Journal of Earthquake Engineering, Vol. 8, No. 2 (2004) 175–207

Imperial College Press
www.icpress.co.uk

THE VERTICAL-TO-HORIZONTAL RESPONSE SPECTRAL RATIO AND TENTATIVE PROCEDURES FOR DEVELOPING SIMPLIFIED V/H AND VERTICAL DESIGN SPECTRA

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Received 18 April 2003
Revised 17 July 2003
Accepted 8 August 2003

This paper presents the results of a study on the engineering characteristics of vertical ground motion. A ground-motion model for the vertical-to-horizontal ratio (V/H) of peak ground acceleration and 5%-damped acceleration response spectra was derived by using a database of 443 near-source accelerograms recorded from 36 worldwide earthquakes of M_W 4.7-7.7. The recordings were all located within 60 km of the seismogenic rupture zone of worldwide shallow crustal earthquakes in active tectonic regions. We found no bias in the V/H estimates from independent analyses of vertical and horizontal response spectra. We also found V/H to be a strong function of natural period, local site conditions, and source-to-site distance; and a relatively weaker function of magnitude, faulting mechanism, and sediment depth. V/H exhibits its greatest differences at long periods on firm rock (NEHRP site category BC), where it has relatively low amplitudes, and at short periods on firm soil (NEHRP site category D), where it has amplitudes that approach 1.8 at large magnitudes and short distances. We propose a tentative simplified model for estimating V/H spectra and two relatively simple procedures for developing a preliminary vertical design spectrum that could be used for practical engineering applications where site-specific spectra (e.g. from a seismic hazard analysis) are not available. Extensive vetting from the seismological and engineering communities will be needed before such simplified spectra are officially accepted and adopted in codified procedures in the United States.

Keywords: Vertical ground motion; vertical design spectrum; vertical component; attenuation.

1. Introduction

The characteristics of vertical ground motion have been examined by a number of investigators. Niazi and Bozorgnia [1989, 1990, 1991, 1992] analysed several hundred horizontal and vertical response spectra from several earthquakes recorded by the SMART-1 strong-motion array in Taiwan to study the effect of magnitude and distance on the vertical-to-horizontal ratio (V/H) of strong-motion response spectra. In two follow-up studies, Bozorgnia and Niazi [1993] examined horizontal and vertical response spectra on soil and rock sites from the 1989 Loma Prieta, California, earthquake, and Bozorgnia *et al.* [1995, 1996] analysed horizontal and vertical response spectra recorded on soil sites during the 1994 Northridge, California, earthquake. This series of studies revealed for the first time that V/H is very sensitive to the spectral period and the distance from the fault, and that it has a distinct peak at short periods that exceeds a value of 2/3 in the near-source region. Bozorgnia *et al.* [1995] also suggested that these characteristics are universal.

Watabe *et al.* [1990], using strong-motion recordings from the United States, found a systematic dependence between the amplitudes of the vertical and horizontal components of ground motion and recommended that it should be possible to develop simple rules for estimating a vertical response spectrum from a horizontal spectrum. Silva [1997], using an extensive strong-motion database, showed the effects of magnitude, distance, local site conditions, and tectonic environment on the difference in the shapes of the horizontal and vertical components of acceleration response spectra.

All of the previously mentioned studies found V/H to be a strong function of period with short periods exhibiting higher ratios than long periods, consistent with observed differences in spectral shapes between the vertical and horizontal components of ground motion. These differences cause V/H to have a maximum at periods of 0.05–0.1 sec and a minimum at periods of 0.4–0.8 sec. At longer periods, V/H slowly increases with period. These investigators also found that V/H is less dependent on magnitude, distance, and local site conditions than either the horizontal or the vertical components. Those studies that looked at near-source recordings [Niazi and Bozorgnia 1991, 1992; Bozorgnia and Niazi 1993; Bozorgnia *et al.*, 1995] found that V/H generally exceeds unity and can approach values as high as 1.8 at short periods and short distances and that this ratio is generally higher on soil than on rock. At long periods, these studies found that V/H is generally less than 1/2, especially near the trough in the V/H spectrum, and is generally higher on rock than on soil.

Within the last decade, several investigators have developed attenuation relations for the horizontal and vertical components of strong ground motion that can be used to evaluate V/H. Attenuation relations for individual earthquakes were developed by Bozorgnia and Niazi [1993] for the 1989 Loma Prieta earthquake and by Bozorgnia *et al.* [1995] for the 1994 Northridge earthquake. Regional attenuation relations were developed by Abrahamson and Litehiser [1989], Trifunac and Lee [1989, 1992], Sadigh *et al.* [1993], Abrahamson and Silva [1997], and Campbell [1997] for western North America; by Niazi and Bozorgnia [1991, 1992] for Taiwan; by Ambraseys [1995] for Europe; by Sabetta and Pugliese [1996] for Italy; and by Ansary and Yamazaki [1998] for Japan. More recently, Campbell and Bozorgnia [2003] developed a mutually consistent set of attenuation relations for both vertical and horizontal components. Predicted peak acceleration and response spectra from these attenuation relations generally confirm the empirical observations of V/H discussed above.

Bureau [1981] and Campbell [1982] recognised that the behaviour of V/H in the near-source region of large earthquakes was significantly different than that predicted at smaller magnitudes and larger distances. Based on these studies, Campbell [1985] suggested that the standard engineering rule-of-thumb of assuming V/H = 2/3 when estimating vertical ground motion for design should be re-evaluated. Many of the papers mentioned previously have come to similar conclusions.

Several investigators have offered seismological explanations for the observed dependence of V/H on distance and local site conditions. Silva [1997] contends that for short distances at soil sites the large contrast in shear-wave (S-wave) velocity at the rock/soil interface causes incident inclined SV-waves to be converted to P-waves (compressional waves) as they propagate through this boundary. These converted P-waves are subsequently amplified and refracted into a more vertical angle of incidence by a shallow P-wave velocity gradient. Because earthquake sources emit much larger S-wave amplitudes than P-wave amplitudes (by about a factor of 5), this has the effect of significantly increasing the amplitude of the vertical component of ground motion over that caused by direct P-waves only. Silva explains that this effect is diminished at near-source rock sites because of the smaller S-wave velocity impedance and the smaller S-wave and P-wave velocity gradients, which result in less S-to-P converted energy and a subsequently smaller value of V/H. According to Kawase and Aki [1990] and Silva [1997], at larger distances the SV-wave is beyond its critical angle of incidence and does not propagate to the surface very effectively. Therefore, at large distances, the lower-amplitude direct P-waves will dominate the vertical component of ground motion causing relatively smaller values of V/H.

Amirbekian and Bolt [1998] examined the differences between the spectral characteristics of near-source vertical and horizontal ground motions from a seismological point of view. They concluded that the high-amplitude, high-frequency vertical accelerations that are observed on near-source accelerograms are most likely generated by the S-to-P conversion within the transition zone between the underlying bedrock and the overlying softer sedimentary layers, consistent with Silva's hypothesis.

Based on an analysis of five significant earthquakes in California, Beresnev *et al.* [2002] found that SV-waves dominate vertical ground motions at periods longer than about 0.1 second; and at shorter periods, P-waves may become a significant contributor to these ground motions.

Even with all of the evidence to the contrary, some engineering guidelines in the United States still recommend the use of a constant value of 2/3 for V/H over the entire period range of engineering interest [e.g. see FEMA-356, 2000]. It is interesting to note that the US Atomic Energy Commission [1973], in Regulatory Guide 1.60 for developing design response spectra for nuclear power plants, recognised long ago that V/H could approach unity at short periods, but the United States engineering community has been reluctant to adopt new guidelines because of the conception that vertical ground motion is not important to design. A decade ago, the Commission of the European Communities [1993] allowed V/H to vary with period in the *European Building Code* (EC8), but mainly as a means of reducing V/H from 2/3 at short periods to 1/2 at long periods. The 1997 *Uniform Building Code* (UBC-97) recognised the fact that V/H is dependent on source-to-site distance at relatively short distances and recommended using site-specific vertical response spectra for sites located close to active faults. However, neither the UBC-97 nor the 2000 *International Building Code* (IBC-2000) offers guidance on how a general vertical design spectrum should be developed, especially in the near-source region. The American Petroleum Institute, in *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms* (RP 2A-WSD), recommends using V/H = 1/2, but the main focus is on long-period structures.

Some recent studies have focused on the shape of the vertical design spectrum. For example, a design spectral shape for the vertical ground motion has been proposed by Elnashai [1997] and Elnashai and Papazoglou [1997]. They proposed a vertical design acceleration spectrum consisting of a flat portion at short periods (0.05–0.15 sec) and a decaying spectral acceleration portion for periods longer than 0.15 sec.

As a step towards providing some additional guidance on the selection of an appropriate value of V/H to use in engineering practice, we initiated a study to better understand the scaling characteristics of this ratio by developing a mutually consistent set of near-source attenuation relations for the horizontal and vertical components of strong ground motion [Bozorgnia *et al.*, 1999; Campbell and Bozorgnia, 2000a, 2000b]. The final versions of the attenuation relations are the subject of another paper [Campbell and Bozorgnia, 2003]. In the present paper, we first provide a brief overview of our latest horizontal and vertical attenuation relations, followed by an evaluation and validation of the implied V/H ground-motion model. We then propose simplified V/H spectra for practical engineering applications. Finally, we present a relatively simple procedure for generating a tentative vertical design spectrum.

2. Strong-Motion Database

We used a comprehensive database of near-source worldwide accelerograms recorded between 1957 and 1998 for our analysis. A summary of the database is given below. More details can be found in Campbell and Bozorgnia [2003]. The database was expanded and updated from that originally used by Campbell and Bozorgnia [1994] and Campbell [1997, 2000, 2001]. The list of earthquakes along with the number of recordings used in the study are provided in Table 1.

The strong-motion parameters included in the analysis were peak ground acceleration and 5%-damped pseudo-acceleration response spectra (PSA) at natural periods ranging from 0.05 to 4.0 sec. We used the geometric mean of the two

Table 1. Database of strong-motion recordings.

Earthquake	Location	Year	M_W	Faulting Mechanism	No. of Recordings	
					Horizontal	Vertical
Daly City	California	1957	5.3	Reverse Oblique	1	1
Parkfield	California	1966	6.1	Strike Slip	4	4
Koyna	India	1967	6.3	Strike Slip	1	1
Lytle Creek	California	1970	5.3	Reverse	4	4
San Fernando	California	1971	6.6	Reverse	9	9
Sitka	Alaska	1972	7.7	Strike Slip	1	1
Stone Canyon	California	1972	4.7	Strike Slip	2	2
Managua	Nicaragua	1972	6.2	Strike Slip	1	1
Point Magu	California	1973	5.6	Reverse	0	0
Hollister	California	1974	5.1	Strike Slip	1	1
Oroville	California	1975	6.0	Normal	1	1
Kalapana	Hawaii	1975	7.1	Thrust	0	0
Gazli	Uzbekistan	1976	6.8	Reverse	1	1
Caldiran	Turkey	1976	7.3	Strike Slip	1	1
Mesa de Andrade	Mexico	1976	5.6	Strike Slip	0	0
Santa Barbara	California	1978	6.0	Thrust	1	1
Tabas	Iran	1978	7.4	Thrust	3	3
Bishop	California	1978	5.8	Strike Slip	0	0
Malibu	California	1979	5.0	Reverse	0	0
St. Elias	Alaska	1979	7.6	Thrust	1	0
Coyote Lake	California	1979	5.8	Strike Slip	9	9
Imperial Valley	California	1979	6.5	Strike Slip	37	37
Livermore	California	1980	5.8	Strike Slip	0	0
Livermore Aftershock	California	1980	5.4	Strike Slip	0	0
Westmorland	California	1981	6.0	Strike Slip	0	0
Coalinga	California	1983	6.4	Thrust	46	46
Morgan Hill	California	1984	6.2	Strike Slip	24	24
Nahanni	Canada	1985	6.8	Thrust	3	2
North Palm Springs	California	1986	6.1	Strike Slip	12	12
Chalfant Valley	California	1986	6.3	Strike Slip	0	0
Whittier Narrows	California	1987	6.0	Thrust	91	90
Whittier Narrows Aftershock	California	1987	5.3	Reverse Oblique	9	9
Elmore Ranch	California	1987	6.2	Strike Slip	1	1
Superstition Hills	California	1987	6.6	Strike Slip	2	2
Spitak	Armenia	1988	6.8	Reverse Oblique	1	0
Pasadena	California	1988	5.0	Strike Slip	0	0
Loma Prieta	California	1989	6.9	Reverse Oblique	29	29
Malibu	California	1989	5.0	Thrust	0	0
Manjil	Iran	1990	7.4	Strike Slip	3	3
Upland	California	1990	5.6	Strike Slip	2	2
Sierra Madre	California	1991	5.6	Reverse	4	4
Landers	California	1992	7.3	Strike Slip	8	8
Big Bear	California	1992	6.5	Strike Slip	1	1
Joshua Tree	California	1992	6.2	Strike Slip	0	0
Petrolia	California	1992	7.0	Thrust	5	5
Petrolia Aftershock	California	1992	7.0	Strike Slip	0	0
Erzincan	Turkey	1992	6.7	Strike Slip	1	1
Northridge	California	1994	6.7	Thrust	108	108
Kobe	Japan	1995	6.9	Strike Slip	15	15

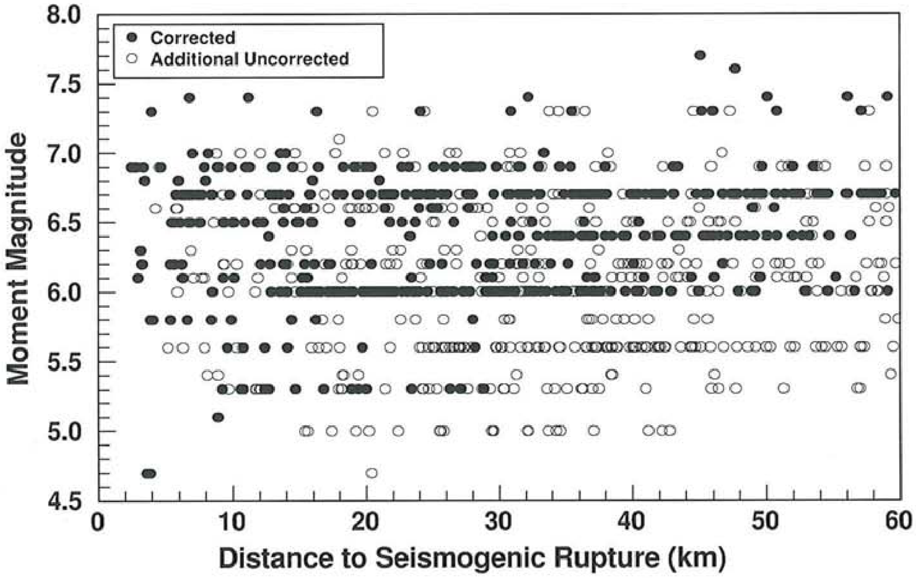

Fig. 1. Distribution of recordings used to derive the V/H ground-motion model developed in this study. Solid circles represent recordings from the Corrected database (PGA and 5%-damped PSA) and open circles represent additional recordings from the Uncorrected database (PGA only). Only results from the Corrected database are evaluated. See Campbell and Bozorgnia [2003] for a description of Uncorrected and Corrected databases.

horizontal components of PGA and PSA to define what we refer to as the average horizontal component of ground motion. The database consisted of 443 average horizontal components from 36 worldwide earthquakes and 439 vertical components from 34 worldwide earthquakes with moment magnitudes (M_W) of 4.7–7.7. The distribution of the recordings with respect to magnitude and distance is shown in Fig. 1 and their distribution by faulting mechanism and local site conditions is given in Table 2.

Table 2. Distribution of recordings by faulting mechanism and local site conditions.

	No. of Recordings		No. of Events		Minimum Magnitude		Maximum Magnitude	
Category	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.
			Faulting Mechanism					
Strike slip faulting	127	127	20	20	4.7	4.7	7.7	7.7
Reverse faulting	58	57	8	7	5.3	5.3	6.9	6.9
Thrust faulting	258	255	8	7	6.0	6.0	7.6	7.4
TOTAL	443	439	36	34	–	–	–	–
			Local Soil Conditions					
Firm soil	241	240	30	29	4.7	4.7	7.4	7.4
Very firm soil	84	83	14	14	4.7	4.7	7.0	7.0
Soft rock	63	62	9	8	5.3	5.3	7.6	6.9
Firm rock	55	54	21	21	5.3	5.3	7.7	7.7
TOTAL	443	439	–	–	–	–	–	–

We uniformly defined the size of an earthquake in terms of M_W and defined the source-to-site distance in terms of r_{seis}, the shortest distance between the recording site and the zone of the seismogenic energy release on the causative fault, referred to as the distance to seismogenic rupture. We restricted recording sites to $r_{\text{seis}} \leq$ 60 km to avoid complications related to the arrival of multiple reflections from the lower crust, as was observed during the 1989 Loma Prieta earthquake [Somerville and Yoshimura, 1990; Campbell, 1991, 1998]. We believe that this distance range includes most ground-motion amplitudes of engineering interest.

The faulting mechanism, also known as the style of faulting, was classified into one of three categories defined as strike slip, reverse, or thrust. The classification was based on rake angle, which is a quantitative description of the direction of slip on the fault. The strike-slip category includes earthquakes on vertical or near-vertical faults with rake angles within $\pm 22.5°$ of the strike of the fault. The reverse and thrust categories include steeply and shallow ($\leq 45°$) dipping earthquakes with rake angles between 22.5° and 157.5°.

The site condition at each recording site was classified into one of four categories defined as firm soil, very firm soil, soft rock, or firm rock. The firm soil category generally includes soil deposits of Holocene age (less than 11,000 years old), described on geologic maps as recent alluvium, alluvial fans, or undifferentiated Quaternary deposits. The very firm soil category generally includes soil deposits of Pleistocene age (11,000 to 1.5 million years old), described on geologic maps as older alluvium or terrace deposits. The soft rock category generally includes sedimentary rock and soft volcanic deposits of Tertiary age (1.5 to 100 million years old) as well as the "softer" units of the Franciscan Complex and other low-grade metamorphic rocks generally described as melange, serpentine, and schist. The firm rock category generally includes older sedimentary rock and hard volcanic deposits, high-grade metamorphic rock, crystalline rock, and the "harder" units of the Franciscan Complex generally described as sandstone, greywacke, shale, chert, and greenstone. The geologic-based site categories defined in this study can be approximately correlated with the average shear-wave velocity in the top 30 m of a soil profile, V_{30}, according to relationships between V_{30} and geologic units developed by Park and Elrick [1998], Wills and Silva [1998], and Wills *et al.* [2000]. The preferred Wills and Silva [1998] relationships indicate that firm soil, very firm soil, soft rock and firm rock, as defined in our study, are generally consistent with mean values of V_{30} equal to 298 ± 92 , 368 ± 80 , 421 ± 109 and 830 ± 339 m/sec, respectively, where the value after the $\pm$ sign is the standard deviation. These velocities respectively correspond to NEHRP site categories D, C, C and B as originally defined in UBC-97 and IBC-2000 and D, CD, CD and BC as modified by Wills *et al.* [2000].

All of the selected recordings come from a "free-field" site, which we defined as an instrument shelter or non-embedded building less than three storeys high (less than seven storeys high if located on firm rock). We included recordings on dam abutments to enhance the database of rock recordings even though there could be some influence of the interaction of the dam and the recording site. We excluded recordings located in the basement of a building of any size, in a building over three storeys high (over seven storeys high if located on firm rock), and on the toe or base of a dam because of the potential adverse effects of instrument embedment and soil-structure interaction [Campbell, 1997; Stewart, 2000].

Four important earthquakes occurred towards the end of our study and, therefore, could not be incorporated. These included the 17 August 1999 Kocaeli (Izmit), Turkey earthquake of $M_W = 7.4$, the 21 September 1999 Chi-Chi, Taiwan earthquake of $M_W = 7.6$, the 16 October 1999 Hector Mine, California earthquake of $M_W = 7.1$, and the 12 November 1999 Düzce, Turkey earthquake of $M_W = 7.1$. These earthquakes are important because they provide near-source recordings at magnitudes for which the strong-motion database is limited. However, an inspection of the ground motions from the two largest earthquakes indicates that their short-period ground motions are significantly smaller than those predicted from contemporary shallow-crustal attenuation relations [Anderson, 2000; Tsai and Huang, 2000; Boore, 2001]. There has since been some speculation that these ground motions might be lower than expected because the causative faults have large total slip [Anderson, 2002] or that the earthquakes ruptured to the Earth's surface [Somerville, 2000]. Including these recordings would likely lower the predicted near-source ground motions. These recordings will be incorporated at a later time once we better understand the causes of the seemingly low ground motions and whether they are typical of large earthquakes worldwide [Campbell and Bozorgnia, 2003].

3. Ground-Motion Model

We first attempted to independently develop a ground-motion model for V/H. This proved to be difficult due to its complex scaling characteristics. Instead, we found that we could develop a statistically robust and unbiased V/H model from the expression

$$\ln \mathrm{V/H} = \ln Y_V - \ln Y_H \,, \tag{1}$$

where Y_V and Y_H are the vertical and average horizontal components of PGA or PSA calculated from the near-source attenuation relations of Campbell and Bozorgnia [2003]. These attenuation relations are given by

$$\ln Y = c_1 + f_1(M_W) + c_4 \ln \sqrt{f_2(M_W, r_{\text{seis}}, S)} + f_3(F) + f_4(S) + f_5(\mathrm{HW}, F, M_W, r_{\text{seis}}) + \varepsilon \,, \tag{2}$$

where the magnitude scaling characteristics are given by

$$f_1(M_W) = c_2 M_W + c_3(8.5 - M_W)^2 \,, \tag{3}$$

the distance scaling characteristics are given by

$$f_2(M_W, r_{\text{seis}}, S) = r_{\text{seis}}^2 + g(S)^2(\exp[c_8 M_W + c_9(8.5 - M_W)^2])^2 \,, \tag{4}$$

in which the near-source effect of local site conditions is given by

$$g(S) = c_5 + c_6(S_{VFS} + S_{SR}) + c_7 S_{FR}\,, \tag{5}$$

the effect of faulting mechanism is given by

$$f_3(F) = c_{10}F_{RV} + c_{11}F_{TH}\,, \tag{6}$$

the far-source effect of local site conditions is given by

$$f_4(S) = c_{12}S_{VFS} + c_{13}S_{SR} + c_{14}S_{FR}\,, \tag{7}$$

and the effect of the hanging wall (HW) is given by

$$f_5(\text{HW}, F, M_W, r_{\text{seis}}) = \text{HW} f_3(F) f_{\text{HW}}(M_W) f_{\text{HW}}(r_{\text{seis}})\,, \tag{8}$$

where

$$\text{HW} = \begin{cases} 0 & \text{for } r_{jb} \geq 5 \text{ km or } \delta > 70^\circ \\ (S_{VFS} + S_{SR} + S_{FR})(5 - r_{jb})/5 & \text{for } r_{jb} < 5 \text{ km and } \delta \leq 70^\circ \end{cases}, \tag{9}$$

$$f_{\text{HW}}(M_W) = \begin{cases} 0 & \text{for } M_W < 5.5 \\ M_W - 5.5 & \text{for } 5.5 \leq M_W \leq 6.5 \\ 1 & \text{for } M_W > 6.5 \end{cases}, \tag{10}$$

and

$$f_{\text{HW}}(r_{\text{seis}}) = \begin{cases} c_{15}(r_{\text{seis}}/8) & \text{for } r_{\text{seis}} < 8 \text{ km} \\ c_{15} & \text{for } r_{\text{seis}} \geq 8 \text{ km} \end{cases}. \tag{11}$$

In the above equations, Y is either the vertical component, Y_V, or the average horizontal component, Y_H, of PGA or 5%-damped PSA in g ($g = 981$ cm/sec^2); M_W is moment magnitude, r_{seis} is the closest distance to seismogenic rupture in km; r_{jb} is the closest distance to the surface projection of fault rupture in km [Boore *et al.*, 1997]; δ is the dip of the fault plane; $S_{VFS} = 1$ for very firm soil, $S_{SR} = 1$ for soft rock, $S_{FR} = 1$ for firm rock, and $S_{VFS} = S_{SR} = S_{FR} = 0$ for firm soil; $F_{RV} = 1$ for reverse faulting, $F_{TH} = 1$ for thrust faulting, and $F_{RV} = F_{TH} = 0$ for strike-slip and normal faulting; and ε is a random error term with zero mean and standard deviation equal to $\sigma_{\ln Y}$.

The standard deviation, $\sigma_{\ln Y}$, is defined either as a function of magnitude,

$$\sigma_{\ln Y} = \begin{cases} c_{16} - 0.07M_W & \text{for } M_W < 7.4 \\ c_{16} - 0.518 & \text{for } M_W \geq 7.4 \end{cases}, \tag{12}$$

or as a function of PGA,

$$\sigma_{\ln Y} = \begin{cases} c_{17} + 0.351 & \text{for PGA} \leq 0.07g \\ c_{17} - 0.132 \ln \text{PGA} & \text{for } 0.07g < \text{PGA} < 0.25g \\ c_{17} + 0.183 & \text{for PGA} \geq 0.25g \end{cases}. \tag{13}$$

The parameters c_1 through c_{17} are regression coefficients determined from the data and are listed in Table 3. A more detailed discussion of the attenuation relations and their mathematical basis is given in Campbell and Bozorgnia [2003].

As discussed by Campbell and Bozorgnia [2003], sediment depth (depth to basement rock) was not included as a parameter in the regression analysis even though an analysis of residuals indicated that it was an important parameter, especially at long periods. Therefore, the results represent an average sediment depth. We do not believe this is a serious practical limitation in these relations or in the resulting V/H ground-motion model, since sediment depth is generally not used in engineering analyses and is not included in any other widely used attenuation relation. Also, in order to simplify the issues and examine the effects of other main parameters, the effects of the hanging wall and footwall on the V/H and vertical design spectra are not considered in this paper. The V/H ground-motion model for firm soil and selected response spectral ordinates are shown in Fig. 2. Predicted V/H spectra showing the effects of magnitude, distance, site conditions, and faulting mechanism are shown in Fig. 3. On these and subsequent figures, horizontal lines are shown at V/H = 1/2, 2/3 and 1 for reference.

Figure 2 shows that, except at period $T = 0.1$ sec, V/H is not very sensitive to magnitude and distance. For $T = 0.1$ sec and firm soil, V/H increases with magnitude and decreases rapidly with distance, especially at short distances. The rate of falloff decreases with period until at periods between 0.3 and 0.4 sec the trend reverses and the ratio begins to decrease slowly with magnitude and increase slowly with distance. The effect of both magnitude and distance at short periods is less prominent for firm rock, and for that matter the other site conditions, than for firm soil. Figures 3(a) and 3(b) confirm the strong effect of distance, and to a lesser degree of magnitude, on V/H at short periods for firm soil and the reversed scaling at longer periods. Figure 3(c) shows that the difference in V/H between the site categories is most pronounced at short periods, where firm soil has the highest ratio and the other soil categories have similar, but smaller, ratios. At long periods V/H has larger values for firm rock and similar values for the other site categories. At small magnitudes and large distances, the only significant effect of site conditions is the tendency for V/H to be higher on firm rock for periods exceeding 0.2 sec [Campbell and Bozorgnia, 2000a]. As shown in Fig. 3(d), the effect of faulting mechanism is only marginally important at short periods for strike-slip faulting. The modelled characteristics are consistent with those noted by Niazi and Bozorgnia [1992] for the Taiwan SMART-1 strong-motion array, by Bozorgnia and Niazi [1993] for the 1989 Loma Prieta earthquake, and by Bozorgnia *et al.* [1995] for the 1994 Northridge earthquake.

The V/H estimates from the independent attenuation relations for the horizontal and vertical components of PGA and PSA were validated using an analysis of residuals. For purposes of this analysis, we defined a residual as

$$\delta_i = (\ln \mathrm{V/H}_i - \overline{\ln \mathrm{V/H}_i})/\sigma_{\ln \mathrm{PGA}}\,, \tag{14}$$

Table 3. Coefficients and statistical parameters from the regression analysis of PGA and PSA.

T_n (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	c_{16}	c_{17}	No.	r^2
Average Horizontal Component																			
PGA	−4.033	0.812	0.036	−1.061	0.041	−0.005	−0.018	0.766	0.034	0.343	0.351	−0.123	−0.138	−0.289	0.370	0.920	0.219	443	0.949
0.05	−3.740	0.812	0.036	−1.121	0.058	−0.004	−0.028	0.724	0.032	0.302	0.362	−0.140	−0.158	−0.205	0.370	0.940	0.239	435	0.940
0.075	−3.076	0.812	0.050	−1.252	0.121	−0.005	−0.051	0.648	0.040	0.243	0.333	−0.150	−0.196	−0.208	0.370	0.952	0.251	439	0.923
0.10	−2.661	0.812	0.060	−1.308	0.166	−0.009	−0.068	0.621	0.046	0.224	0.313	−0.146	−0.253	−0.258	0.370	0.958	0.257	439	0.901
0.15	−2.270	0.812	0.041	−1.324	0.212	−0.033	−0.081	0.613	0.031	0.318	0.344	−0.176	−0.267	−0.284	0.370	0.974	0.273	439	0.862
0.20	−2.771	0.812	0.030	−1.153	0.098	−0.014	−0.038	0.704	0.026	0.296	0.342	−0.148	−0.183	−0.359	0.370	0.981	0.280	439	0.844
0.30	−2.999	0.812	0.007	−1.080	0.059	−0.007	−0.022	0.752	0.007	0.359	0.385	−0.162	−0.157	−0.585	0.370	0.984	0.283	439	0.859
0.40	−3.511	0.812	−0.015	−0.964	0.024	−0.002	−0.005	0.842	−0.016	0.379	0.438	−0.078	−0.129	−0.557	0.370	0.987	0.286	439	0.871
0.50	−3.556	0.812	−0.035	−0.964	0.023	−0.002	−0.004	0.842	−0.036	0.406	0.479	−0.122	−0.130	−0.701	0.370	0.990	0.289	439	0.890
0.75	−3.709	0.812	−0.071	−0.964	0.021	−0.002	−0.002	0.842	−0.074	0.347	0.419	−0.108	−0.124	−0.796	0.331	1.021	0.320	438	0.917
1.0	−3.867	0.812	−0.101	−0.964	0.019	0	0	0.842	−0.105	0.329	0.338	−0.073	−0.072	−0.858	0.281	1.021	0.320	438	0.935
1.5	−4.093	0.812	−0.150	−0.964	0.019	0	0	0.842	−0.155	0.217	0.188	−0.079	−0.056	−0.954	0.210	1.021	0.320	428	0.960
2.0	−4.311	0.812	−0.180	−0.964	0.019	0	0	0.842	−0.187	0.060	0.064	−0.124	−0.116	−0.916	0.160	1.021	0.320	405	0.971
3.0	−4.817	0.812	−0.193	−0.964	0.019	0	0	0.842	−0.200	−0.079	0.021	−0.154	−0.117	−0.873	0.089	1.021	0.320	333	0.976
4.0	−5.211	0.812	−0.202	−0.964	0.019	0	0	0.842	−0.209	−0.061	0.057	−0.054	−0.261	−0.889	0.039	1.021	0.320	275	0.978
Vertical Component																			
PGA	−3.108	0.756	0	−1.287	0.142	0.046	−0.040	0.587	0	0.253	0.173	−0.135	−0.138	−0.256	0.630	0.975	0.274	439	0.958
0.05	−1.918	0.756	0	−1.517	0.309	0.069	−0.023	0.498	0	0.058	0.100	−0.195	−0.274	−0.219	0.630	1.031	0.330	434	0.934
0.075	−1.504	0.756	0	−1.551	0.343	0.083	0.000	0.487	0	0.135	0.182	−0.224	−0.303	−0.263	0.630	1.031	0.330	436	0.910
0.10	−1.672	0.756	0	−1.473	0.282	0.062	0.001	0.513	0	0.168	0.210	−0.198	−0.275	−0.252	0.630	1.031	0.330	436	0.900
0.15	−2.323	0.756	0	−1.280	0.171	0.045	0.008	0.591	0	0.223	0.238	−0.170	−0.175	−0.270	0.630	1.031	0.330	436	0.899
0.20	−2.998	0.756	0	−1.131	0.089	0.028	0.004	0.668	0	0.234	0.256	−0.098	−0.041	−0.311	0.571	1.031	0.330	436	0.915
0.30	−3.721	0.756	0.007	−1.028	0.050	0.010	0.004	0.736	0.007	0.249	0.328	−0.026	0.082	−0.265	0.488	1.031	0.330	436	0.941
0.40	−4.536	0.756	−0.015	−0.812	0.012	0	0	0.931	−0.018	0.299	0.317	−0.017	0.022	−0.257	0.428	1.031	0.330	436	0.949
0.50	−4.651	0.756	−0.035	−0.812	0.012	0	0	0.931	−0.043	0.243	0.354	−0.020	0.092	−0.293	0.383	1.031	0.330	436	0.957
0.75	−4.903	0.756	−0.071	−0.812	0.012	0	0	0.931	−0.087	0.295	0.418	0.078	0.091	−0.349	0.299	1.031	0.330	435	0.962
1.0	−4.950	0.756	−0.101	−0.812	0.012	0	0	0.931	−0.124	0.266	0.315	0.043	0.101	−0.481	0.240	1.031	0.330	435	0.967
1.5	−5.073	0.756	−0.150	−0.812	0.012	0	0	0.931	−0.184	0.171	0.211	−0.038	−0.018	−0.518	0.240	1.031	0.330	420	0.973
2.0	−5.292	0.756	−0.180	−0.812	0.012	0	0	0.931	−0.222	0.114	0.115	0.033	−0.022	−0.503	0.240	1.031	0.330	395	0.977
3.0	−5.748	0.756	−0.193	−0.812	0.012	0	0	0.931	−0.238	0.179	0.159	−0.010	−0.047	−0.539	0.240	1.031	0.330	321	0.978
4.0	−6.042	0.756	−0.202	−0.812	0.012	0	0	0.931	−0.248	0.237	0.134	−0.059	−0.267	−0.606	0.240	1.031	0.330	274	0.980

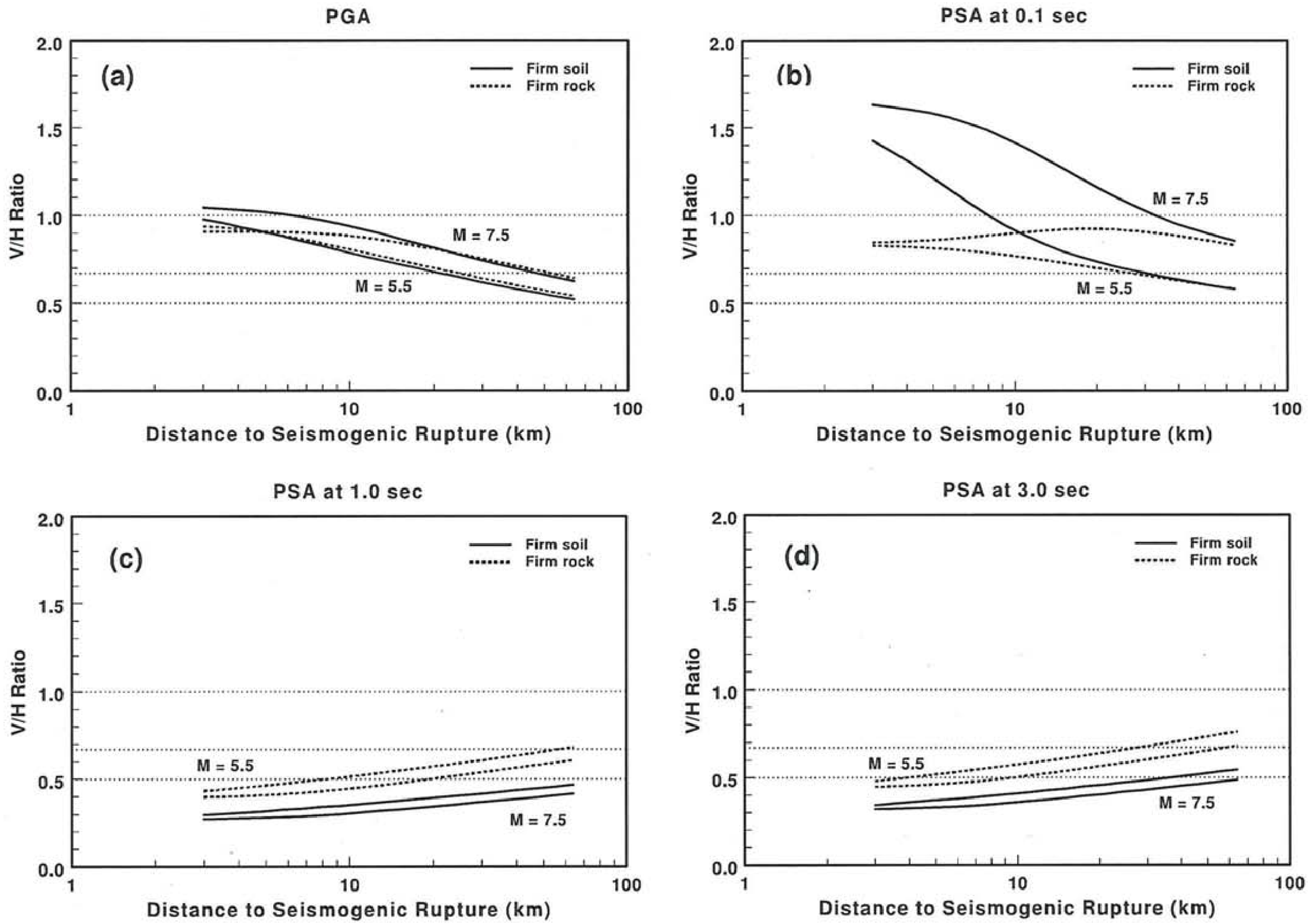

Fig. 2. V/H ground-motion model developed in this study evaluated for strike-slip faulting, firm soil (solid curve), and firm rock (dashed curve): (a) PGA, (b) PSA at 0.1 sec, (c) PSA at 1.0 sec, and (d) PSA at 3.0 sec.

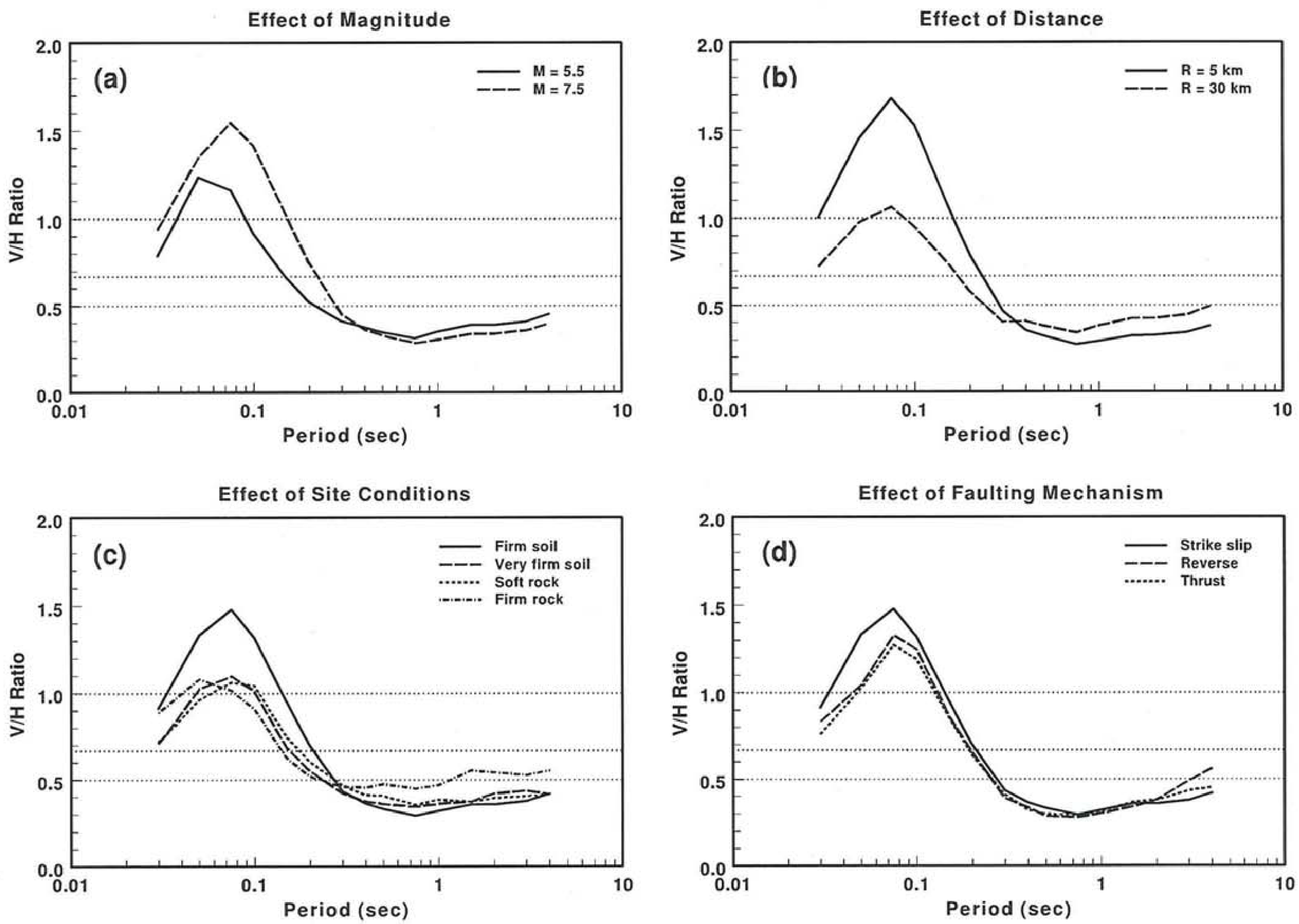

Fig. 3. V/H spectra predicted by the ground-motion model developed in this study showing the effects of: (a) magnitude (plotted for magnitude 5.5 and 7.5), (b) distance, (c) site conditions, and (d) faulting mechanism. Unless otherwise noted, the V/H ground-motion model is evaluated for $M_W = 7.0$, $r_{\text{seis}} = 10$ km, strike-slip faulting, and firm soil. For presentation purposes, PGA is plotted at a period of 0.03 sec.

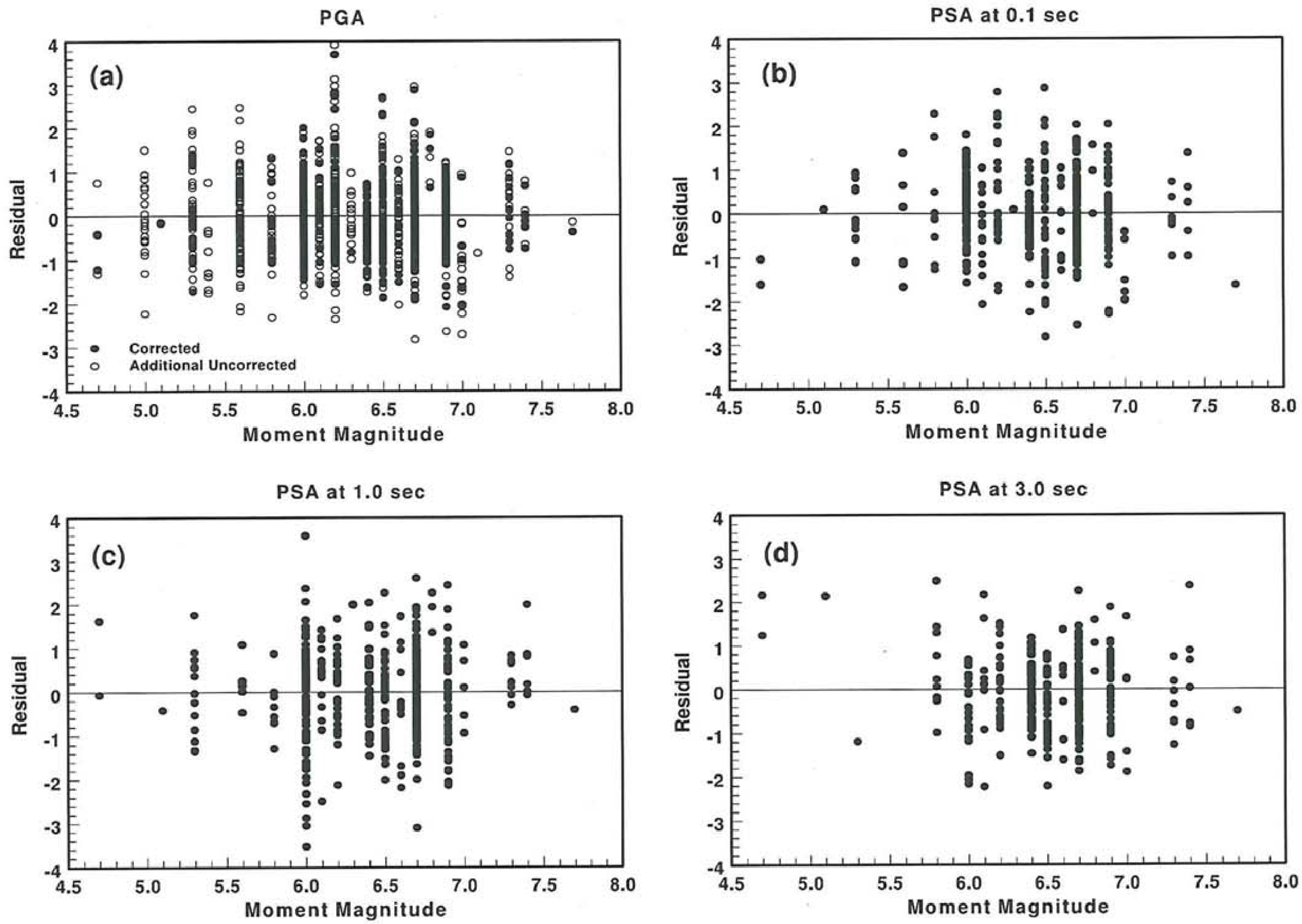

Fig. 4. Residuals of the V/H ground-motion model developed in this study plotted as a function of magnitude: (a) Uncorrected PGA (solid circles) and additional Uncorrected PGA (open circles), (b) PSA at 0.1 sec, (c) PSA at 1.0 sec, and (d) PSA at 3.0 sec. See Campbell and Bozorgnia (2003) for an explanation of the Uncorrected and Corrected databases.

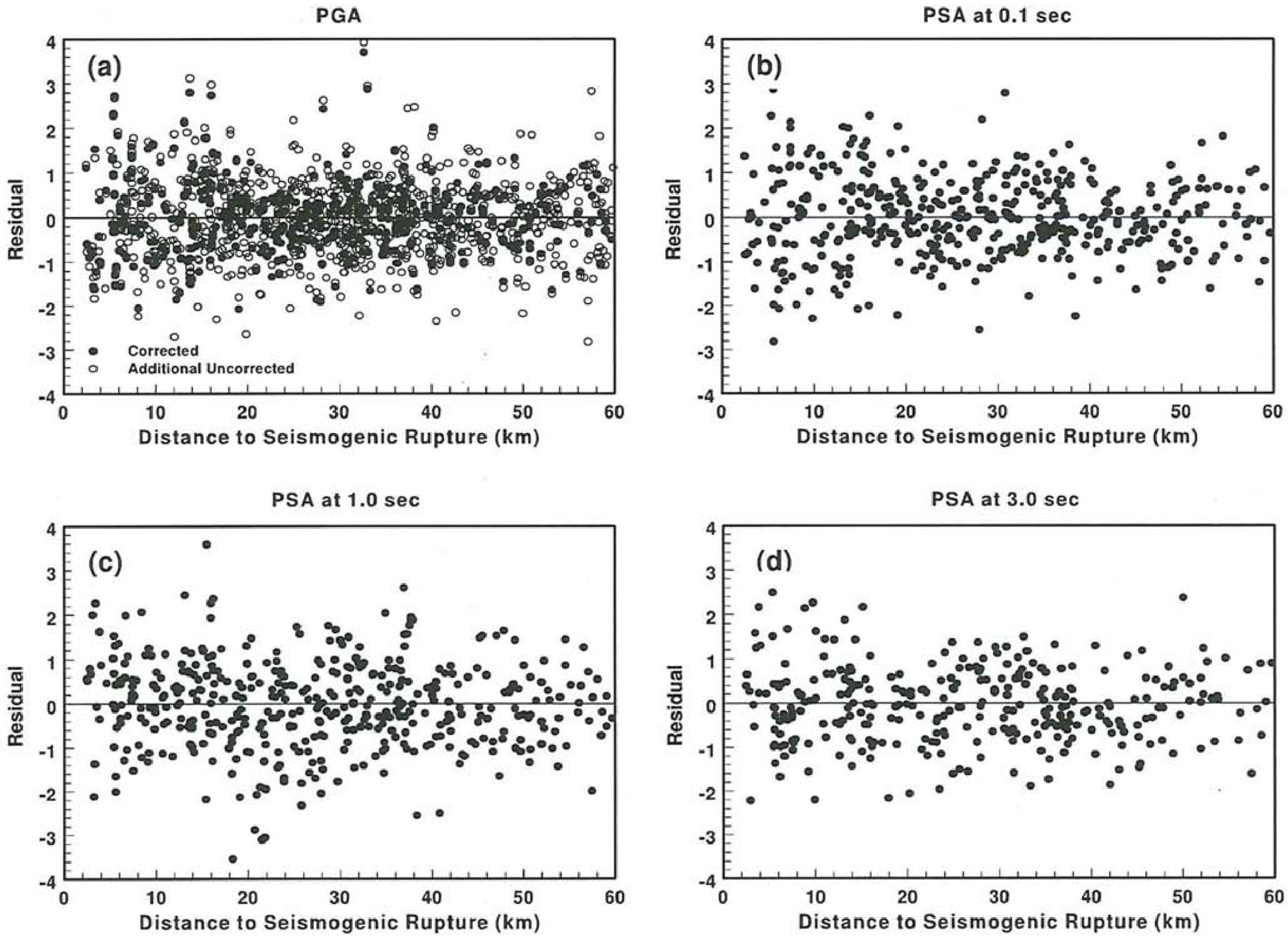

Fig. 5. Residuals of the V/H ground-motion model developed in this study plotted as a function of distance: (a) Corrected PGA (solid circles) and additional Uncorrected PGA (open circles), (b) PSA at 0.1 sec, (c) PSA at 1.0 sec, and (d) PSA at 3.0 sec. See Campbell and Bozorgnia (2003) for an explanation of the Uncorrected and Corrected databases.

where $\ln V/H_i$ is the natural logarithm of the ith observed value of V/H, and $\overline{\ln V/H_i}$ is the corresponding predicted value. The residuals were normalised by $\sigma_{\ln \text{PGA}}$ in order to visualise the relative differences in the scatter in the residuals between different strong-motion parameters and natural periods. For the model to be unbiased, the residuals should have zero mean and be uncorrelated with respect to the parameters in the regression model. Residual plots of V/H as a function of magnitude and distance for selected response spectral ordinates are shown in Figs. 4 and 5, respectively. These figures indicate that the regression models are unbiased with respect to these two parameters. Other plots show similar results for faulting mechanism, site conditions, and other natural periods [Campbell and Bozorgnia, 2000a].

A statistical estimate of the overall model bias, defined as the mean residual without normalising by $\sigma_{\ln \text{PGA}}$, is given in Table 4. Also given in Table 4 is the bias factor, a multiplicative factor defined by exp(bias in ln V/H). The biases are all near zero and the bias factors are all near unity, confirming that the predicted values of V/H from Eq. (1) are unbiased overall for all periods, even though they were calculated from independent regression analyses on the horizontal and vertical components of ground motion. The standard deviation of ln V/H ($\sigma_{\ln \text{V/H}}$), again calculated from the unnormalised residuals, was found to be adequately modelled by Eqs. (12) and (13). However, they were found to be smaller than those of either the horizontal or vertical components due to their statistical correlation. The factors, $\sigma_{\ln \text{V/H}}/\sigma_{\ln Y_H}$, by which the horizontal values of c_{16} and c_{17} can be multiplied to obtain $\sigma_{\ln \text{V/H}}$ are listed in the last column of Table 4. In Tables 5 and 6, we provide some guidance on how to evaluate the horizontal and vertical attenuation relations and, therefore, the V/H ground-motion model for different types of site conditions

Table 4. Statistical bias in predicted value of vertical-to-horizontal (V/H) ratio.

Period (sec)	No.	ln V/H Bias	ln V/H Bias Factor	$\sigma_{\ln \text{V/H}}/\sigma_{\ln Y_H}$
PGA	439	−0.0074	0.99	0.91
0.05	432	0.0003	1.00	0.96
0.075	436	−0.0081	0.99	0.95
0.10	436	−0.0098	0.99	0.93
0.15	436	−0.0110	0.99	0.95
0.20	436	−0.0100	0.99	0.91
0.30	436	−0.0094	0.99	0.90
0.40	436	−0.0074	1.00	0.91
0.50	436	−0.0044	1.00	0.92
0.75	435	−0.0057	0.99	0.86
1.0	435	−0.0033	1.00	0.88
1.5	419	−0.0183	0.98	0.87
2.0	393	−0.0292	0.97	0.84
3.0	313	−0.0370	0.96	0.78
4.0	262	0.0055	1.01	0.78

Table 5. Guidance on evaluating local site conditions.

Site Category	Site Parameter			Approximate V_{30} (m/sec)	Approximate NEHRP Site Category	
	S_{VFS}	S_{SR}	S_{FR}		UBC-97 and IBC-2000	Wills *et al.* [2000]
Firm soil	0.00	0.00	0.00	298 ± 92	D	D
Very firm soil	1.00	0.00	0.00	368 ± 80	C	CD
Soft rock	0.00	1.00	0.00	421 ± 109	C	CD
Firm rock	0.00	0.00	1.00	830 ± 339	B	BC
Generic soil	0.25	0.00	0.00	≈ 310	D	D
Generic rock	0.00	0.50	0.50	≈ 620	C	C

Table 6. Guidance on evaluating faulting mechanism.

Faulting Category	Faulting Parameter F_{RV}	F_{TH}
Strike slip and normal	0.00	0.00
Reverse	1.00	0.00
Thrust	0.00	1.00
Reverse or thrust	0.50	0.50
Generic (unknown)	0.25	0.25

and faulting mechanisms. In Table 5, the terms "generic soil" and "generic rock" refer to sites classified as soil or rock without specifying the type or stiffness of the deposits that make of these site classes. Generally speaking, generic soil is composed of geologic units that fall into NEHRP site categories D and CD and generic rock is composed of geologic units that fall into NEHRP site categories CD, C and B [Wills *et al.*, 2000]. Both generic categories contain units defined as CD, indicating one of the problems with such a generalised classification system. Furthermore, generic rock contains units that span a very large range of stiffnesses (i.e., $V_{30} = 360 - 1500$ m/sec). Nevertheless, these generalised site classifications are used in several contemporary attenuation relations.

4. Comparison with Previous Studies

Besides Campbell and Bozorgnia [2003], there are three other western North America (WNA) attenuation relations that are commonly used in engineering practice that provide estimates of horizontal and vertical components of ground motion and, therefore, can be used to predict V/H spectra. These relations are Sadigh *et al.* [1993], Abrahamson and Silva [1997], and Campbell [1997, 2000, 2001]. The Sadigh *et al.* [1993] relation is valid for generic rock only, whereas the other relations address other site conditions as well. All of these relations represent an active shallow crustal tectonic environment, consistent with our study. They all define the faulting mechanism as either strike slip or reverse slip, with the latter category including both reverse and thrust faulting as defined in our study. Sadigh *et al.* defined rock as a geologic unit with no more than a metre of soil overlying bedrock, although others have found that deeper soil units were also apparently used [Stewart *et al.*, 2003]. Abrahamson and Silva classified sites as either generic soil or generic rock, where generic soil is a geologic unit with at least 20 m of soil overlying bedrock and generic rock is a geologic unit with less than 20 m of soil overlying bedrock. They differentiate between these two site categories using an amplitude-dependent site factor. Campbell [1997] classified sites as either alluvium (firm soil with at least 10 m of soil overlying bedrock), soft rock, or hard rock. His alluvium category is similar to the combined firm and very firm soil categories defined in our study. His soft rock and hard rock categories are consistent with the soft rock and firm rock categories in our study. Campbell [2003a, 2003b, 2003c] presents a more thorough summary and comparison of all four attenuation relations. The spectral attenuation relations of Sabetta and Pugliese [1996] and Ansary and Yamazaki [1998] have very few near-source recordings from moderate-to-large magnitude earthquakes and are, therefore, not suitable for comparison with the near-source relationships developed in our study.

Figure 6 compares the V/H spectra predicted from the four attenuation relations for a site located 10 km from the surface trace of a vertical strike-slip earthquake of $M_W = 7.0$. This distance corresponds to $r_{\rm rup} = 10$ km, where $r_{\rm rup}$ is the distance measure used by Abrahamson and Silva, and, if we assume a depth to seismogenic faulting of 3 km, to $r_{\rm seis} = 10.4$ km, where $r_{\rm seis}$ is the distance measure used in our study [based on Campbell and Bozorgnia, 2003] and by Campbell [1997]. The specific values of magnitude and distance used in the comparison were selected to be consistent with those typically used by engineers in high seismic areas. In Fig. 6(a), comparisons are shown for soft and firm rock, the two rock categories defined in our study, and in Fig. 6(b), comparisons are shown for firm and very firm soil, the two soil categories defined in our study. The Campbell [1997] attenuation relations were evaluated for generic rock [Fig. 6(a)] and for generic soil [Fig. 6(b)] by setting the site parameters to values recommended by Campbell [2000]. Even though the Campbell [1997] relations distinguish between soft and hard rock, they predict virtually the same V/H for these two site conditions. The other attenuation relations were evaluated for either generic rock [Fig. 6(a)] or generic soil, as defined by these developers [Fig. 6(b)].

Figure 6(a) demonstrates the relatively small differences in the value of V/H predicted from our new soft rock and firm rock attenuation relations and those from previous relations. The Abrahamson and Silva generic rock relations predict V/H values that are generally between our soft rock and firm rock values for $0.1 \leq T \leq 2.0$ sec. The Campbell [1997] generic rock relations predict V/H values that are closer to our soft-rock values at $T \leq 0.5$ sec and midway between our soft-rock and firm-rock values at longer periods. The Sadigh *et al.* generic rock relations predict V/H values that are closer to our firm rock values at all periods. The variability amongst the different estimates is less than 30%. Figure 6(b) indicates

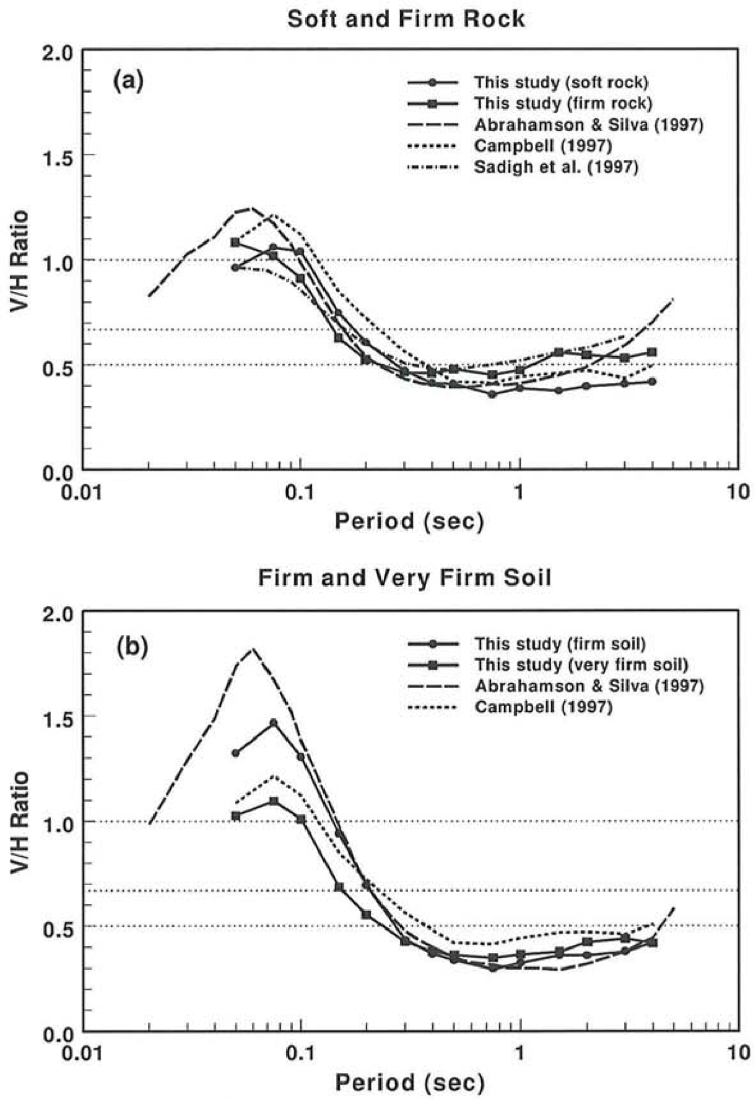

Fig. 6. Comparison of the V/H ratios of PSA predicted from the attenuation relations of Campbell and Bozorgnia [2003] with those predicted from three other attenuation relations that are widely used to estimate horizontal and vertical ground motion in western North America: (a) soft and firm rock, and (b) firm and very firm soil. The spectra are evaluated for $M_W = 7.0$, $r_{rup} = 10$ km, $r_{\text{seis}} = 10.4$ km, and vertical strike-slip faulting.

that there is considerable variability in the short-period V/H estimates for generic soil. The Campbell [1997] generic soil values were found to be virtually identical to his generic rock values, suggesting a lack of sensitivity to different site conditions. The Abrahamson and Silva generic soil values were found to be similar to our firm soil values at $T \geq 0.1$ sec and their peak V/H is about 25% higher than ours. We believe that our results demonstrate the importance of subdividing generic soil into firm and very firm soil categories and generic rock into soft and hard rock categories.

5. Simplified V/H Spectra

In this section we explore simplified V/H spectra for use in practical engineering applications. These tentative simplified V/H spectra are also compared with the V/H spectra predicted from our V/H ground motion model. As observed previously, V/H is a strong function of natural period, source-to-site distance, and local site conditions; and a relatively weak function of magnitude and faulting mechanism (e.g., see Fig. 3). Furthermore, the dependence of V/H on distance is much different for firm soil than for very firm soil, soft rock, and firm rock. Based on these observations, the following tentative simplified model for estimating a V/H spectrum is proposed.

The tentative simplified procedure uses two general site categories, as shown in Fig. 7: firm soil (NEHRP D) and all other site conditions (primarily NEHRP C and

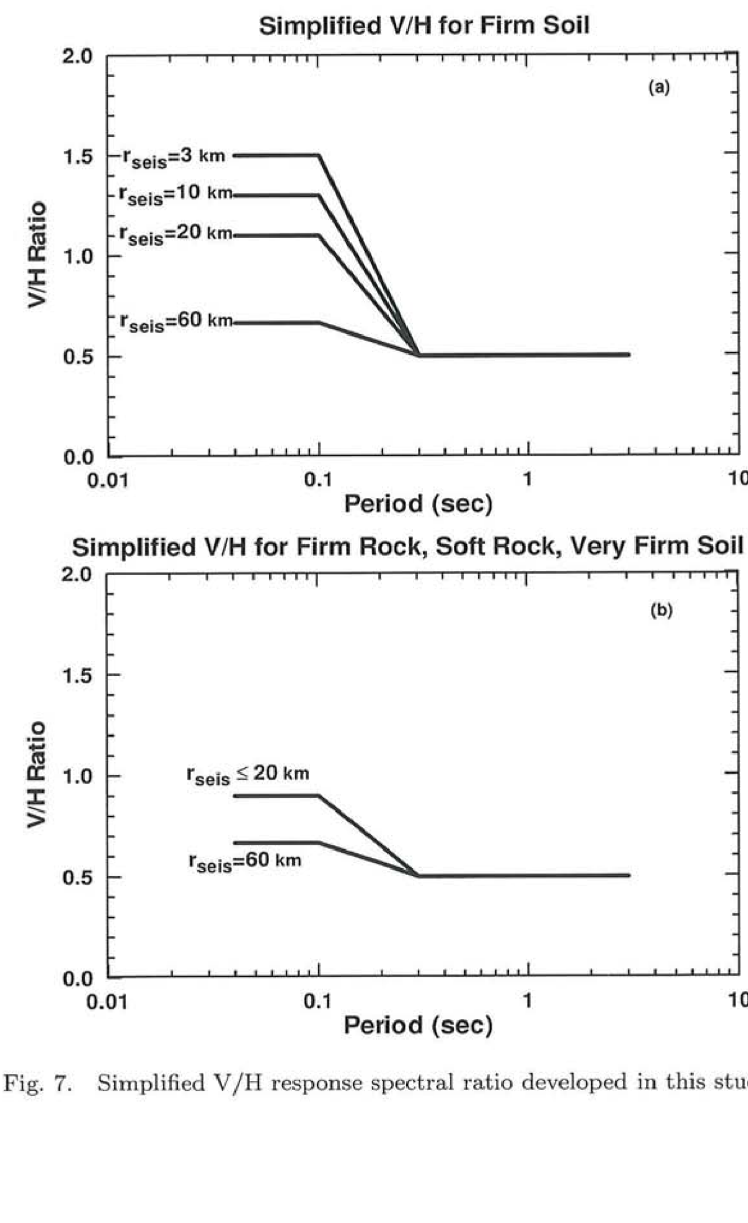

Fig. 7. Simplified V/H response spectral ratio developed in this study.

BC). For both categories, the ratio is higher at short periods than at intermediate and long periods. However, for firm soil the short-period V/H ratio is larger than that for the other three site conditions, as shown in Fig. 7. For generic soil (see Table 5), a weighted combination of the V/H cases shown in Figs. 7(a) and 7(b) can be used. The simplified V/H ratio is assumed to be relatively insensitive to the magnitude and faulting mechanism of the earthquake as compared to its sensitivity to the source-to-site distance and local site conditions.

Figures 8 and 9 show a comparison between the tentative simplified V/H spectra and the V/H spectra predicted from the V/H ground-motion model developed in this study for different magnitudes, distances, site conditions, and faulting mechanisms. There is a reasonable agreement between these spectra. For firm soil, the simplified mid-period V/H ratio of 0.5 is relatively conservative and can also be used for periods longer than 1.0 sec. For the other three site categories, the predicted V/H ratio is slightly greater than 0.5 beyond 1.0 sec, approaching a value of 0.7 at about 4.0 sec. Hence, for these soil categories, the proposed mid-period V/H ratios of 0.5 can only be used for periods of 1.0 sec or less.

6. Preliminary Vertical Design Spectra

For practical applications, especially if site-specific vertical response spectra are not available, it is desirable to be able to generate a preliminary vertical design spectrum using a relatively simple procedure. For this purpose, special attention should be given to the short-period range of the spectra for the following reasons: (a) the peak of the vertical response spectrum occurs at short periods [Bozorgnia and Niazi, 1993; Campbell and Bozorgnia, 2003]; and (b) the natural periods of the vertical response of many building components and systems fall at short periods. For example, based on analyses of measured vertical responses, Bozorgnia *et al.* [1998] found that vertical natural periods for numerous building components were shorter than 0.26 sec. For structures with long vertical periods (e.g. longer than about 0.5 sec), we still recommend using a site-specific vertical response spectrum. The preliminary vertical design spectrum is for 5% damping. The development and verification of adjustment factors to generate vertical spectra for other damping ratios was beyond the scope of our study.

The preliminary vertical design spectrum is based on the observed behaviour of the vertical response spectra developed by Campbell and Bozorgnia [2003] and the V/H ground motion model presented in our study. As a function of period, the preliminary vertical design spectrum has both a flat and a decaying portion, as shown in Fig. 10. The amplitude of the flat portion, A_{vs}, is equal to an estimate of the vertical spectral acceleration at $T = 0.1$ sec, as explained next. The flat portion extends to a corner period at $T = 0.15$ sec. For $T > 0.15$ sec, the preliminary vertical design spectrum decays as

$$A_{vs}(0.15/T)^{0.75}\,. \tag{15}$$

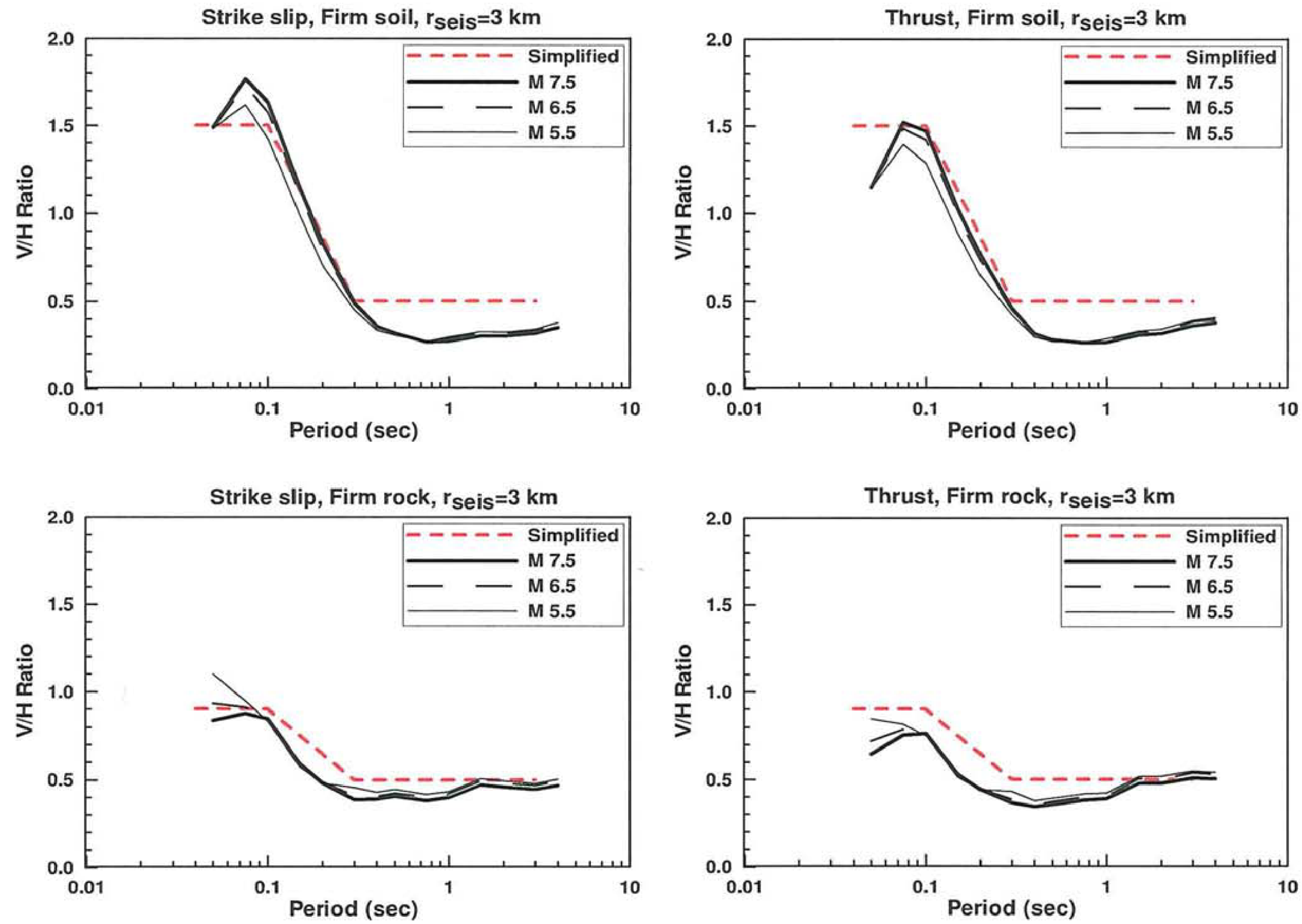

Fig. 8. Comparison of simplified and predicted V/H response spectral ratios developed in this study for $r_{\mathrm{seis}} = 3$ km and selected values of magnitude and local site conditions.

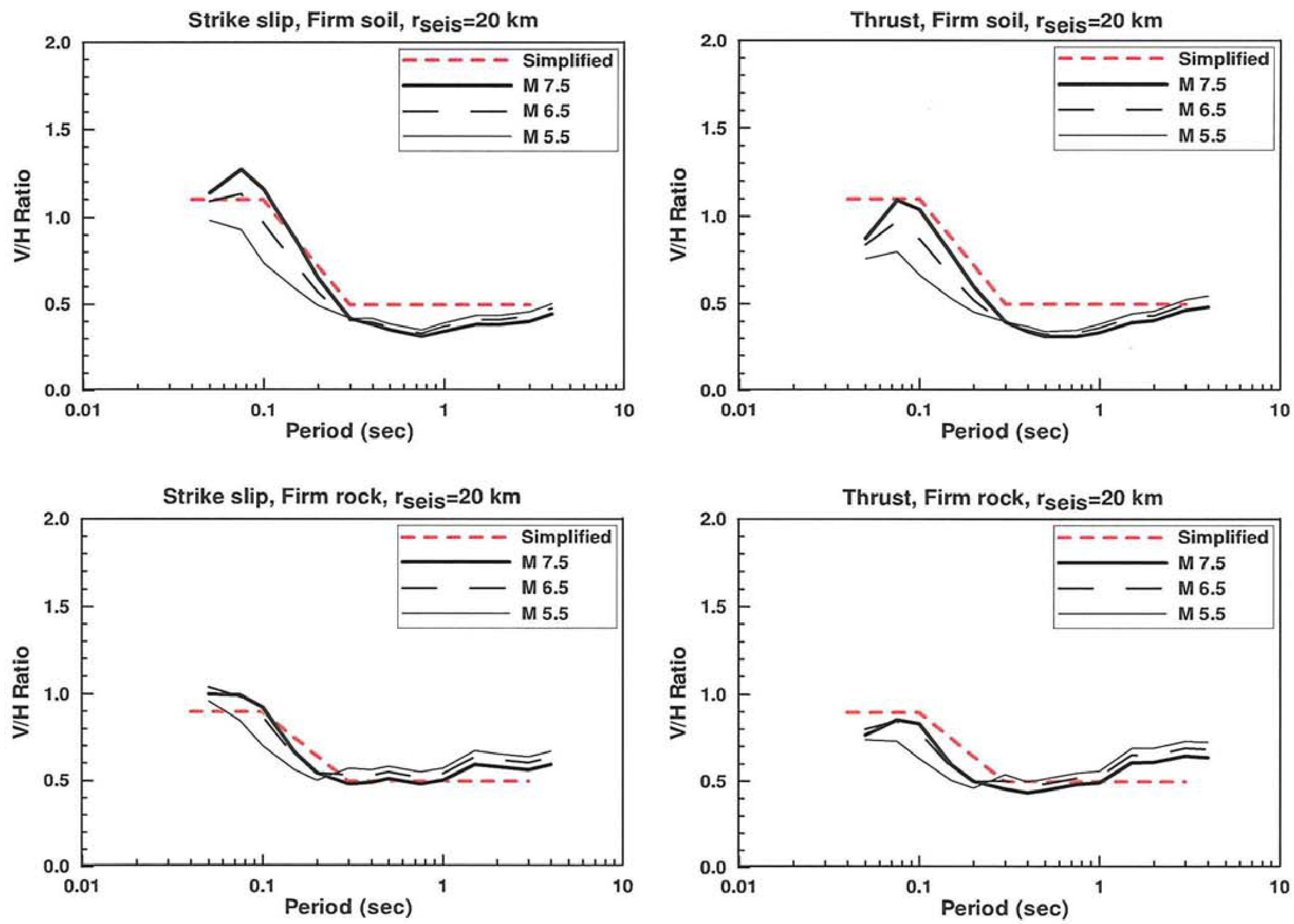

Fig. 9. Comparison of the simplified and predicted V/H response spectral ratios developed in this study for $r_{\mathrm{seis}} = 20$ km and selected values of magnitude and local soil conditions.

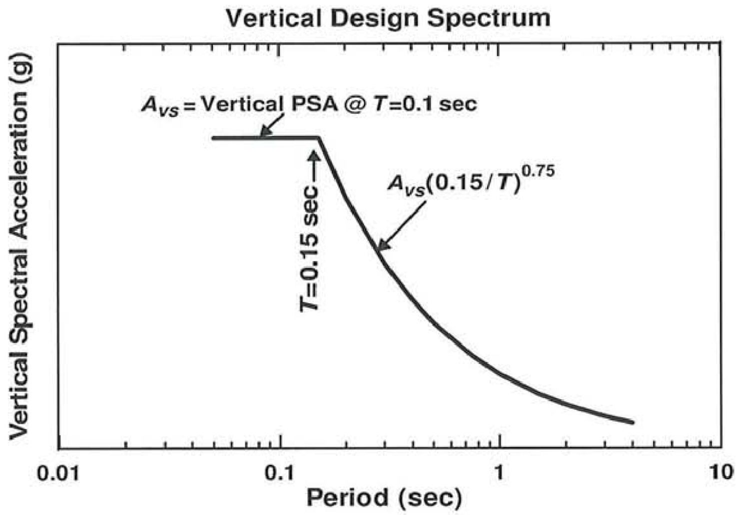

Fig. 10. Proposed preliminary vertical design spectrum developed in this study.

The corner period of 0.15 sec is consistent with that previously proposed by Elnashai [1997] and Elnashai and Papazoglou [1997]. The ordinate of the flat potion of the spectrum (A_{vs}) can be estimated according to one of the preliminary procedures for developing a vertical design spectrum defined below.

6.1. *Case 1: Given the vertical spectral ordinate at* $T = 0.1$ *sec*

If an estimate of the vertical spectral ordinate at $T = 0.1$ sec is available (e.g. from a seismic hazard analysis), this value can be used for the ordinate of the flat portion of the vertical design spectrum (i.e. for $T \leq 0.15$ sec). Having this information is sufficient to generate the vertical design spectrum, as shown in Fig. 10.

The proposed vertical design spectrum compared to that predicted by the vertical attenuation relation developed by Campbell and Bozorgnia [2003] are presented in Figs. 11 and 12. The agreement between these spectra is reasonable over a wide range of seismological parameters.

6.2. *Case 2: Given the horizontal spectral ordinate at* $T = 0.1$ *sec*

If only an estimate of the horizontal spectral ordinate at $T = 0.1$ sec is available (e.g. from a seismic hazard analysis or a national seismic hazard map), the ordinate of the flat portion of the vertical design spectrum (see Fig. 10) can be computed by multiplying this horizontal spectral ordinate by the corresponding ordinate of the simplified V/H ratio at $T = 0.1$ sec (e.g. from Fig. 7). The resulting estimate of vertical amplitude (A_{vs}) can then be used to generate the vertical design spectrum, as shown in Fig. 10.

We demonstrate the method by using the 0.1-sec horizontal spectral ordinate obtained from the horizontal attenuation relation of Campbell and Bozorgnia [2003],

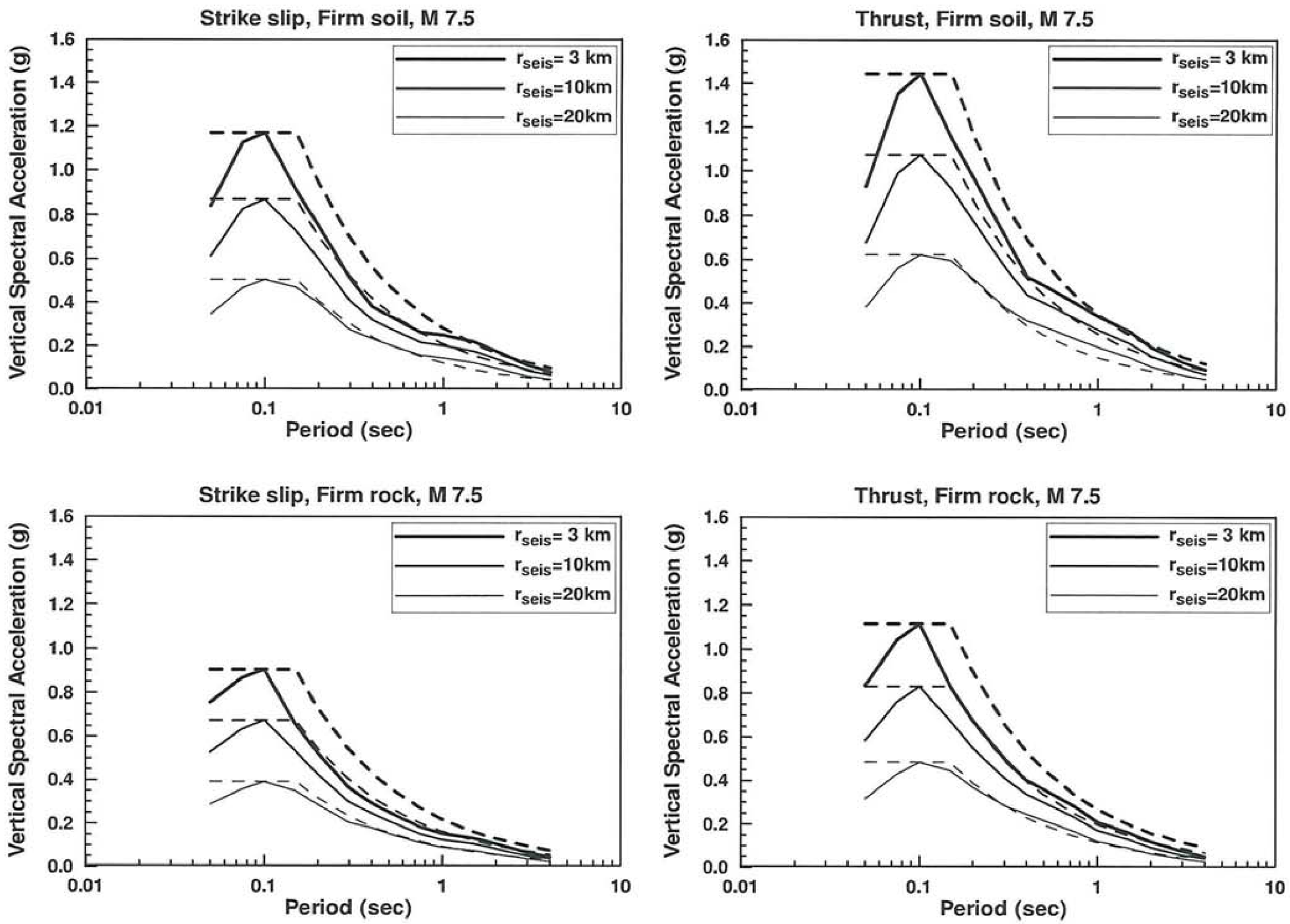

Fig. 11. Preliminary vertical design spectra developed in this study for a magnitude 7.5 earthquake derived from the vertical spectral ordinate at 0.1 sec (dashed lines) compared to the vertical spectra predicted from the attenuation relation of Campbell and Bozorgnia [2003] (solid lines).

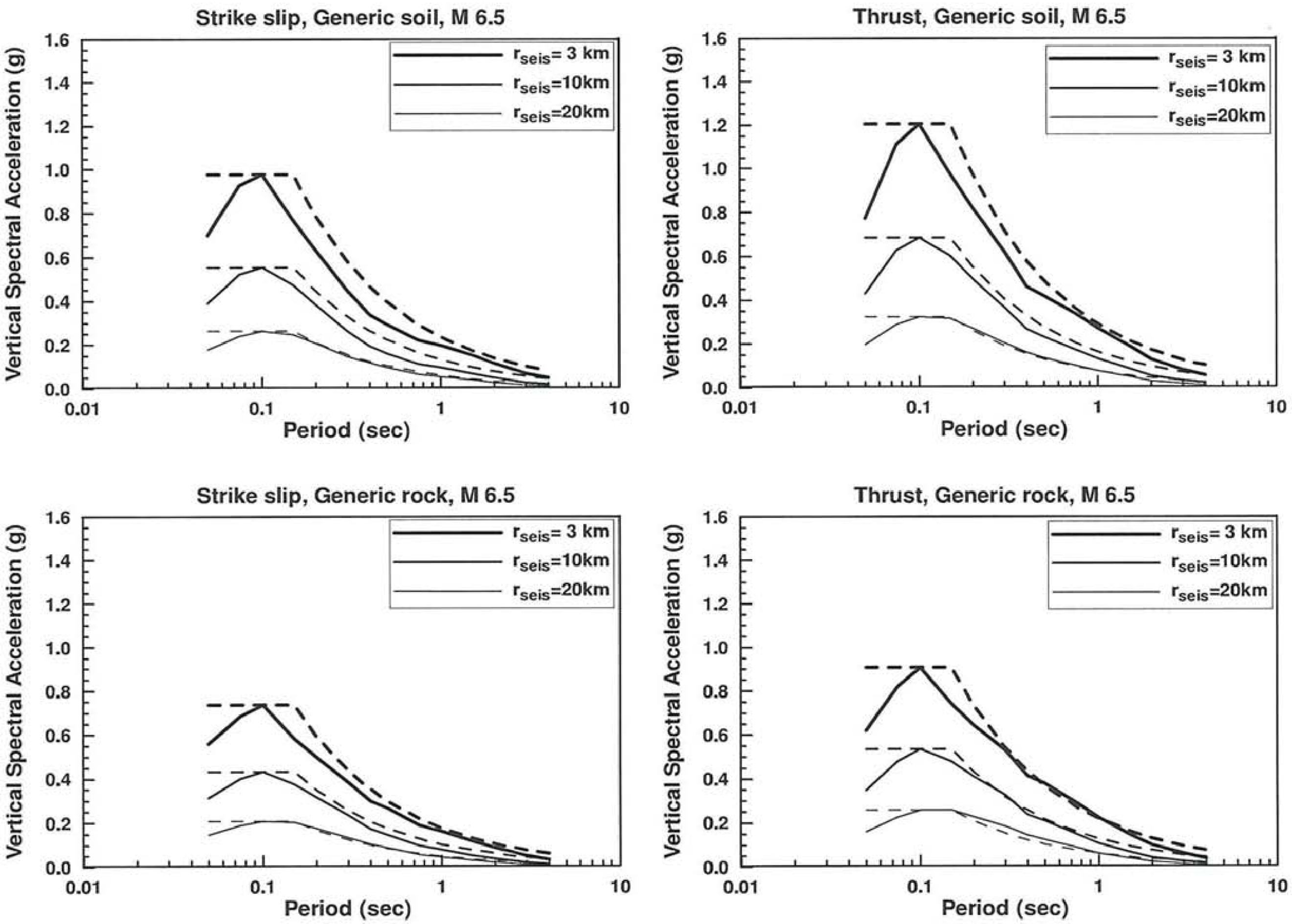

Fig. 12. Preliminary vertical design spectra developed in this study for a magnitude 6.5 earthquake derived from the vertical spectral ordinate at 0.1 sec (dashed lines) compared to the vertical spectra predicted from the vertical attenuation relation of Campbell and Bozorgnia [2003] (solid lines).

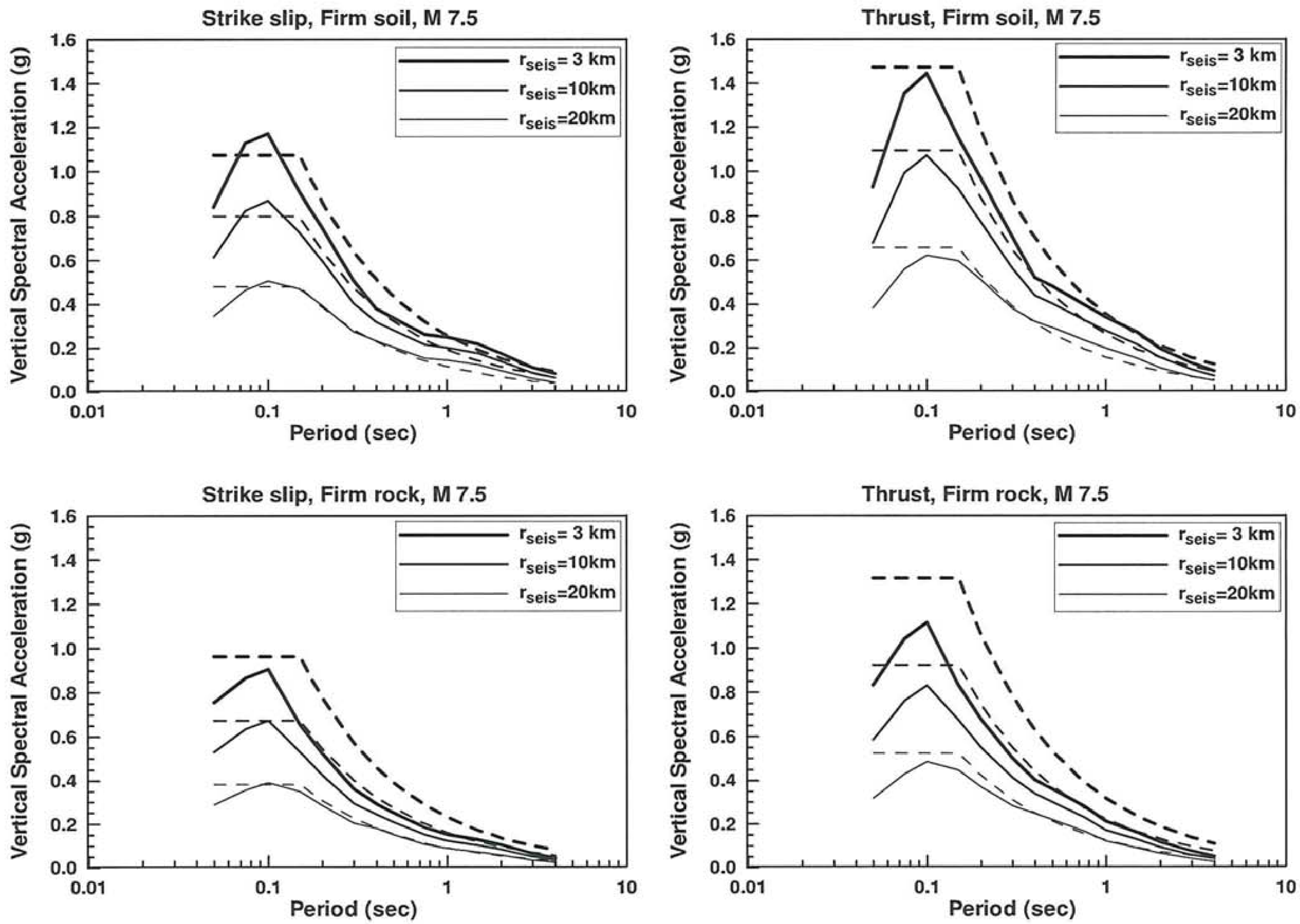

Fig. 13. Preliminary vertical design spectra developed in this study for a magnitude 7.5 earthquake derived from the horizontal spectral ordinate at 0.1 sec (dashed lines) compared to the vertical spectra predicted from the vertical attenuation relation of Campbell and Bozorgnia [2003] (solid lines).

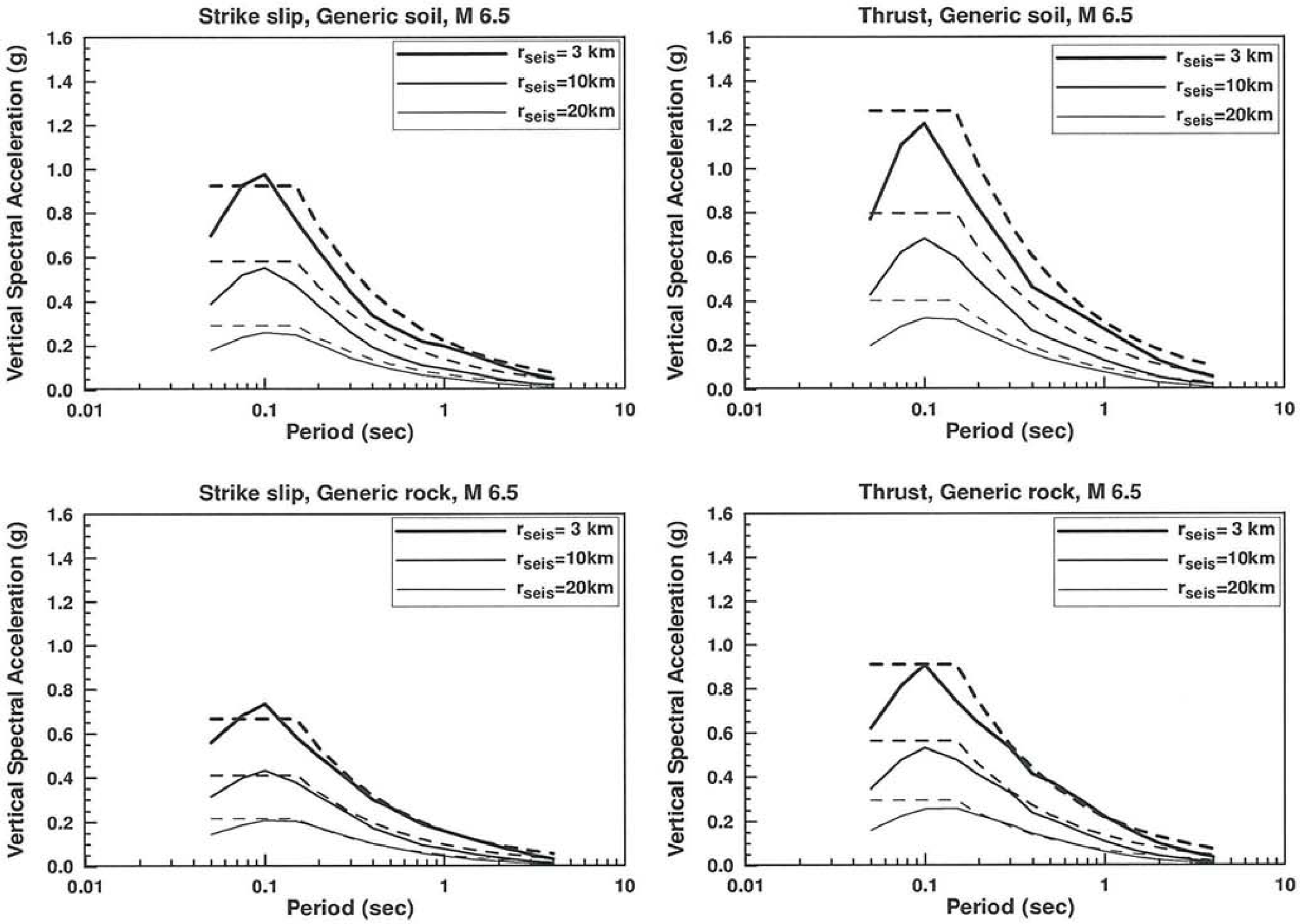

Fig. 14. Preliminary vertical design spectra developed in this study for a magnitude 6.5 earthquake derived from the horizontal spectral ordinate at 0.1 sec (dashed lines) compared to the vertical spectra predicted from the vertical attenuation relation of Campbell and Bozorgnia [2003] (solid lines).

given here as Eq. (2). The vertical design spectra generated by using this procedure, along with the actual vertical spectra predicted from the same attenuation relation, are compared in Figs. 13 and 14. Considering the very limited information needed (only the horizontal spectral ordinate at $T = 0.1$ sec) and its simplicity, this procedure would appear to be a reasonable, albeit somewhat conservative, alternative to developing a site-specific vertical response spectrum for many practical engineering applications.

7. Discussion and Conclusions

In our previous study [Campbell and Bozorgnia, 2003], we analysed a comprehensive near-source strong ground motion database that allowed us to develop in this study a ground-motion relation for predicting the vertical-to-horizontal (V/H) ratios of peak ground acceleration and acceleration response spectra in terms of source-to-site distance, local site conditions, earthquake magnitude, and faulting mechanism. We consider this model to be valid for earthquakes of $M_W \geq 5.0$ and distances of $r_{\text{seis}} \leq 60$ km for shallow crustal earthquakes in active tectonic regions worldwide.

Our analysis, together with many of those discussed in the Introduction, has enabled us to quantitatively confirm the hypothesis stated by the famous and insightful California seismologist Charles Richter [Richter, 1958] that "There is evidence, which should be regarded less as established fact than as working hypothesis, that in the neighbourhood of the epicentre the vertical component of motion is larger relative to the horizontal components than elsewhere".

We found that the observed and predicted V/H spectra are strong functions of natural period, source-to-site distance, and local site conditions; and a relatively weak function of earthquake magnitude and faulting mechanism. Furthermore, the behaviour of the V/H spectra with distance is different for firm soil (NEHRP site category D) than for stiffer soil and rock deposits. At firm soil sites, our analysis predicts that V/H can easily exceed unity, approaching a factor of 1.8 at short periods, close distances, and large magnitudes.

We also demonstrated that there is no bias in the predicted V/H spectral ordinates from attenuation relations developed from independent analyses of vertical and horizontal response spectra by Campbell and Bozorgnia [2003]. Therefore, these V/H estimates can be used to develop an unbiased vertical response spectrum given an estimate of the horizontal spectrum.

Based on the observed and predicted behaviour of the V/H spectra, we proposed a tentative simplified model for estimating V/H spectral ordinates for practical engineering applications. We found a reasonable agreement between the simplified and predicted V/H spectral ordinates over a wide range of seismological parameters. We also proposed a simple procedure for generating a preliminary vertical design spectrum. For this preliminary vertical spectrum, special consideration was given to the shorter periods that are most critical to the vertical response of structures. Extensive vetting from the seismological and engineering communities will be needed before such simplified spectra are officially accepted and adopted in codified procedures in the United States.

Acknowledgements

This study was supported by the California Geological Survey, Strong Motion Instrumentation Program, Contract 1097-606. We are grateful for constructive comments provided by Dr. Mansour Niazi during the course of the study. Comments by two anonymous reviewers are also greatly appreciated.

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