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Extrapolation Algorithm for Computing $z_{1.0}$ From Shallow Measured Velocity Profile

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ABSTRACT

Ground motion models (GMMs) use depth to shear wave velocity (V_S) isosurfaces to quantify site response effects arising from sediment thickness, with $z_{1.0}$ (i.e., the depth to V_S = 1000 m/s) often used. However, direct measurements of $z_{1.0}$ are rare, and $z_{1.0}$ is poorly resolved in tomographic measurements often used to develop community velocity models (CVMs), particularly in shallow layers and near basin edges. To address this challenge, we present an algorithm for estimating $z_{1.0}$ for shear wave velocity profiles that do not reach V_S = 1000 m/s. The model is conditioned on the shear wave velocity at the bottom of the profile, $V_S(z_p)$, and the average gradient near the bottom of the profile (dV_S/dz). Using 253 direct $z_{1.0}$ measurements from the shear wave velocity profile database (VSPDB), we regressed coefficients for $V_S(z_p)$ = 500 to 1000 m/s. We then used the algorithm to extend 622 V_S profiles that reach ≥ 500 m/s, but not 1000 m/s, and quantify distributions of $z_{1.0}$ based on surficial geologic unit. These relationships are useful at locations where a velocity profile and reliable CVM-based estimate are not available. The resulting dataset enhances development of site response terms in GMMs, especially in regions where basin depth data are sparse or unreliable, supporting more accurate seismic hazard assessment.

INTRODUCTION

Ground motion models (GMMs) are essential for seismic hazard assessment (e.g., Abrahamson et al. 2014; Boore et al. 2014; Campbell and Bozorgnia 2014; Chiou and Young 2014), and involve event, path, and site effects. Site response predictions are particularly complicated in sedimentary basins where multidimensional subsurface conditions influence ground motion amplification. These GMMs rely on $z_{1.0}$ or $z_{2.5}$, which are the depths at which the shear-wave velocity (V_S) first exceeds 1000 m/s or 2500 m/s, respectively. Accurate estimation of $z_{1.0}$ is therefore important for reliable seismic hazard assessments. Currently, community velocity models (CVMs) are the primary source for determining $z_{1.0}$, but they often lack resolution at shallow depth, where the velocity structure is defined by a geotechnical layer that is constrained by local velocity measurements and judgment. Geotechnical layers are generally available within sedimentary basins, but not in sedimentary rock units outside of basins (Small et al., 2017; Graves et al., 2019). As a result, $z_{1.0}$ from CVMs is often zero in these units, even when the time-averaged V_S in the upper 30 m (V_{S30}) < 1000 m/s, which is a logical inconsistency. Furthermore, velocity profiles that do not reach 1000 m/s are often available at ground motion recording station locations, but a model for estimating $z_{1.0}$ from these profiles has not been developed.

To address these challenges, we herein present an extrapolation model based on measured V_S profiles from the shear-wave velocity profile database (VSPDB, Kwak et al., 2021). The model is based on 253 V_S profiles that reach or exceed 1000 m/s with locations shown in Figure 1, following the steps presented in the next section. The model is suitable for direct application at sites with a measured profile that reaches at least 500 m/s, but not 1000 m/s. However, $z_{1.0}$ is often desired at sites where geophysical measurements are unavailable. Toward this end, we use the extrapolation model to compute $z_{1.0}$ and its uncertainty at locations in California that reach at least 500 m/s but not 1000 m/s. These extrapolations are then aggregated for various surficial geologic units (Wills et al. 2015) to form the basis of a model that can be applied where geophysical measurements and a reliable CVM with a suitable geotechnical layer are absent. The models presented herein have been used to compute $z_{1.0}$ values for the NGA-West3 database (Buckreis et al 2025a & b) and are being used in ongoing northern California basin modelling efforts (Mohammed et al. 2025).

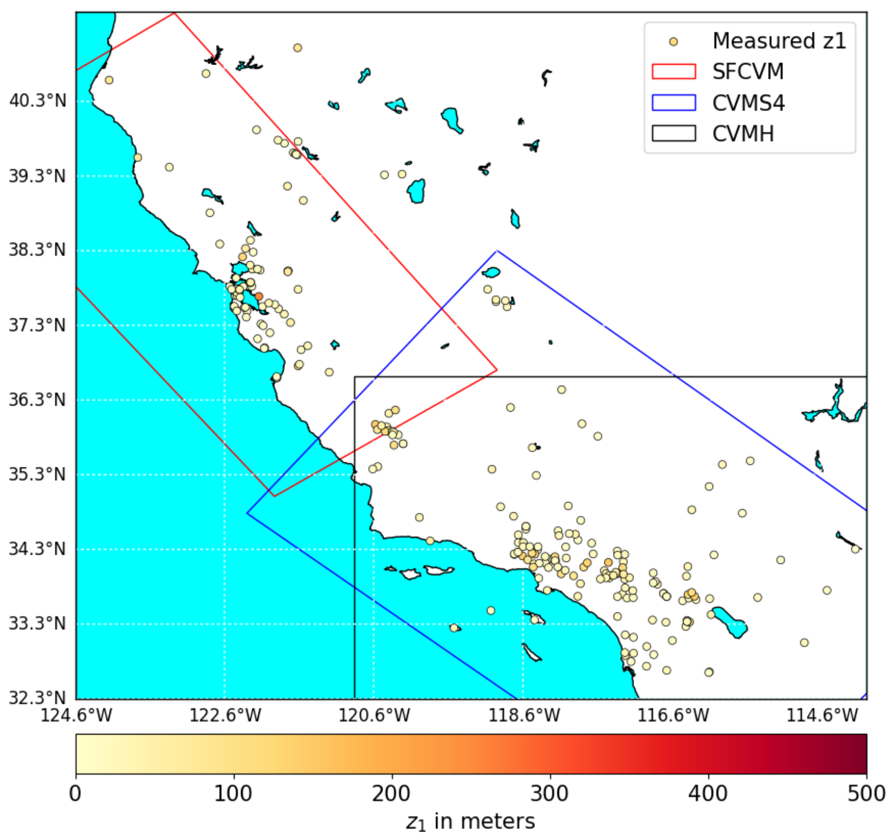

Figure 1. Map of velocity profiles exceeding 1000 m/s in VSPDB for CA. The boundaries represent CVM domains for SFCVM 21.1 (Aagaard and Hirakawa, 2021), CVMS4 (Lee et al. 2014) and CVMH 15.1.1 (Shaw et al. 2015).

EXTRAPOLATION MODEL

The extrapolation model is conditioned on the shear wave velocity at the bottom of the profile, V_S (z_p), and a gradient term near the bottom of the profile (dV_S/dz). We incorporated the gradient term to reflect geologic conditions in which unconsolidated sediment transitions to sedimentary rock, which often results in a change in gradient that has predictive power for estimating $z_{1.0}$. Defining V_S (z_p) and the surficial geologic unit are straightforward, but the definition of gradient is non-trivial. For example, the tangent slope at the bottom of a profile is highly variable and may be negative in some cases. However, the secant between the surface and the bottom of the profile may smooth over details that reflect a geologic transition from unconsolidated sediment into rock. We explored five methods to compute dV_S/dz, each capturing different aspects of velocity variation within profiles:

1. Method 1: Average gradient over the last five meters of the profile, emphasizing sharp transitions near the base.
2. Method 2: Average gradient from the surface to z_p, capturing the overall velocity trend but potentially smoothing local transitions.
3. Method 3: Average gradient from 1/2 z_p to z_p, focusing on the bottom half of the profile.
4. Method 4: Average gradient for depth interval from 2/3 z_p to z_p, focusing on the bottom 1/3rd of the profile.
5. Method 5: Average gradient between the depth where 2/3 of the change in V_S has occurred to z_p, focusing on the bottom portion of the profile containing 1/3 of the velocity change.

Among these, Method 5 was found to be the most stable, making it the preferred approach for developing the $z_{1.0}$ extrapolation model. The choice for method 5 We believe this is because it focuses on changes in velocity rather than arbitrarily assigned depths and therefore is better equipped to capture geologic contacts.

The functional form of the model is provided in Eq. 1, where β_0, β_1, and β_2 are regression coefficients, $\sigma_{ln\Delta z1}$ is the standard deviation of the model error. Eq. 1 is valid for V_S (z_p) up to 1000 m/s. Δz_1 is a difference between depth at base velocity in the profile (z_p) and $z_{1.0}$. The limit of Eq. 1 as V_S (z_p) approaches 1000 m/s is Δz_1 = 0, which ensures that the model extrapolates properly. Furthermore, Δz_1 is assumed to be lognormally distributed, which means that its standard deviation decreases as Δz_1 decreases, ultimately becoming zero when $V_S(z_p)$ = 1000 m/s. In this manner, more uncertainty exists in profiles that are extrapolated from lower V_S (z_p) values.

$$\ln(\Delta z_1) = \beta_0 \ln[1000 - V_S(z_p)] + \beta_1 \ln\left(\frac{dV_S}{dz}\right) + \beta_2 + \sigma_{ln\Delta z1} \quad (1)$$

The model was developed by identifying 253 V_S profiles in the VSPDB that reach at least 1000 m/s, assigning a surficial geology unit to each profile, truncating the profiles at z_p values from 500 to 950 m/s in increments of 50 m (as if the profiles were terminated before reaching $z_{1.0}$), computing z_p and dV_S/dz for these truncated profiles, and regressing the model coefficients in Eq. 1. Figure 2 shows ln(Δz_1) vs. 1000 – V_S (z_p). The trend is observed to be reasonably linear and homoscedastic, which supports linear regression in this space. As dV_S/dz increases, Δz_1 decreases, which is the expected trend since 1000 m/s would be expected at shallower depths for sites with a steep gradient. Model coefficients are presented in Table 1.

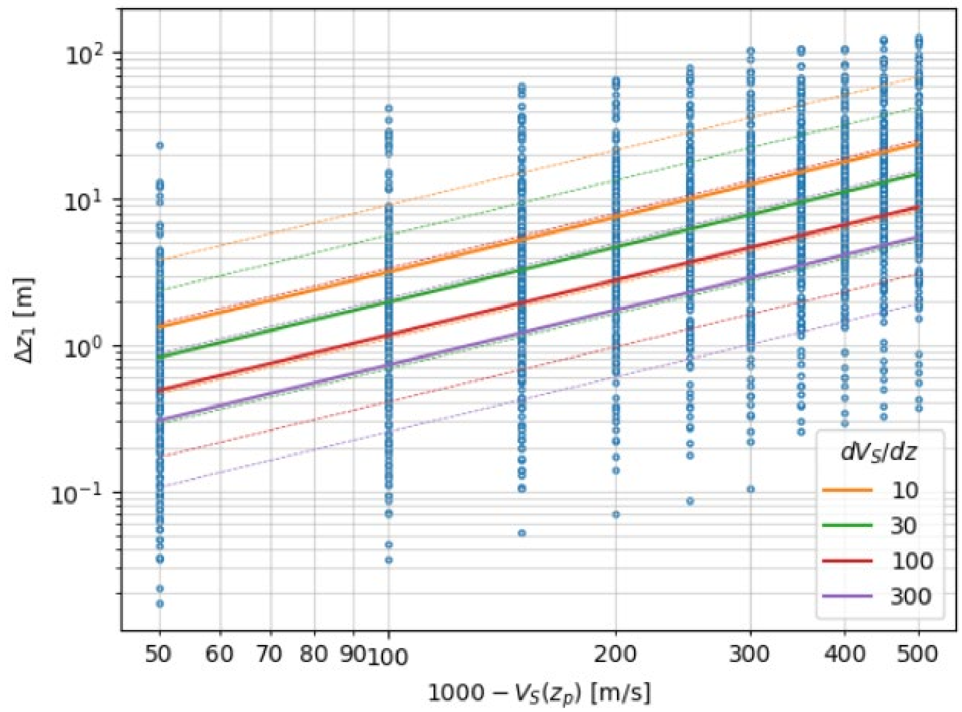

Figure 2. Values of Δz_1 as a function of $1000 - V_S(z_p)$.

Table 1. Model regression coefficients.

β_0	β_1	β_2	$\sigma_{ln\Delta z1}$
1.254	-0.431	-3.634	1.053

After computing Δz_1 from Eq. 1, the expected value of $z_{1.0}$ is obtained using Eq. 2.

$$z_{1.0} = z_p + \Delta z_1 \qquad (2)$$

Residuals were calculated as the difference between the observed $\ln(\Delta z_1)$ and the predicted $\ln(\Delta z_{predicted})$, and $\sigma_{ln\Delta z1}$ was computed as the standard deviation of the residuals.

GEOLOGY-BASED AVERAGE $z_{1.0}$ VALUES

Using the basin depth extrapolation model above, we estimate $z_{1.0}$ for 622 *Vs* profiles in California that reach $Vs \geq 500$ m/s but not 1000 m/s. Figure 3 illustrates the cumulative distribution of *Vs* profiles exceeding various velocity thresholds, highlighting a total of 875 profiles where $Vs \geq 500$ m/s of which 253 profiles were used for model development, while the remaining 622 were extrapolated to $z_{1.0}$.

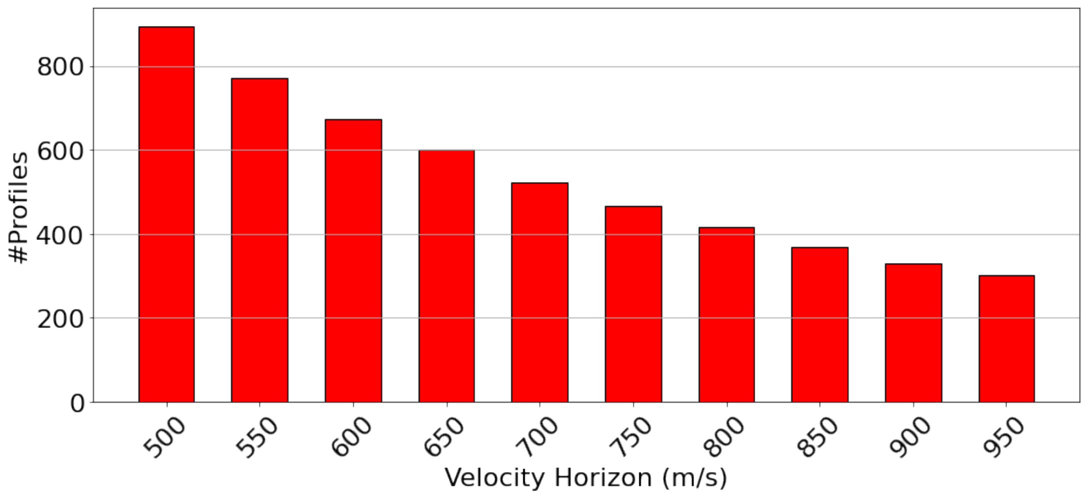

Figure 3. Number of profiles in CA from VSPDB exceeding different velocity horizons.

We computed $z_{1.0}$ values for all of these profiles and subsequently binned them according to geologic units from Wills et al. (2015). Two sources of error are present in the estimated $z_{1.0}$ values: extrapolation error for profiles that do not reach 1000 m/s, and measurement error for all profiles. The extrapolation error is represented by the $\sigma_{ln\Delta z1}$ term and increases as $1000 - V_S\,(z_p)$ increases. For simplicity, we assumed that the measurement error of $\ln(\Delta z_1)$ is normally distributed with a standard deviation of 0.1. The variance of the total error is computed as the sum of the variances of the extrapolation error and the measurement error.

Figure 4 shows weighted mean and standard deviations for $z_{1.0}$ for each geologic unit in California, where weights were assigned as the inverse of the variance of the total error. The figure clearly shows differences with respect to surficial geology. We suggest that these values provide a means for estimating $z_{1.0}$ and its uncertainty at locations in California where a velocity profile is unavailable, and where a CVM with a suitable geotechnical layer is also unavailable. The relationship is scalable as it allows for continual updates as new V_s profiles become available and may ultimately be extended to interpolation methods such as Kriging once spatial correlation structures have been defined. We have not yet performed this work, though plan to do so in the future.

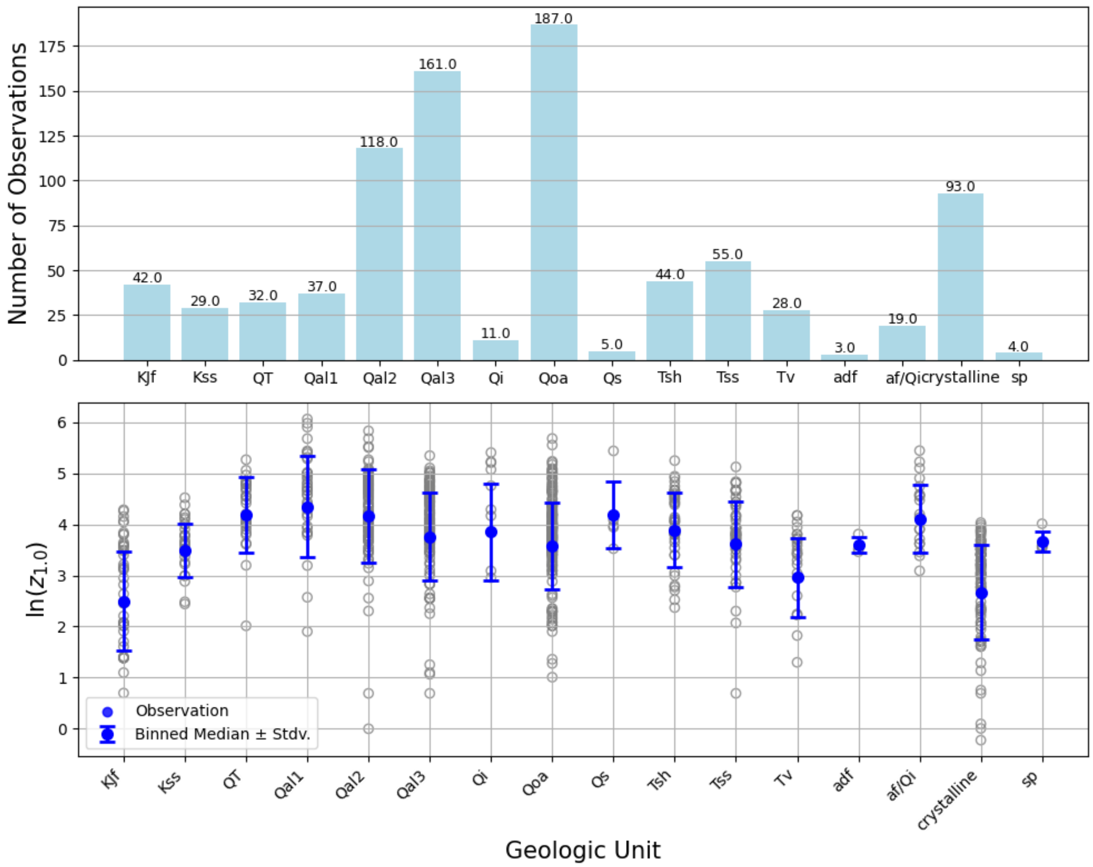

Figure 4. Top panel plots number of measured/or extrapolated V_s profiles in each geologic unit while bottom panel plot summarizes mean and standard deviation for $z_{1.0}$ (from both measured and extrapolated profiles) within each geologic unit.

DISCUSSION

The extrapolation model was derived from velocity profiles that reach 1000 m/s, which is more likely to occur for profiles where $z_{1.0}$ is shallow. For this reason, there is likely sampling bias in the profiles used to form the extrapolation model. In particular, profiles that reach 1000 m/s at locations with quaternary surficial geology are often located near basin edges rather than in the middle of sedimentary basins. Sampling bias can only reasonably be evaluated by gathering deeper profiles in locations where sediment is thick. Errors in the extrapolation algorithm are likely to increase as V_S (z_p) decreases. We therefore urge caution when using the model to extrapolate shallow profiles in deep basins, and suggest performing deeper geophysical measurements, or using CVMs with suitable geotechnical layers to assign $z_{1.0}$.

The proxy model has limitations, as it simplifies local geological variability, averaging $z_{1.0}$ values across broad geologic units, which may overlook site-specific heterogeneities in sediment thickness or velocity transitions. Additionally, its accuracy depends on the quality and density of measured $z_{1.0}$ data used for calibration. However, we suggest that the proposed geology-based model is particularly useful at sedimentary rock locations without a measured profile, where CVMs predict $z_{1.0} = 0$.

We computed standard deviation and residuals for sites binned by geology to validate model performance where models showed good performance and decreasing standard deviation with increasing $V_S(z_p)$. These models are being utilized to provide improved $z_{1.0}$ estimates for a subset of ground motion recording stations at sites located in California for the NGA-West3 database (Buckreis et al. 2025). The extrapolation model described by Eqs. 1 and 2 is used at sites located outside of deep sedimentary structures when a nearby V_S profile with 500 m/s ≤ $V_S(z_p)$ < 1000 m/s is available. The geology-based $z_{1.0}$ estimates presented in Figure 4 are used at sites in Quaternary and Tertiary deposits located outside of deep sedimentary structures when there is no nearby V_S profile. At sites located inside of deep basins, where we believe CVMs to be well calibrated, we recommend the CVM-based estimates to be used, unless $z_{1.0}$ can be obtained from a measured V_S profile.

CONCLUSION

This study develops a $z_{1.0}$ extrapolation model to improve/supplement basin depth estimates for ground motion sites in California. Using a dataset of V_s profiles extending to 1000 m/s, the model captures velocity-depth relationships and provides reliable $z_{1.0}$ predictions for sites with incomplete profiles. A geology-based proxy model further refines estimates in non-basin regions, addressing limitations of CVMs. While the model enhances seismic hazard assessments by reducing uncertainty in site amplification predictions, its applicability in deep basins is limited due to the dataset's non-basin bias. Future improvements include expanding the V_S profile dataset and incorporating basin-specific adjustments. Also studying geologic dependence of model estimates and developing a standard deviation model. By integrating measured, extrapolated, and proxy-based $z_{1.0}$ estimates, this framework improves site response modeling and supports resilient infrastructure design in earthquake-prone regions.

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