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REVIEW OF SITE RESPONSE MODELING CONDITIONAL ON HVSR

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ABSTRACT

Frequency-dependent horizontal-to-vertical spectral ratios (HVSRs) of three-component recordings can provide useful information on site resonant frequencies, which may be useful for predicting site response. Despite this potential, HVSR-conditioned site response models have not been adopted in the ground motion models most often employed for ground motion prediction in the United States and most global regions. We suggest that this stems from HVSR data resources being unavailable to support model development until recently, ongoing questions related to how HVSR should be measured and interpreted, and lack of consensus on how HVSR data should be utilized for site response prediction. Despite those challenges, we argue that the stage is set for future implementation of HVSR-conditioned models because a public dataset is now available, it is increasingly recognized that models should be conditioned on microtremor-based HVSR (mHVSR), and several modeling approaches have appeared in recent literature. This brief article focuses on site response modeling approaches, which include machine learning methods, models conditioned on mHVSR ordinates, and models conditioned on attributes of mHVSR peaks (i.e., peak frequency, amplitude, and width) or the lack of peaks.

Keywords: Site response, microtremors, HVSR

INTRODUCTION

In U.S. seismic design practice, ground motions are derived using one of two general approaches: (1) probabilistic seismic hazard analyses that use ergodic ground motion models (GMMs), either for specific sites or for national maps (Petersen et al. 2023) or (2) site-specific seismic hazard analyses in which site response is modeled for the individual site and the results are merged with reference site hazard results to estimate surface ground motions. This paper focuses on the first type of analysis. The GMMs used in such analyses include site amplification models conditioned on simplified site parameters, such as the time-averaged shear-wave velocity in the upper 30 m (V_{S30}) and depths to shear-wave velocity isosurfaces. These parameters only partially characterize the underlying site conditions and are generally unable to capture site-specific effects such as resonances caused by large impedance contrasts.

Horizontal-to-vertical spectral ratios (HVSR) can identify site resonances from peaks in HVSR-frequency curves. In particular, the fundamental resonance frequency (f_0) has been found to be associated with the lowest-frequency peak in microtremor HVSR curves (e.g., Lermo and Chávez-García, 1993), which are denoted mHVSR. Despite this promise, utilization of HVSR in the derivation of design ground motions has been limited. We posit that there are several historical reasons for this that have been addressed in recent years, setting the stage for future implementation. One major reason is the lack of availability of mHVSR data co-located with ground motion recording stations to the broader research community relative to alternative site metrics such as V_{S30} and depth parameters that appear in Next Generation Attenuation (NGA) databases. However, this data gap has been addressed by the addition of mHVSR data to the Shear Wave Velocity Profile database (Wang et al. 2022), which currently contains mHVSR data for ~700 sites across the U.S. Another obstacle has been the conditioning of some early HVSR models (Ghofrani and Atkinson 2014; Kwak et al. 2017; Hassani and Atkinson 2018) on earthquake signals (eHVSR) – such models cannot be used in forward application because mHVSR and eHVSR have distinct characteristics for an appreciable percentage of sites (Wang et al. 2023) and eHVSR data is seldom available for forward applications.

As we look towards a future in which mHVSr-conditioned models may be used for practical applications, we briefly summarize three general modeling approaches that have been used in recent work. These are machine learning methods, models conditioned on mHVSr ordinates, and models conditioned on attributes of mHVSr peaks (i.e., peak frequency, amplitude, and width) or the lack of peaks. Each of these models use estimates of site response derived from ground motions through residuals analysis, in particular using site terms derived from mixed effects analyses.

MACHINE LEARNING MODELS

Machine learning models use different methods to “map” input parameters to predicted quantities (“output”). In the present context, the input parameters are derived from HVSr curves (e.g., fundamental frequency, amplitude, etc.) and the output is site response, taken as the sum of site terms and the ergodic model prediction for a given site. These methods frequently do not provide equations that can be applied in forward application. In some cases, papers presenting machine learning models provide access to numerical tools and in other cases they do not. Where access is provided, it functions essentially as a black box in the sense that the operations that occur within the tool are opaque to users. Model performance is generally assessed based on reduction to site-to-site variability (ϕ_{S2S}).

Figure 1 shows ϕ_{S2S} reduction relative to a baseline GMM of machine learning-based HVSr models (Esteghamati et al. 2022). The baseline GMM does not consider HVSr. The uncertainty reduction is up to 0.2 at periods ranging from about 0.5-0.8 sec, which is appreciable. These models were trained on parameters derived from eHVSr curves. Subsequent work by Ornelas et al. (2025a, 2026a) used mHVSr data and various mHVSr attributes (ordinates and peak fit parameters).

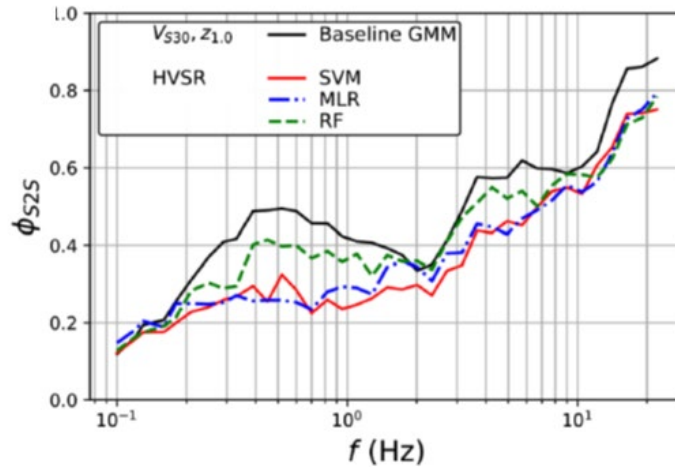


Figure 1. Reduction of ϕ_{S2S} from eHVSr-conditioned machine learning models (Esteghamati et al. 2022)

PARAMETRIC MODELS USING HVSr ORDINATES

As the term is used here, “parametric models” refer to equations and regression coefficients that are provided in the model documentation. As such, the models are more transparent and interpretable than machine learning models. Pinilla-Ramos et al. (2022) presented such a model to predict site terms (denoted here η_S) using a linear model in which the independent variable is $HVSr^*(T)$, defined as

$$HVSr^*(T) = \frac{mHVSr(T)}{mHVSr(0.25-15Hz)} \quad (1)$$

where $HVSr(T)$ is an individual ordinate at $T = 1/f$ and the denominator is the average of ordinates between $f = 0.25$ to 15 Hz. An example linear model for 1.5 sec spectral acceleration is shown in Figure 2, which shows positive and negative values of $HVSr^*(T)$ tend to produce stronger- and weaker-than-average site response, respectively. The data used in these analyses are from 196 sites in California, which were not made available and therefore have not been used in studies by others. Application of models like that in Figure 2 produced reductions of ϕ_{S2S} on the order of 10% for periods > 0.4 s.

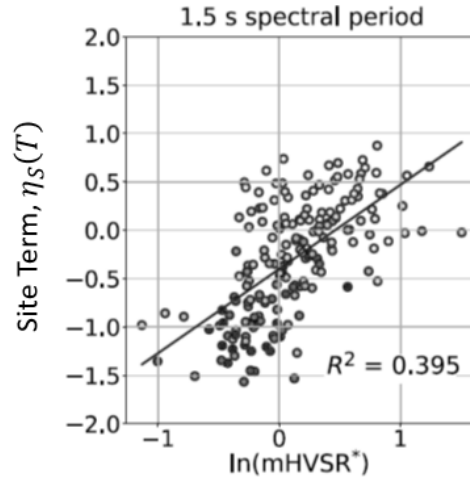


Figure 2. Data and linear model fit showing dependence of site terms for 1.5 sec spectral acceleration on $HVSR^*(T)$ as derived from Eq. (1) (adapted from Pinilla-Ramos et al. 2022)

PARAMETRIC MODELS USING HVSR FEATURES

Parametric models derived from HVSR features do not use HVSR ordinates directly, but instead use parameters derived from them such as peak frequency. These models use either the site term directly or site response as the modeled quantity. The HVSR parameters that have been considered in different models include peak frequency (either the tallest peak or the lowest prominent peak), peak amplitude, and an index indicating whether a peak was identified.

The first parametric models were presented by Ghofrani and Atkinson (2014) (data from Japan and California) and Hassani and Atkinson (2018) (data from central and eastern North America). These studies used eHVSR peak frequency derived from response spectral ratios (the highest amplitude peak was used when eHVSR contains multiple peaks). Figure 3 illustrates how the models were developed, which was by plotting site response against site frequency and modeling trends with a series of line segments. A similar approach using data from California and residuals of a geomorphic province-based model was recently presented by Roberts et al. (2026).

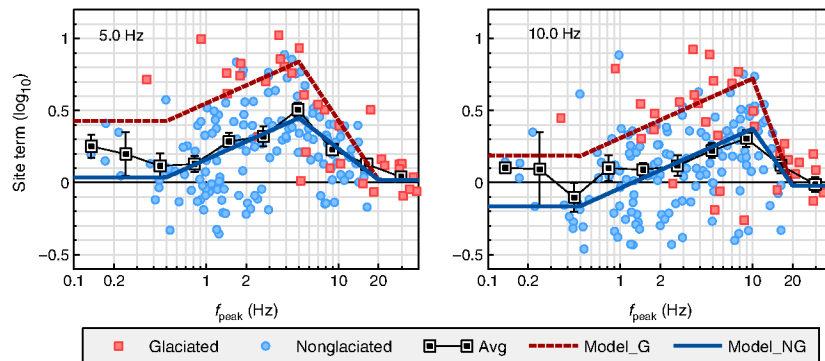


Figure 3. Variation of site response relative to GMM reference condition with frequency of highest peak in eHVSR as computed from response spectral ratios. Data shown separately for glaciated and non-glaciated portions of central and eastern North America with fit lines (Hassani and Atkinson, 2018)

A different modeling framework involves (1) development and application of protocols for identifying peaks in HVSR curves and site term vs. frequency plots; (2) for sites with peaks, developing relationships to predict site response peaks from HVSR features; and (3) for sites without peaks, developing period-dependent adjustment factors. This approach was first used with Japanese data and eHVSR by Kwak et al. (2017). It was then used with mHVSR for local soft soil regions in Japan and California by Wang et al. (2022) and Buckreis et al. (2024), respectively. It is currently being used with a broader California data set, with preliminary results in Ornelas et al. (2025b).

CONCLUSIONS

Advantages and disadvantages of the aforementioned modeling approaches are as follows:

Machine Learning Methods: Advantages of this approach include the largest observed reductions of ϕ_{S2S} and the ability of the routines to identify dependencies that might otherwise be missed. Disadvantages are that the relationships between independent and dependent variables can be unclear; this obfuscation creates difficulties in forward application (e.g., assessing whether a model is likely to be effective outside of its calibration region) (Ornelas et al. 2026b).

Parametric Models, HVSR Ordinates: Advantages include model simplicity and the clear trends in the data that are reported, especially for $T > \sim 0.4$ sec. Disadvantages are that mHVSR ordinates are known to have a high degree of spatial and temporal variability, so conditioning on such ordinates is potentially problematic, and ϕ_{S2S} reductions are relatively small.

Parametric Models, HVSR Features: Advantages of these models are that they have a strong physical basis (i.e., relationships between mHVSR and site response peaks). Disadvantages are that such models are not currently available outside of narrow application regions and ϕ_{S2S} reductions are modest.

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