*16th World Conference on Earthquake, 16WCEE 2017*

*Santiago Chile, January 9th to 13th 2017*

*Paper N° 4228*

*Registration Code: S-U1464548127*

# NGA-West2 Ground Motion Model for V/H Response Spectra

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## *Abstract*

A ground motion model (GMM) was developed for the vertical-to-horizontal (V/H) ratio of 5%-damped elastic response spectra at periods ranging from 0.01 to 10 sec. The V/H GMM includes equations for the median V/H ratio and for the aleatory within-event, between-event, and total standard deviations. The V/H model is based on the GMMs that we have developed for the vertical and "average" horizontal components of ground motion using a mathematical formation that accounts for the correlation between these two components. We validated the V/H model against the NGA-West2 empirical database. We consider our V/H model to be valid for worldwide shallow crustal earthquakes in active tectonic regions for moment magnitudes ranging from 3.3 to 8.5, depending on the style of faulting, and for site-to-source fault rupture distances ranging from 0 to 300 km. The V/H ratios predicted from the model show a strong dependence on spectral period and site response.

*Keywords: NGA; ground motion; vertical; V/H; response spectra*

## 1. Introduction

The vertical-to-horizontal (V/H) spectral ratio has both conceptual and practical importance in earthquake engineering. The V/H ratio can quantitatively provide a contrast between the frequency contents of the vertical and horizontal ground motions as a function of the fundamental parameters such as earthquake magnitude, site-to-source distance, and local site condition. In practice, the V/H ratio is also commonly used in conjunction with probabilistic seismic hazard analysis (PSHA) to develop a vertical design spectrum by using it to scale the horizontal design spectrum from seismological parameters of scenario earthquakes (e.g., Bozorgnia and Campbell, 2016b).

Traditionally, researchers have developed ground motion models (GMMs) for the V/H spectral ratio by two methods. The first method is to independently develop vertical and horizontal GMMs using the same database and functional forms and use these GMMs to estimate the median value of the V/H ratio. However, most researchers have not commonly computed the residuals and standard deviations of the V/H spectral ratios that are estimated in this manner. For example, Bommer et al. (2011) listed 16 studies that developed both vertical and horizontal GMMs and only one of them (Bozorgnia and Campbell 2004) computed V/H residuals and standard deviations.

The second approach is to empirically develop a GMM directly for the V/H spectral ratio using V/H ratios from recorded data. The potential disadvantage of this approach is that the modeling assumptions made in the process of developing an independent V/H GMM can result in a vertical response spectrum that is not fully consistent with one directly developed from empirical vertical ground motion data.

Herein, we summarize the results of a generalized and more rigorous formulation of the first approach using vertical and horizontal GMMs. This mathematical formulation provides equations for the median V/H ratio and for the within-event, between-event, and total aleatory standard deviations of the V/H ratio. The process preserves all of the scaling characteristics of the original vertical and horizontal GMMs and explicitly accounts for the correlation between the vertical and horizontal ground motion intensity measures (GMIMs), or more precisely between the residuals of the logarithms of these GMIMs. In this way, no further assumptions are needed to develop the V/H model. In this paper, we use the vertical and horizontal GMMs (Bozorgnia and Campbell 2016a, Campbell and Bozorgnia 2014) that we developed from the comprehensive NGA-West2 database of shallow crustal events in active tectonic regions (Ancheta et al. 2014), which was compiled as part of the NGA-West2 research program (Bozorgnia et al. 2014). Our V/H formulation is validated by checking the V/H results against the NGA-West2 empirical V/H ratios.

## 2. Summary of Methodology

Details of the mathematical formulation are provided in Bozorgnia and Campbell (2016b). A summary of the methodology is provided here.

Consider a pair of vertical and horizontal GMMs, such as the Bozorgnia and Campbell (2016a) vertical GMM and the Campbell and Bozorgnia (2014) RotD50 "average" horizontal (Boore 2010) GMM, that were developed using a consistent ground motion database. The formulation of the vertical to horizontal ground motion ratio is:

$$\ln y_{V/H,ij} = \ln Y_{V/H,ij} + \eta_{V/H,i} + \varepsilon_{V/H,ij} \tag{1}$$

where, $Y_{V/H,ij}$ is the median predicted value of V/H at station *j* for event *i*, $y_{V/H,ij}$ is the observed value of V/H for the intensity measure of interest, and $\eta_{V/H,i}$ and $\varepsilon_{V/H,ij}$ are the between-event and within-event residuals of the V/H predictions. The median prediction of V/H is related to the median predictions of vertical and horizontal components through:

$$\ln Y_{V/H,ij} = \ln\left(Y_{V,ij} / Y_{H,ij}\right) \tag{2}$$

It can also be shown (Bozorgnia and Campbell, 2016b) that $\eta_{V/H,i}$ and $\varepsilon_{V/H,ij}$ are Normally distributed random variables with the following standard deviations, respectively:

$$\tau_{V/H} = \sqrt{\tau_V^2 + \tau_H^2 - 2\rho_{V,H}^B \tau_V \tau_H} \quad (3)$$

$$\phi_{V/H} = \sqrt{\phi_V^2 + \phi_H^2 - 2\rho_{V,H}^W \phi_V \phi_H} \quad (4)$$

where, $\tau_V$ and $\tau_H$ are the between-event aleatory standard deviations; $\phi_V$ and $\phi_H$ are the within-event aleatory standard deviations, each for vertical and horizontal components respectively; and $\rho_{V,H}^B$ is the correlation coefficient of the between-event residuals and $\rho_{V,H}^W$ is the correlation coefficient of the within-event residuals, each for the predicted logarithms of the vertical and horizontal intensity measures. The total aleatory standard deviation of the V/H prediction is computed from the equation:

$$\sigma_{V/H} = \sqrt{\tau_{V/H}^2 + \phi_{V/H}^2} \quad (5)$$

In this study, the Bozorgnia and Campbell (2016a) vertical GMM is used to compute $Y_{V,ij}$, $\tau_V$, and $\phi_V$ and the Campbell and Bozorgnia (2014) horizontal GMM is used to compute $Y_{H,ij}$, $\tau_H$ and $\phi_H$ for peak ground acceleration (PGA, *g*), peak ground velocity (PGV, cm/sec), and 5%-damped pseudo-acceleration response spectra (PSA, *g*). We calculated the correlation coefficients $\rho_{V,H}^W$ and $\rho_{V,H}^B$ from the residuals of the vertical and horizontal GMMs. The complete mathematical formulations of $Y_{X,ij}$, $\tau_X$, and $\phi_X$, where *X* can be *V* or *H*, are presented in Bozorgnia and Campbell (2016b).

## 3. V/H Results

Summary results of V/H spectral ratios are presented here. Figure 1 presents scaling of V/H with distance. It is evident that for "rock" condition, where soil nonlinearity in horizontal direction is negligible, the V/H ratio is relatively insensitive to distance. We note that using the traditional 2/3 ratio grossly underestimates the V/H ratio for softer soil sites at short periods.

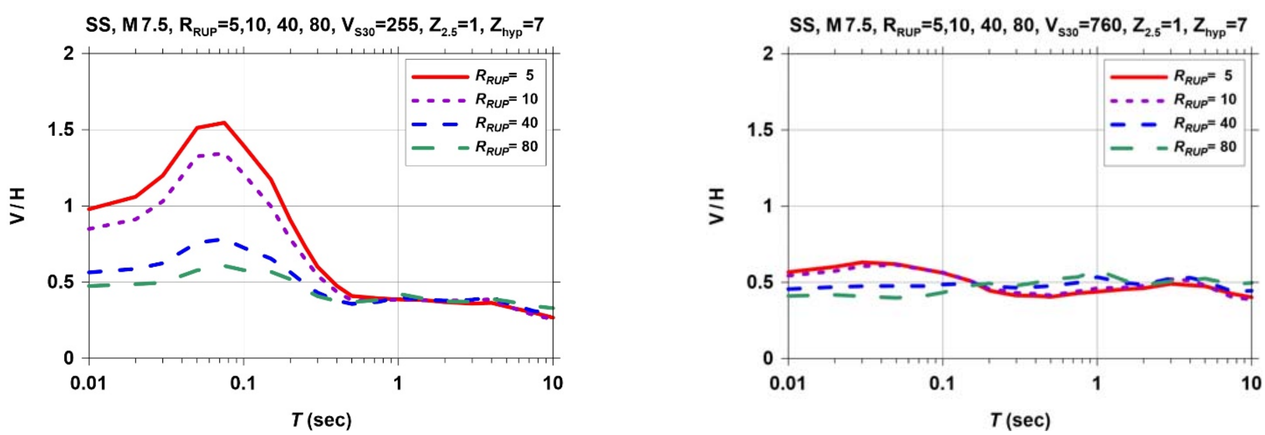


Figure 1. Scaling of the median V/H response spectral ratio with distance for a site with $V_{S30} = 255$ m/sec (left panel) and $V_{S30} = 760$ m/sec (right panel). The V/H ratios are evaluated for a $\mathbf{M} = 7.5$ vertical strike-slip (SS) event with a hypocentral depth ($Z_{HYP}$) of 7 km and for a site with a sediment depth ($Z_{2.5}$) of 1 km.

Figure 2 shows scaling of the V/H spectral ratio with $V_{S30}$. This figure shows the predicted median V/H spectral ratio for sites with $V_{S30} = 180$, 255, 360, 525, and 760 m/sec located at a distance of $R_{RUP} = 10$ km from earthquakes of $\mathbf{M} = 5.5$ (left panel) and $\mathbf{M} = 7.5$ (right panel). All other parameters are the same as in Figure 1. It is evident from this figure that the V/H spectral ratio is very sensitive to local site conditions at short periods and is higher on softer sites than on harder sites. This is mainly due to the influence of soil nonlinearity on the horizontal motion.

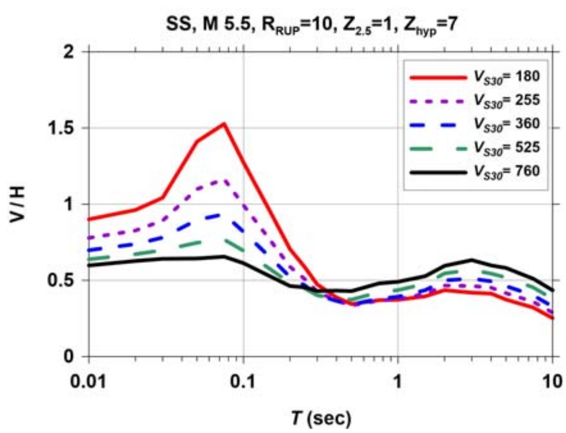


Figure 2. Scaling of the median V/H response spectral ratio with 30-m shear-wave velocity ($V_{S30} = 180$, 255, 360, 525, and 760 m/sec) for $\mathbf{M} = 5.5$ (left panel) and $\mathbf{M} = 7.5$ (right panel).

Figure 3 compares the results of the current study with those of Bozorgnia and Campbell (2004). The results are comparable especially for "soil" conditions. For the "rock" site condition, the current NGA-West2 database is much more comprehensive than the old database; thus, the recent results are more reliable. More detailed comparisons with other recent studies are presented in Bozorgnia and Campbell (2016b). Overall, the current results are qualitatively comparable with those of other recent studies.

Figure 4 presents the within-event ($\phi_{V/H}$), between-event ($\tau_{V/H}$), and total ($\sigma_{V/H}$) aleatory standard deviations for the V/H spectral ratio from Equations (3), (4), and (5). The values shown in this figure are for a vertical strike-slip earthquake with $\mathbf{M} = 4.5$ (left panels) and $\mathbf{M} = 7.5$ (right panels) and for a site located on soil ($V_{S30} = 255$ m/sec) at $R_{RUP} = 10$ km. All other parameters are the same as in Figure 1. For comparison purposes, Figure 4 also plots the within-event, between-event, and total aleatory standard deviations for the vertical (V) and horizontal (H) components of motion from Bozorgnia and Campbell (2016a) and Campbell and Bozorgnia (2014). This comparison shows that the standard deviations of the V/H spectral ratio are less than or equal to those of the horizontal and vertical motions at all periods.

In Figure 4 we also validate the V/H standard deviations by comparing our V/H model standard deviations given in Equations (3), (4), and (5) with the standard deviations computed from the residuals of our V/H model with respect to the NGA-West2 V/H database computed using a mixed-effects analysis. The results presented in this figure show that the standard deviations calculated using our mathematical formulation are consistent with those based directly on the NGA-West2 database.

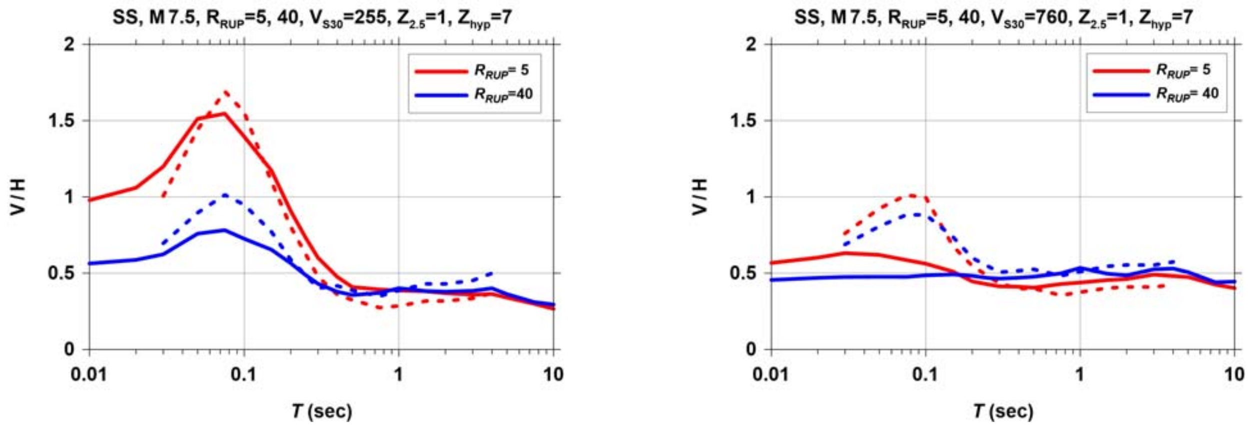


Figure 3. Comparison of median V/H response spectral ratios predicted from the model of this study (solid lines) with those from Bozorgnia and Campbell (2004) (dashed lines) for sites with 30-m shear-wave velocities of $V_{S30} = 255$ m/sec (left panels) and $V_{S30} = 760$ m/sec (right panels), for $\mathbf{M} = 5.5$ and for $R_{RUP} = 5$ and 40 km. All other parameters are given in the caption to Figure 1.

## 4. Summary and Conclusions

We developed a V/H model that provides the median prediction and the within-event, between-event, and total aleatory standard deviations of the V/H ratio that account for the correlation between the residuals of the horizontal and vertical GMIMs. Therefore, if our V/H model is used to develop a vertical response spectrum from a horizontal response spectrum predicted from our NGA-West2 horizontal GMM, the resulting vertical spectrum will be consistent with the vertical spectrum predicted from our NGA-West2 vertical GMM in terms of both the median value and the between-event, within-event, and total standard deviations.

We validated the mathematical formulation used to develop our median V/H model as well as its between-event, within-event and total standard deviations by evaluating the residuals between our predictions and the comprehensive empirical NGA-West2 database that was used to develop our vertical and horizontal GMMs. This analysis demonstrates that the modeling assumptions of excluding soil nonlinearity and deep basin effects in our vertical GMM do not appear to have a material influence on the predictive power of the V/H model.
The V/H behavior at short periods is influenced by the effects of nonlinear site response on the horizontal motion, which reduces its amplitude compared to the near-linear site response of the vertical motion.

Consistent with our horizontal and vertical GMMs, we consider our V/H model to be valid for worldwide shallow crustal earthquakes in active tectonic regions for moment magnitudes ranging from 3.3 to 8.5, depending on the style of faulting, and for fault rupture distances ranging from 0 to 300 km. Additional application guidelines are given in Bozorgnia and Campbell (2016a,b).

## 5. Acknowledgements

This study was sponsored by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority, California Department of Transportation, and the Pacific Gas & Electric Company. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsoring agencies.

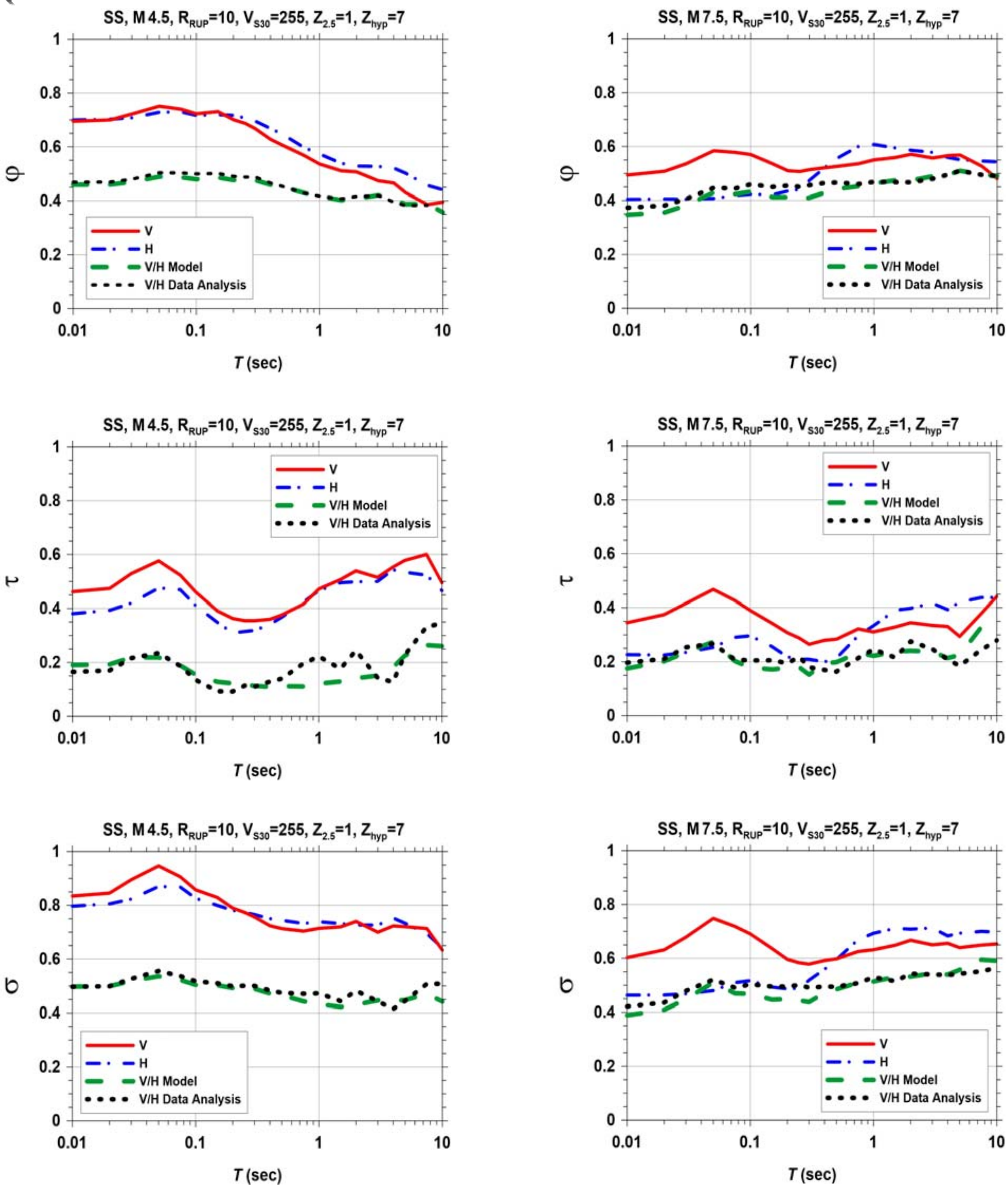


Figure 4. Within-event (top panels), between-event (middle panels), and total (bottom panels) standard deviations of the vertical ("V", Bozorgnia and Campbell 2016a), horizontal ("H", Campbell and Bozorgnia 2014), and V/H ("V/H Model" from theoretical formulation in this study; Bozorgnia and Campbell, 2016b). Also shown are the V/H standard deviations computed directly from the residuals of the V/H GMM of this study from the NGA-West2 empirical data ("V/H Data Analysis"). The plots are for $R_{RUP} = 10$ km, $V_{S30} = 255$ m/sec, and $\mathbf{M} = 4.5$ (left panels) and $\mathbf{M} = 7.5$ (right panels).

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