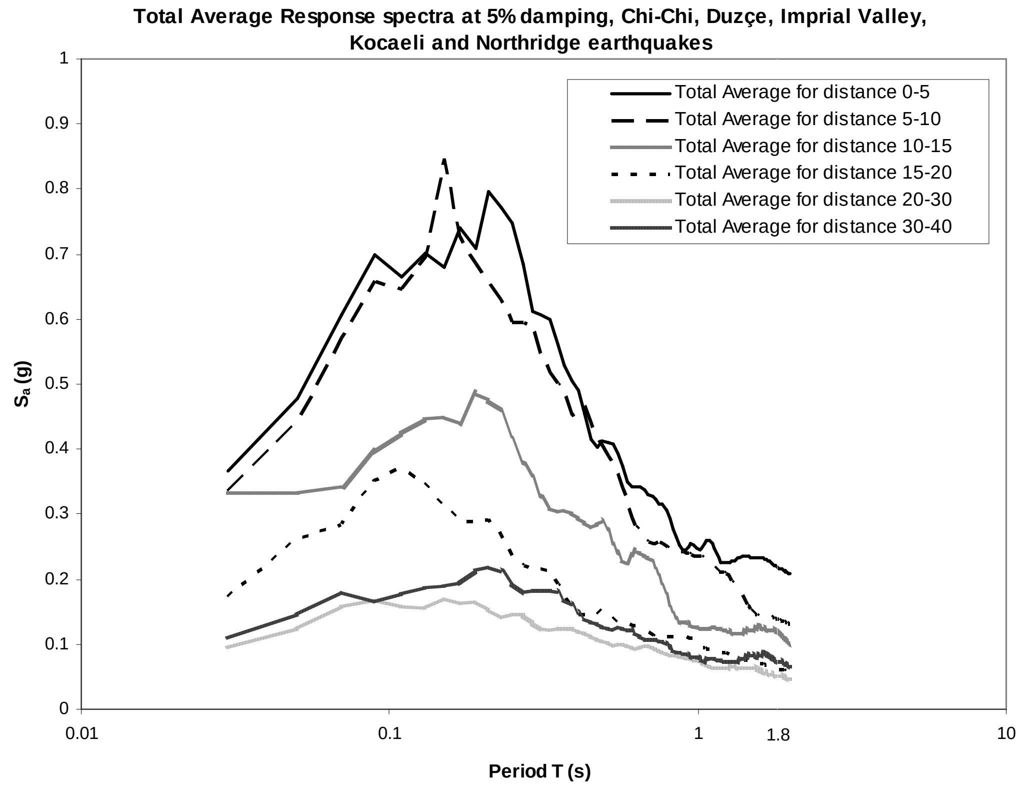

Figure 3. Level of acceleration in total average spectra in classified boundaries

In order to find the ratio of variation of spectra in near-field regions, it is necessary to compare the spectra in these regions with the ones obtained from far-field areas. As a result, because of the insignificance change between spectra obtained in 30 and 40 km from fault, this boundary was considered as far field. Consequently, the change in value of other total average spectra was evaluated in proportion to far field. Based on this comparison, for the first time, the average value of the acceleration-constant domain (predominant period, 0.05 to 0.4 s) of each spectrum was compared to the far-field spectrum. Subsequently, the average of entire values of each spectrum (0 to 5 s) was appraised concerning far field average value. (Table 2)

Table 2. Ratio of average spectra to far field

Spectrum	0-5 km	5-10 km	10-15 km	15-20 km	20-30 km
30-40 km (0.05 to 0.4 s)	4.49	3.92	2.42	1.59	1.14
30-40 km (0 to 5 s)	3.49	2.82	1.96	1.34	1.07

THE RATIO OF VERTICAL TO HORIZONTAL RESPONSE SPECTRA

The ratio of vertical to horizontal (V/H) response spectra has been found to be strongly dependent on period and site distance from seismic source. At high frequencies the V/H spectra ratio significantly exceeds the commonly assumed ratio of 2/3 (Newmark et al., 1973) for site distances up to 40 km. the closer the site to the source, the higher the exceedance. At long periods, V/H ratio is shown to be lower (Bozorgnia and Niazi, 1993; Bozorgnia et al., 1995; Ambraseys and Simpson, 1996; Ambraseys and Douglas, 2000). Thus, the factor of 2/3 underestimates the effects of vertical motion at short periods and overestimates the effects at long periods. (Figure 4)

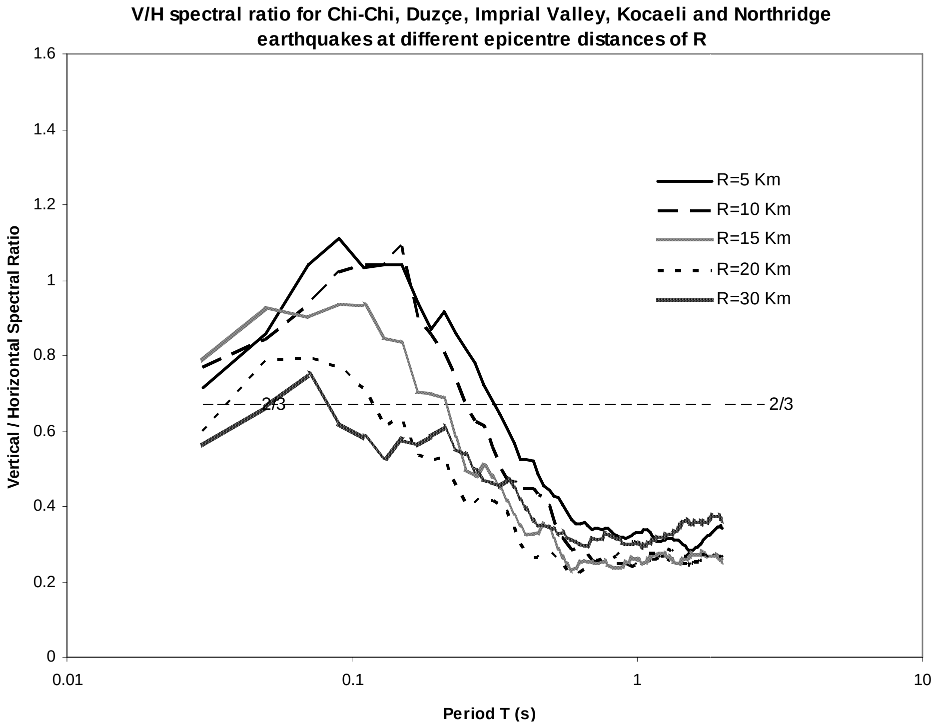

Figure 4. V/H spectral ratio for Chi-Chi, Duzçe, Imperial Valley, Kocaeli and Northridge

COMPARISON OF VERTICAL AND HORIZONTAL AVERAGE SPECTRA

Subsequent to computing the vertical average spectra, it is the time for the average horizontal spectra to be obtained from available data. Observations from both obtained average horizontal and vertical spectra would lead to the following consequences; 1) maximum acceleration occurs at incipient stage (very short periods, 0.03 to 0.6 s) of the vertical spectra in comparison to the horizontal in which the maximum acceleration happens at periods between 0.1 and 2.5 s (Figure 5). 2) Maximum content of energy boundary in vertical spectra is much shorter than the boundary in horizontal spectra. It means the velocity spectra (commonly assumed as damage potential (Foutch, 1997) deviated from horizontal is much longer in time than the one obtained from vertical spectra, and, consequently, much more destructive than the vertical velocity spectra.

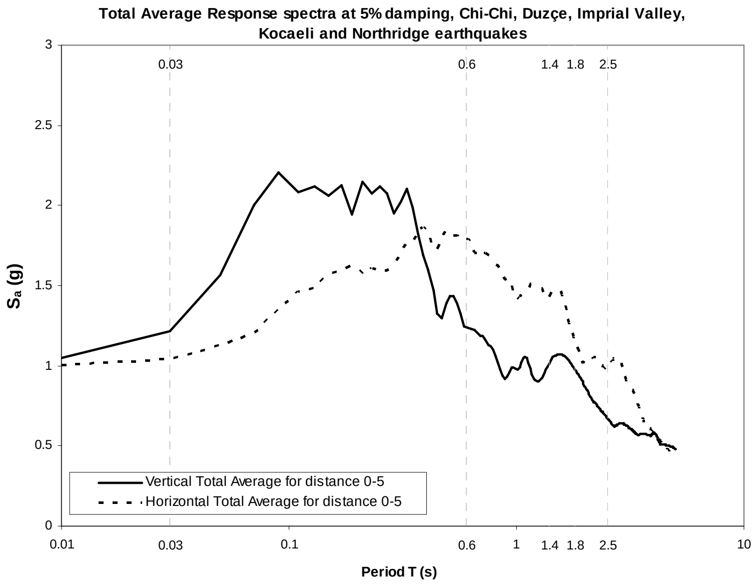

Figure 5. Comparison of vertical and horizontal average spectrum

COMPARISON OF TOTAL AVERGAE SPECTRA, UBC 1997 SPECIFICATION AND THE VERTICAL SPECTRUM OF EUROPEAN CODE OF PARACTICE WITHIN NEAR-FIELD REGION

In order to specify the vertical effects of earthquakes within near-field regions, UBC (1997) and Eurocode have provided some recommendations. There is no any defined vertical spectral shape in current design codes and when the vertical component is included, it is normally specified as a spectrum based on the horizontal spectrum. To consider the 2/3 of the amplitude of horizontal spectrum after applying the near-field coefficients provided in version 1997 (Kircher, 2003) is the recommendation of UBC to specify the vertical spectrum. Besides, Eurocode (2001) have provided a vertical spectrum separate from horizontal spectra. Only by comparing these spectra, the consistency and compatibility of them can evidently be represented. Therefore, at the outset, the recommended UBC spectra (soil type S_D compatible with the obtained data) for distances less than 2 km, 5 and 10 km from fault were respectively depicted in a diagram versus average vertical spectra obtained in this study (Figures 6 to 8). Thereafter, Eurocode's vertical spectra compared to the average spectra in another diagram. The consequences of this comparison portend of incongruity between UBC and average spectra. This inconsistency can be interpreted by the fact that the recommended vertical spectrum in UBC is fundamentally relied on the basis of horizontal spectrum which is quite different with the essence of vertical spectrum (predominant period in vertical spectrum takes place earlier than horizontal spectrum). On the other hand, despite the time coincidence of predominant periods in Eurocode vertical spectrum and the average, there is a considerable difference between the levels of acceleration within near-field regions, so that the level of acceleration in average spectrum is significantly higher than the level in Eurocode's spectrum (Figure 9).

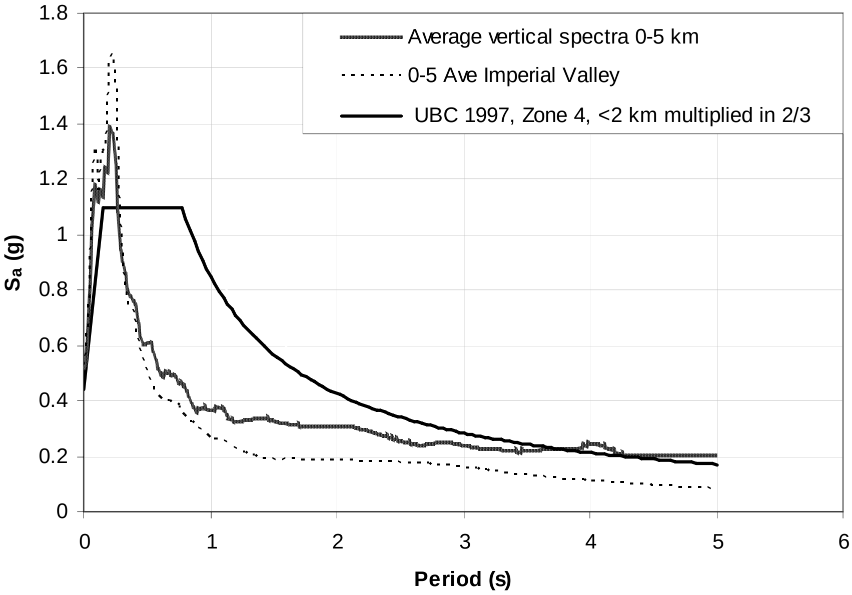

Figure 6. 2/3 of UBC's horizontal spectrum (< 2 km) versus vertical average spectrum in < 5 km

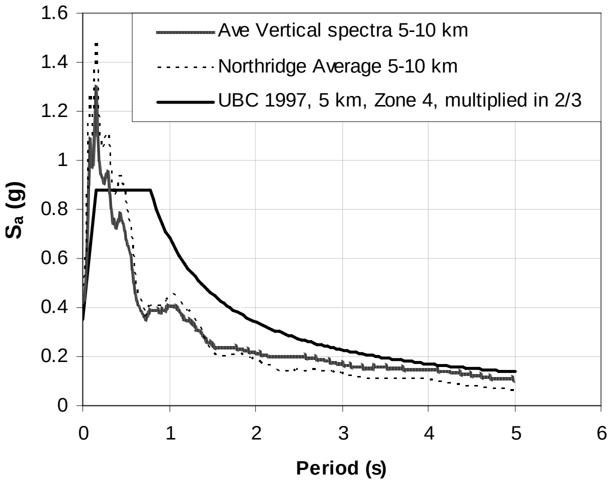

Figure 7. 2/3 of UBC's horizontal spectrum (5 km) versus vertical average spectrum in 5-10 km

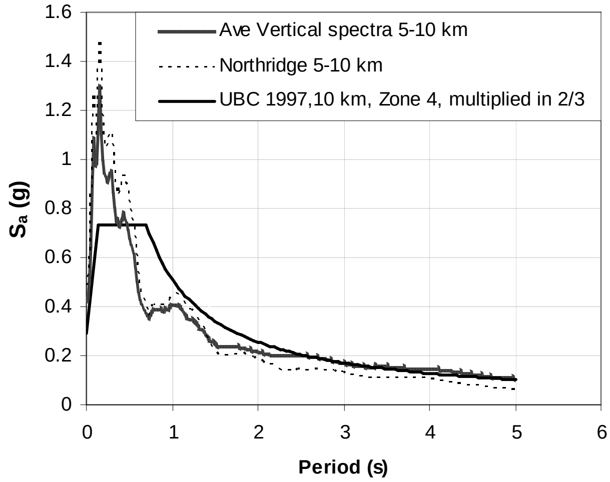

Figure 8. 2/3 of UBC's horizontal spectrum (10 km) versus vertical average spectrum in 5-10 km

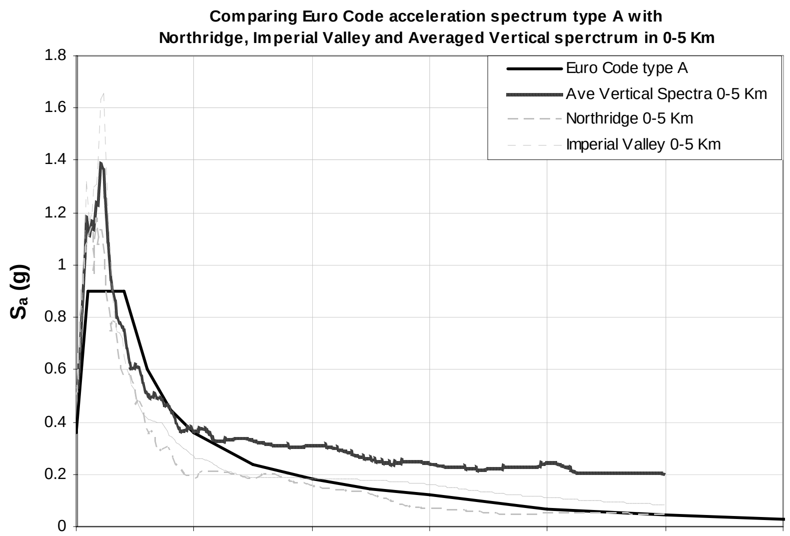

Figure 9. Eurocode's vertical spectrum versus vertical average spectrum in < 5 km

INVESTIGATION OF VERTICAL MOTION EFFECTS ON RESPONSE OF BRIDGES IN NEAR-FIELD REGION

INTRODUCTION

Another objective of this study is to determine conditions in which the vertical component of seismic ground motion is critical in determining the demands placed on key elements of typical highway structures. In current design practice, the vertical component of motion is not usually included in the analysis of bridges, though the Uniform Building Code (1997) specifies increased multipliers on dead loads that are intended to approximate its effects. These multipliers are 0.9DL and 1.2DL for non-isolated buildings, and 0.8DL and 1.2DL for isolated buildings. In recent years, there has been much effort to show that the vertical-to-horizontal ratio underestimates the strength of the vertical component in the near fault region and at short periods. In present study the research approach is to analyze a representative group of bridges with a various range of natural frequencies subjected to vertical component of earthquake. The results of the dynamic analyses were compared and conclusions were drawn.

MODELS

The scope of the study involves linear analysis of finite element models (Priestley et al., 1996) of six typical highway bridges using a broad range of input spectra. For each bridge, response spectrum analysis was performed, and results compared. Descriptions of bridge number 1 through 6 are given in Table 3. The description of each bridge includes the overall physical dimension and structural materials.

Table 3. Description and properties of Bridges 1 to 6

Bridge No.	Description	Super structure type	Span length (m)	Deck depth (m)	Deck width (m)	Moment of inertia about 3 axis (m^3)	Cross section area (m^2)	T (s)
Bridge 1	Single span	AASHTO Precast Concrete Girder	21.34	1.37	13.41	1.1626	5.67	0.201
Bridge 2	Three-span Continuous	CIP concrete	36.58 30.48	1.83	13.12	3.43	6.635	0.303
Bridge 3	Three-span Continuous	CIP concrete Box	22.4 44.8	2.56	8.8	1.7807	3.867	0.386
Bridge 4	Two-span continuous	CIP concrete Box	44.34 31.54	1.73	22.49	5.7	11.78	0.452
Bridge 5	Single span	Steel Girder	54	3.23	11.8	0.9953	0.623	0.386
Bridge 6	Single span	Steel Box	72.2	3.73	11.8	15.2696	6.13	0.755

RESPONSE SPECTRUM ANALYSIS

Response spectrum analyses were performed on each of the six bridges using a wide range of input spectra with soil type C (S_D in UBC). Six average spectra obtained through previous sections were used to cover the range of distances <5, 10, 15, 20, 30 and 40 km. Moreover, the two-thirds of horizontal spectrum of UBC and the vertical spectrum of Eurocode were also applied to the bridges.

All of the linear dynamic analyses were performed using the analysis program SAP2000. The results of response spectrum analyses on the six bridges are presented in Table 4. It shows vertical bending moment quantities in the deck at the mid span and in each bridge. In multi-span bridges, responses were monitored at selective piers and spans. The format for the final presentation of results was measured by the ratio of the response of the seismic input to the dead load response. Figure 10 shows curves for the ratio of the response of the average spectra input over the dead load only. Subsequently, Figure 11 shows the ratio of the response of the UBC, Erocode, Imperial Valley and Northridge spectra input over the dead load as well.

CONCLUSIONS

CHARACTERISTICS OF VERTICAL GROUND MOTION SPECTRA

Brought together from stations through the distances less than 40 km from source, the vertical motion data were classified based on their distances and soil type in this study. In order to prevent from affection of soil type on characteristics of vertical component in near field region, records with soil type C were used in this investigation alone. The average spectrum for each earthquake was separately computed in classified boundaries. The total average spectrum was subsequently calculated from average spectra obtained in previous section for all earthquakes in each boundary. The comparison of the total average spectra can reveal the following consequences:

1. With increasing the distance to the fault, Peak Vertical Acceleration significantly diminishes.
2. The maximum content of energy in vertical motions occurs in high-frequency domains or short periods between 0.03s and 0.6 s. while, this domain begins from 0.1 to 2.5 s in horizontal motion.
3. In near field regions, the ratio of vertical spectrum to the horizontal is more than the two-thirds of the horizontal recommended in some code provisions to specify the vertical spectrum. This ratio for the distances less than 5 km to the source can get the value more than unit and for the distances more than 15 km is much less than 2/3. It means that to consider the two-thirds of the horizontal spectra's domain as the vertical spectra seems unreasonable in near field regions.
4. The ratio of variation for the near-field vertical spectrum to the far field can approximately reach to the value 4 in distances less than 5 km to the fault.
5. The comparison of total average vertical spectrum in < 5 km and the two-thirds of the UBC 97 horizontal spectra with the same distance shows that the average spectrum contains a very short acceleration-constant domain. In addition, the average spectrum has a higher level of dominant period with respect to UBC.
6. The comparison of total average vertical spectrum in < 5 km and the Eurocode's vertical spectrum shows that except the incongruity in their PVA, they both have the similar acceleration-constant domain.

THE EFFECTS OF VERTICAL MOTION ON THE DYNAMIC RESPONSE OF BRIDGES

In this study, six bridges with dissimilar section properties and miscellaneous natural period from 0.2 to 0.75 s were used to monitor the effects of vertical motions. The response spectrum analyses were performed on each of the six bridges using a wide range of input spectra and the two-thirds of horizontal spectrum of UBC and the vertical spectrum of Eurocode. These analyses were performed using the analysis program SAP2000. The results of the analyses are presented as the following consequences:

1. The closer the natural period of the deck to the predominant period of the spectrum, the more the influence of the vertical motion on deck.
2. The ratio of maximum deck moment caused by average spectra to the moment caused by dead load is more than unit in distances less than 15 km to the source.

3. The mentioned ratio can reach to 3.5 for bridge No. 4. This sudden increase in deck moment stems from the fact that the bridge has asymmetrical spans and wider deck (two times) in comparison to the others that could, in turn, enhance the stiffness (rigidity) with respect to span, and consequently decrease the natural period, and intensify the effect of vertical motion.
4. Using the two-thirds of the UBC horizontal spectrum in analyses would cause increase in responses' quantities in bridges with the natural period more than 0.75 s. this increase is related to the fact that the acceleration-constant domain in this spectra is longer than the real vertical spectra and as a result can affect the structures with longer natural period.

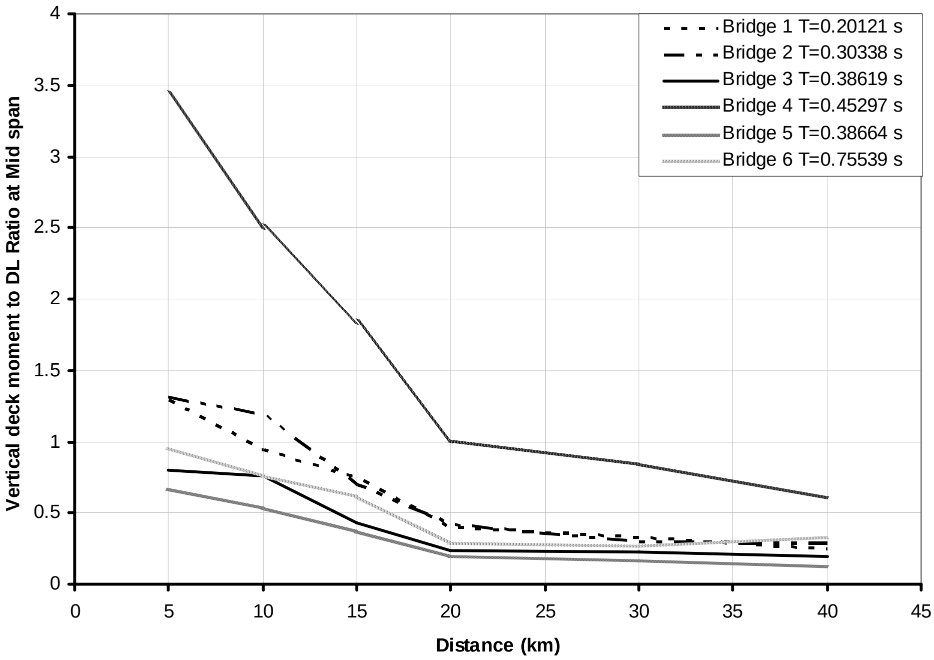

Figure 10. The ratio of maximum vertical deck moment caused by vertical average spectra to the moment caused by DL

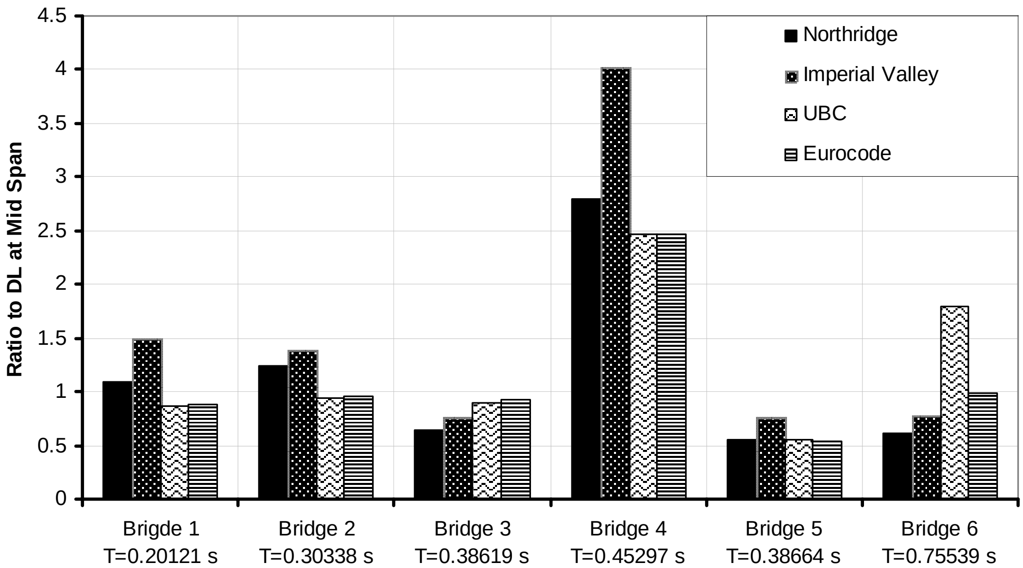

Figure 11. The ratio of responses caused by UBC, Eurocode, Northridge and Imperial valley average spectra to the responses caused by Dead Load

Table 4. Results of response spectrum analyses and vertical moment at mid span and piers

	Bridge1		Bridge2		Bridge3		Bridge4			Bridge5		Bridge6	
	Mid	Pier	Mid	Pier	Mid	Pier	Mid		Pier	Mid	Pier	Mid	Pier
							Short Span	Long Span	-				
T(s)	0.2012		0.3034		0.3862		0.2155	0.4530	-	0.3866		0.7554	
Dead (Ton.m)	774.86	-	1060.30	1800.48	1022.65	1308.44	1192.65	4271.02	5226.73	3011.01	-	6238.03	-
0-5 km	1001.24	-	1387.18	1974.35	819.86	768.10	4103.16	2118.45	3487.58	2365.47	-	5933.98	-
5-10 km	732.91	-	1262.56	1796.91	777.95	714.86	2979.16	2994.11	2776.06	2265.03	-	4704.83	-
10-15 km	577.04	-	740.73	1054.50	440.48	423.99	2193.19	1681.83	1914.85	1256.22	-	3856.92	-
15-20 km	306.22	-	440.77	627.47	244.34	278.07	1201.39	832.20	1042.85	627.12	-	1765.24	-
20-30 km	252.88	-	320.61	456.35	225.72	208.25	999.63	697.36	858.11	650.29	-	1667.63	-
30-40 km	187.67	-	300.39	427.57	203.31	186.95	726.10	684.33	666.10	589.43	-	2027.98	-
Northridge Average	846.15	-	1311.34	1866.48	651.45	645.69	3335.6	2446.63	2892.67	1822.93	-	3862.96	-
Imperial Valley Average	1160.22	-	1476.62	2101.62	786.01	750.09	4801.66	2707.29	3985.40	2247.88	-	4849.88	-
UBC 1997	669.43	-	995.51	1416.82	917.78	799.71	2946.65	3446.79	2876.80	2734.49	-	11200.00	-
Eurocode	684.66	-	1018.17	1449.12	943.75	833.40	2945.07	2867.30	2818.35	2796.90	-	6164.93	-

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