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A Soil Velocity Model for Improved Ground Motion Simulations in the U. S. Pacific Northwest

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Abstract Near-surface seismic velocity structure may significantly impact the intensity, duration, and frequency content of ground shaking during an earthquake. In this study, we compile 649 shear wave velocity (Vs) profiles throughout the U.S. Pacific Northwest and southern British Columbia (PNW) and use these measured profiles to develop a representative soil velocity model for four major Holocene soil provinces: Puget Lowlands, Willamette Valley, fill and alluvium, and 'other' soils. The resulting soil velocity model shows good agreement to measured data for a wide range of site conditions, with variability between different geologic domains reflecting fundamental differences in depositional environments. We then show that using this regional soil velocity model in simulations of the 2001 M6.8 Nisqually, Washington earthquake improves the fit to observed high-frequency ($\geq$ 0.5 Hz) ground motions in the Puget Sound region compared to simulations that do not incorporate shallow ($\leq$ 200 m) seismic velocity structure. Overall, this work shows that incorporating localized soil velocity profiles into seismic velocity models is important for accurately estimating high-frequency ground motion and regional seismic hazard in earthquake simulations. Future earthquake simulations and hazard studies in the PNW could incorporate these soil velocity profiles to capture the region's distinct site response characteristics.

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1 Introduction

The Pacific Northwest (PNW) of North America (defined here as Washington and Oregon States, and southern British Columbia) is a geologically diverse and seismically active region that includes the densely populated Puget Sound area (Olympia, Tacoma, Seattle, and Everett, WA), the Willamette Valley (Portland, Salem, Corvallis, and Eugene, OR), and Vancouver, BC. Seismic hazard throughout the region is high (Petersen et al., 2023; Kolaj et al., 2020) due to possible earthquakes on the offshore Cascadia Subduction Zone, numerous shallow faults in the North American plate, and deep intraslab events in the subducting Juan de Fuca plate. However, few strong ground motion records exist within the PNW for local earthquakes, which limits development and validation of empirical ground motion models for the region. This lack of empirical earthquake data is compounded by the complex network of deep sedimentary basins and Quaternary sediment history throughout the region (e.g., Delorey and Vidale, 2011; Molnar et al., 2014; Stone et al., 2021) that may produce high ground motion amplifications at frequencies impacting tall buildings and critical infrastructure (< ~1 Hz; e.g., Marafi et al., 2019; Somala et al., 2022; Kourehpaz et al., 2020). Available ground motion recordings from the 2001 M6.8 Nisqually, Washington intraslab earthquake and other small-to-moderate magnitude events show complex patterns of strong shaking amplification due to basin amplification and shallow site response (e.g., Frankel et al., 1999, 2002; Thompson et al., 2020; Frankel and Grant, 2020; Rekoske et al., 2021). To account for these complexities in the absence of empirical data, hazards research has increasingly relied on direct simulation of earthquakes. Earthquake simulations employ realistic source, velocity, and site effects to model 3-D seismic wave propagation and constrain estimated shaking intensities. In the PNW, such simulations have been shown to match observed basin amplifications much better than empirical ground motions models (e.g., Frankel et al., 2018). Direct simulations of earthquakes in the PNW are therefore critical to constraining regional seismic hazard and provide a robust means to plan for future earthquake scenarios by state and federal agencies.

Direct earthquake simulations in the PNW (e.g., Frankel et al., 2018; Wirth et al., 2018; Wirth and Frankel, 2019; Stone et al., 2022, 2023; Roten et al., 2019) have typically relied on the Stephenson et al. (2017) Cascadia Velocity Model (CVM). The CVM was developed to support earthquake simulations in the PNW, modeling regional variations in P- and S-wave velocities in the crust, as well as explicit characterization of sedimentary basins with low seismic velocities (Stephenson et al., 2017). While essential for current earthquake simulations in the PNW, the near-surface resolution of the CVM and relatively high minimum shear-wave velocity (Vs) of 600 m/s does not facilitate direct simula-

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tion of high frequency (> 1 Hz) ground motions (e.g., Stone et al., 2023). To address the lack of near-surface sediment characterization in the CVM, previous direct earthquake simulations of great Cascadia subduction zone earthquakes (e.g., Frankel et al., 2018; Wirth et al., 2018) have adopted a generic western U.S. soil velocity model (Boore and Joyner, 1997), applied high-frequency site corrections as a post-processing step (Wirth et al., 2020), or proposed local adjustments to the CVM based on available near-surface Vs profile measurements (e.g., Stone et al., 2023). In particular, Stone et al. (2023) found that incorporating Vs_{30}-dependent (the time averaged Vs in the top 30 m) soil velocity profiles into the CVM substantially improved the fit between simulated high frequency (i.e. > 1 Hz) shaking and the estimates of typical ground motion models for crustal earthquakes. Similar efforts in Southern California (e.g., Yeh and Olsen, 2024), using the 'geotechnical layer' of Ely et al. (2010) and the soil velocity model of Shi and Asimaki (2018), show improved fits to real events when incorporating more realistic soil velocities.

Previous work to develop representative soil velocity profiles in the PNW have aggregated all available data to make singular 'generic' profiles for the region (Marafi et al., 2021; Wirth et al., 2020). Marafi et al. (2021) proposed a generic soil velocity profile for the PNW using a subset of the Ahdi et al. (2017) compilation of Vs measurements and demonstrated the improved performance of a region-specific SVM over that developed elsewhere (the Shi and Asimaki (2018) model for Southern California). A key consideration in the development of the Marafi et al. (2021) generic profile was the exclusive use of Vs measurements that included Vs ≥ 1.0 km/s. The resulting model employed the depth to 1 km/s velocity (Z1.0) to differentiate between basin and non-basin profiles. However, this choice meant a significant proportion of the profiles used in model development (180 of 218) were several kilometer (km) profiles with little resolution at shallow (< 100 m) depths. In contrast, Wirth et al. (2020) only employed the shallow Vs measurements compiled by Ahdi et al. (2017), developing an alternative PNW soil velocity model which they used to compute high-frequency site response in support of simulation-based, ensemble ShakeMaps of M9.0 CSZ earthquakes (ensemble ShakeMaps available from: https://earthquake.usgs.gov/scenarios/catalog/cszm9/). Following the methodology of Wirth et al. (2020), Stone et al. (2023) proposed a shallow soil velocity model based only on glacial Vs profiles in the Puget Lowlands to model Tacoma Fault earthquake ground motions up to 2.5 Hz.

Each of the soil models described above either focuses on a single geologic material (Stone et al., 2023) or neglects the variability in near-surface velocity structure that may arise from the considerable differences between PNW depositional environments (Marafi et al., 2021; Wirth et al., 2020). Differences in surface geology have long been known to influence site response and site characterization (e.g., Borcherdt, 1970; Su et al., 1992; Joyner and Boore, 1988). Unsurprisingly, estimates of site condition (e.g., Vs_{30}) within the PNW show a strong dependence on mapped surficial geology (e.g., Ahdi et al., 2017, 2022). For example, Frankel et al. (2002) noted 1 Hz shaking in fill and alluvial sediments was amplified by a factor of 3–7 relative to local rock sites in Seattle during the 2001 M6.8 Nisqually earthquake. These zones of maximum site amplification also hosted the most significant damage and liquefaction during the earthquake.

In this study, we develop a Soil Velocity Model (SVM) for the PNW by explicitly characterizing unique geologic domains, including the glaciated Puget Lowlands, outburst flood deposits of the Willamette Valley, Anthropogenic fill and Holocene alluvium, and a generalized 'other' class for data-poor regions. The resulting SVM predict Vs as a function of depth based on a compilation of 649 measured Vs profiles. The SVM is shown to improve estimates of Vs as a function of depth in the upper 50 m of the subsurface over existing PNW soil models (Marafi et al., 2021; Wirth et al., 2020). The resulting SVM is then used to modify the CVM, reducing its minimum Vs to ~ 100 m/s, to simulate the 2001 M6.8 Nisqually, Washington earthquake. We compare simulations of ground motions with (CVM+SVM) and without (unmodified Stephenson et al., 2017, CVM) the soil velocity model to recorded ground motions from the Nisqually earthquake. Simulations that include the SVM show improved fit to observational data, with reductions in bias at frequencies ≥ 0.5 Hz.

2 Study Region and Geologic Background

The PNW is bound to the west by the Cascadia Subduction Zone, an active convergent margin that influences much of the region's topography and seismic hazards (Petersen et al., 2023). In western Washington and Oregon, coastal mountain ranges are separated from the active volcanic front (within the older Cascade mountains) by a densely populated system of basins and lowlands, stretching from Vancouver, B.C., to southern Oregon. These lowland-basin structures include the Georgia and Bellingham Basins of southern B.C. and northern Washington (e.g., Lowe et al., 2003; Kelsey et al., 2012); the Everett-Seattle-Tacoma basin complex of the Puget Lowlands, Washington (e.g., Delorey and Vidale, 2011); and the Willamette Valley, Oregon (e.g., Frankel and Grant, 2020). In eastern Washington and Oregon, much of the region is underlain by the Columbia River Basalt flows and Missoula Flood deposits that fundamentally reshaped the landscape (Bretz, 1969). Multiple accreted terrains and the northern extent of the Basin and Range province further complicate the near-surface geologic mosaic of the eastern PNW. In addition to large-scale regional structures, near surface deposits across the region vary widely and include extensive deltaic soils in the Fraser River valley, glacial deposits of the Puget Lowlands, outburst mega flood sequences, and extensive loess.

To account for the significant geologic differences of near-surface sediments across the region, we define five generalized soil classes for SVM development based on two criteria: regional geologic significance, and data availability (N > 50 measured profiles). We considered the following geologic domains, defined in more detail below: the *Puget Lowlands* (Figure 1, white symbols); the *Willamette Valley* (purple symbols); *fill and alluvium* (red symbols); the *Fraser River delta* (yellow symbols), and *other* (Figure 1, blue symbols.) We do not attempt to model specific or generalized hard rock velocity profiles in this work due to both limited data and focus on near-surface velocities slower than the minimum Vs in the current Stephenson et al. (2017) regional velocity model (600m/s). Limits to the applicability of the proposed soil velocity models are defined by available shallow Vs data (see **Profile Selection and Model Fitting**) and regional similarities in sediment deposition and history.

Puget Lowlands sediments are defined in this study by the extent of repeated glacial advance and retreat of the Puget Lobe of the Cordilleran ice sheet during the Pleistocene (Booth, 1994; Booth et al., 2003) and the U.S.-Canada border to the north. This domain encompasses much of Washington State's populated Puget Sound region, from Olympia in the south to the Canadian border in the north, and includes the major cities of Tacoma, Seattle, and Everett. The soil class manifests primarily as a thick mantle of advance and recessional deposits from the Vashon stade of the Fraser glaciation, the boundaries of which were used to define the region of Puget Lowlands profiles modeled in this study (Booth, 1994; Washington Division of Geology and Earth Resources, 2016). Within the boundaries of the Puget Lowland, profiles were excluded from this category if located on mapped outcroppings of bedrock (i.e., *other*), or within mapped fill or Quaternary alluvium in the Seattle metropolitan area (i.e., *fill and alluvium*). Sites within the Fraser River delta in Canada were excluded here due to a lack of available data and the local significance of the Fraser River on near-surface deposits (see below).

Willamette Valley sediments encompass mapped glacial outburst flood (i.e. "Missoula Flood") deposits that mantle the landscape within the Willamette Valley and topographic lows near its confluence with the Columbia River. These deposits are composed of thick sequences (locally more than 35 m) of sediment transported during repeated glacial outburst floods between 21.4 – 14.3 kybp (Benito and O'Connor, 2003). In much of the Willamette Valley, these sediments are observed as rhythmically bedded sand and silt deposits that record as many as 40 flood events (Minervini et al., 2003). Closer to the primary flood channels (e.g., in modern day Portland, OR), coarser gravel facies are also observed. These deposits, which are distributed throughout the Willamette Valley and surrounding lowlands of Washington State, are collectively defined as the *Willamette Valley* sediments in this work. Individual profiles were assigned to this group if they are located within the mapped flood deposit boundaries of Burns and Coe (2012) and Minervini et al. (2003), and do not show evidence of near surface (< 10 m) bedrock. Other regions with widespread Missoula Flood deposits (e.g., the Touchet Beds of southeast Washington, including the cities of Walla Walla, Richland, Kennewick, Pasco, and Yakima) were omitted due to lack of local Vs profiles.

Fill and alluvium sites were defined by surficial geologic mapping of Quaternary alluvium and artificial fill deposits at a scale of 1:100k (Washington Division of Geology and Earth Resources, 2016) and the depth of fill mapping within Seattle (Frankel et al., 2007). *Fill and alluvium* profiles were only modeled using sites within the Puget Lowlands region due to data availability, though these recent alluvial and human depositional processes likely are similar throughout the region.

To ensure modeled geologic domains in this work were sufficiently represented by velocity profiles across a range of site conditions and locations, we imposed a minimum data requirement of 50 Vs profiles for inclusion. For all potential geologic domains not reaching this threshold (e.g., loess deposits in eastern Washington), profiles were pooled into a generalized *other* soil profile domain. While site characterization metrics (i.e. Vs_{30}) do produce meaningful differences for much more finely disaggregated geologic categories in the PNW (Ahdi et al., 2017), we do not consider those finer divisions here given the relative lack of data in each category for SVM development. All profiles not included in one of the above regions were used to predict Vs as a function of depth for this generic (i.e. *other*) PNW soil profile, which encompasses all sites in eastern Washington and Oregon, exposures of soft rock, and coastal sites in both States and southern British Columbia.

Sediments of the *Fraser River delta* are not explicitly considered in this work due to insufficient near-surface resolution. Most openly available *Fraser River delta* profiles compiled by this work and others are deep (> 1 km), typically with a single Vs measurement in the top 50 – 100 m of the subsurface. As this work is trying to capture the shape of velocity profiles in the PNW in the top tens of meters, we omit these data from all processing and analysis. However, we note that Assaf et al. (2022, 2023) used additional shallow velocity profiles and correlated Vs-CPT logs to develop Vs models for post-glacial soft sediments in the Fraser River delta. Future development of the CVM and regionally appropriate SVMs could consider the findings of Assaf et al. (2022, 2023) and the newly developed database of shallow Vs estimates therein to include this geologically distinct region.

Other significant surficial deposit regimes not explicitly considered in this work include the Palouse of eastern Washington, and extensive Columbia River Basalt (CRB) mantled regions of eastern Washington and Oregon. For the loess regions of the Palouse, and CRB, limited Vs profile data currently prohibit meaningful soil model development. Additionally, while deep sedimentary basins are a critical feature in ground motion simulation and seismic hazard in the PNW (e.g., Molnar et al., 2014; Frankel et al., 2018; Stone et al., 2022, 2023; Roten et al., 2019), we also do not divide our soil models within or outside of basins. Basins are not delineated as an explicit category because the existing regional velocity model (Stephenson et al., 2017) implicitly considers basin structure via its Quaternary and Tertiary sediment layers, and because the proposed SVMs only have

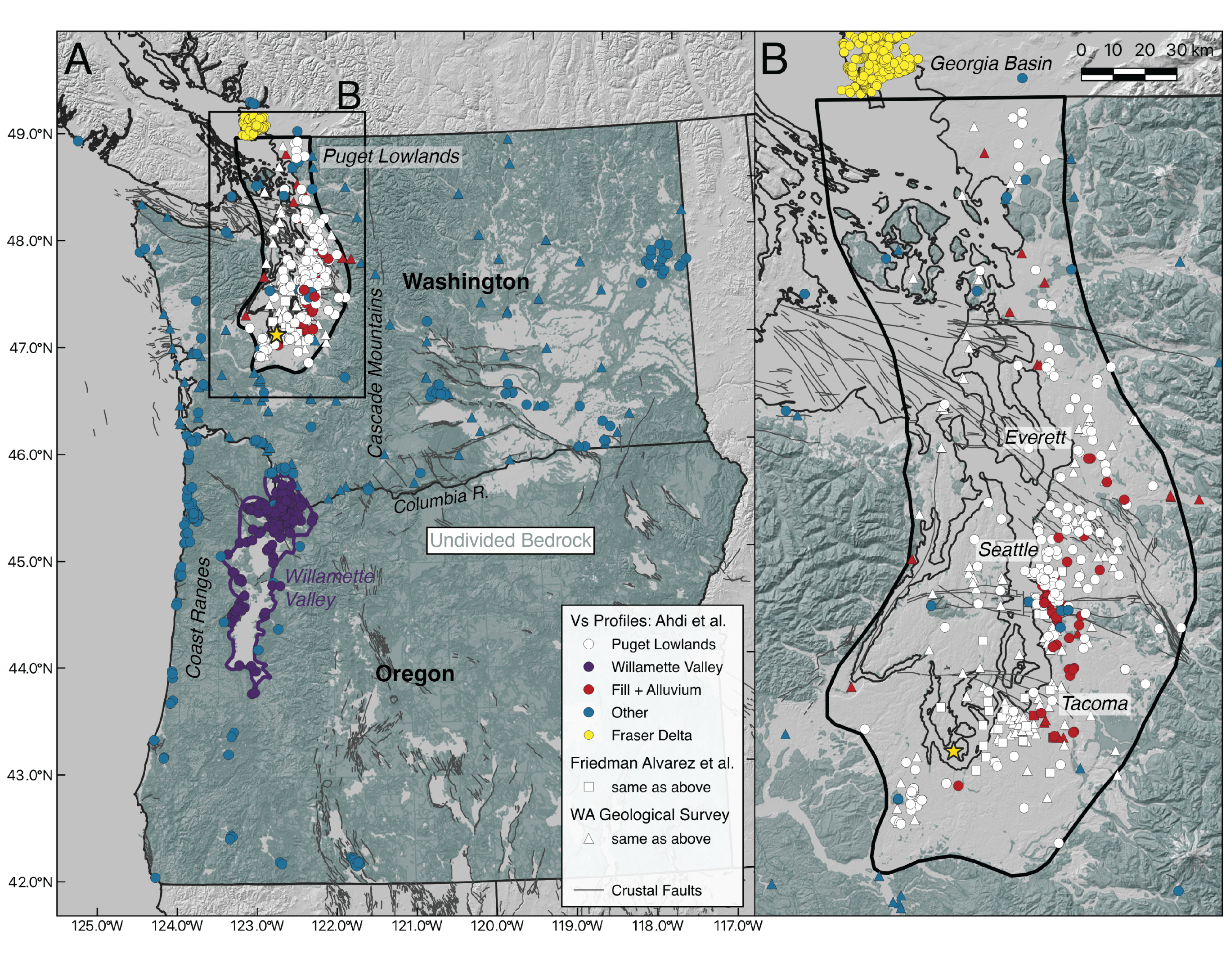

Figure 1 Regional overview showing the locations of measured shear wave velocity profiles used in this study (markers). Unshaded regions show areas of substantial Quaternary or unlithified surface cover including glacial deposits in the Puget Lowlands and outburst flood sediment in the Willamette Valley. Blue-green shading denotes undivided surficial bedrock not modeled in this study. Yellow star shows the epicenter of the M6.8 Nisqually earthquake used to compare changes to the velocity model against recorded ground motions. Thin black lines show mapped crustal faults in the PNW (United States Geological Survey, 2025).

a maximum depth of 100 – 200 m (depth-to-basement beneath the basins is typically a few-to-several kilometers).

3 Profile Selection and Model Fitting

To develop generic shallow soil profiles in the PNW, we compiled 1,058 Vs profiles from three openly available datasets. Most of these data come from the profile compilation of Ahdi et al. (2017), who compiled data from state and local sources in Washington, Oregon, and British Columbia as part of the NGA-Subduction effort, and that spans a variety of geophysical methods. We augmented the Ahdi et al. (2017) dataset with new shear wave velocity profiles from the Washington Geological Survey (WGS) Department of Natural Resources (DNR) as part of the School Seismic Safety program (Washington Geological Survey, 2021). Vs measurements from the WGS dataset include active source multi-channel analysis of surface waves (MASW) and microtremor array measurements (MAM). A third set of profiles within the Seattle and Tacoma basins were collected by Friedman Alvarez et al. (2024) using microtremor array data. Where the number of available Vs profiles allowed (the *Puget Lowlands* and *Willamette Valley*), post-2017 WGS profile data were withheld during model fitting as a test dataset. Post-2017 WGS data were included in the fitting of *other* profiles to provide a sufficiently large dataset for model development and to improve the geographic extent of coverage.

3.1 Profile screening

Following database compilation, we filtered all available profiles based on the following criteria. (1) Profiles with a maximum depth of 1000 m or more were excluded as these profiles typically were developed from passive methods with very poor resolution in the near-surface (typically one measured Vs value in the top 100 m). (2) A maximum Vs_{30} of 1,200 m/s was applied to filter out hard rock sites. (3) Large Vs(z) reversals (i.e., a large reduction in velocity with increasing depth) were removed to screen out profiles that may include layers of Columbia River Basalt flows or other thin rock layers between sediments (as is possible in the Portland and Tualatin basins, e.g., McPhee et al., 2014). A 200 m/s decrease in velocity between layers was adopted as a threshold to remove these complex hard-over-soft profiles, as well as to catch potentially erroneous profiles, while allowing for realistic velocity fluctuations with depth. (4) Measured profiles were required to have at least three datapoints of reported depth and velocity. Datapoint minimums were implemented to remove a handful of published data with one or two layers, typically extending less than 5 m into the subsurface, for stability in model fitting. During this process, 296 profiles are removed for being deeper than 1 km (182) or having invalid depth information, 41 profiles were removed for only having one or two depth-vs pairs, and 72 additional profiles were removed due to large (> 200m/s) Vs reversals with depth. In total, 649 Vs profiles were used to then fit geologic-domain specific SVMs across the PNW (Table 1). The resulting dataset includes 649 measured Vs profiles across the PNW concentrated in the populated Puget Lowlands (267 profiles) and Willamette Valley (107 profiles, Table 1).

Within each geologic domain, we then tested a series of functional forms for Vs as a function of depth, where the only predictor variables are Vs_{30} and Vs^{100} (the Vs at 100 m depth). Vs^{100} was sampled from the existing CVM to facilitate subsequent merging of the shallow soil and deep geology velocity models (see Wirth et al., 2025a,b). During model fitting, we used Vs_{30} computed directly from the available data, extrapolating to Vs_{30} estimates for profiles with less than 30 m of data following the method used in Ahdi et al. (2017). Tested models include those of Shi and Asimaki (2018), Boore and Joyner (1997), Wirth et al. (2020), and alternative mathematical relationships (power, logarithmic, and polynomial scaling with depth). Model performance was scored based on minimizing the root mean squared error (RMSE) and sum of the absolute value of residuals for model predictions of each profile along its entire depth.

4 Results

Using our compiled dataset of 649 Vs profiles in the PNW, we found Equation 1 yields the best unbiased estimator of Vs as a function of depth for three of the geologic domains in this work, the *Puget Lowlands*, *Willamette Valley*, and *other*. In these PNW depositional environments, changes in Vs with depth are best captured using a log term at shallow depths (i.e., modeling near surface curvature in the upper ~ 50 m) and linear term for intermediate depths, plus a constant reflecting the Vs at the ground surface.

$$Vs(z) = A + Bz + C\log z + \sigma \tag{1}$$

For *fill and alluvium* profiles, the preferred soil velocity model is a linear function of depth and Vs_{30} as the available velocity profiles are highly linear with depth and do not include a similar near-surface curvature as other geologic domains:

$$Vs(z) = A + B * z + \sigma \tag{2}$$

To predict profiles of shallow soil velocities, we fit the model parameters of Equation 1, *A*, *B*, and *C*, to readily available continuous estimates of site condition or elements of the CVM velocity model itself. For the *Puget Lowland*, *Willamette*, and *other* sites, Vs_{30} (computed from the profiles directly) and Vs^{100} (sampled from Stephenson et al., 2017) are used to characterize sites. We omitted basin terms like Z1.0 or Z2.5, because they lacked well-constrained estimates across the full model domain. *A*, *B*, and *C* as a function of Vs_{30} and Vs^{100} are given in Equation 3

$$\begin{aligned} A &= Vs_0 = a_0 + a_1 Vs^*_{30} \\ B &= b_0 Vs^*_{30} + b_1 Vs^{100} + b_2 \left(Vs^*_{30} * Vs^{100}\right) \\ C &= c_0 + c_1 Vs^*_{30} + c_2 Vs^{100} \end{aligned} \tag{3}$$

For *fill and alluvium* sites (Equation 2), model parameters were fit solely as a function of Vs_{30}, as these shallow sites should be independent of deeper basin structure as shown in Equation 4.

$$\begin{aligned} A &= A_0 + A_1 * Vs_{30} \\ B &= B_0 + B_1 * Vs_{30} \end{aligned} \tag{4}$$

In general, all available profiles following our filtering and withholding scheme (see **Profile Selection and Model Fitting**) were used to fit parameters for Equations 1 – 4. For glacial sites in the *Puget Lowlands*, the linear term *B* (i.e., controlling Vs at greater depths) of Equations 1 and 3 was fit using exclusively data from Friedman Alvarez et al. (2024), as those profiles reach much greater depths (hundreds of meters) and showed better overall agreement to measured profile data.

Physically realistic constraints were placed on intermediate model fitting parameters *A*, *B*, and *C* in Equations 3 and 4. A minimum value of 0 was imposed for parameters *A*, *B*, and *C*, with negative values from fits to individual profiles omitted, as they represent the linear component of Vs increases with depth, and a curvature term. Negative parameters would lead to unrealistically shaped profiles given the available data. Model parameter *B* (linear component) was also limited to a maximum value of 10 (i.e. 10 m/s increase per meter) to impose a realistic upper bound velocity-depth relationship and remove the influence of shallow soil-rock profiles. For all geologic domains, uncertainty in the prediction of Vs as:

$$\sigma = s_0 + s_1 Vs(z) \tag{5}$$

using all available profiles.

During model testing it was noted that output profile Vs_{30} did not exactly match the specified input Vs_{30} (e.g., when implementing Vs_{30} values from Geyin and Maurer, 2023) To correct this, we add an additional linear Vs_{30} correction term, Vs^*_{30}, defined as:

Domain	N	N_{Ahdi}	N_{WGS}	N_{FA}	V_{S30} Range	Z_{med} (Z_{max})
Puget Lowlands	267	124	111	32	180 - 760	30 (420)
Willamette Valley	107	94	13	-	190 - 600	29 (92)
Fill and Alluvium	93	89	-	4	100 - 300	40 (305)
Other	182	76	106	-	115 - 1000	31 (77)

Table 1 Shear wave velocity counts by geologic domain and source dataset used in this study. Shading indicates profiles used for model fitting and development, unshaded profiles counts were used only for model testing. V_{S30} Range reports the 5 – 95th percentile range in the input dataset. NAhdi: Ahdi et al. (2017); NWGS: Washington Geological Survey (2021); NFA: Friedman Alvarez et al. (2024); Zmed and Zmax: the median and maximum depth of profiles for each geologic domain.

$$Vs_{30}^{*} = d_0 + d_1 Vs_{30} \quad (6)$$

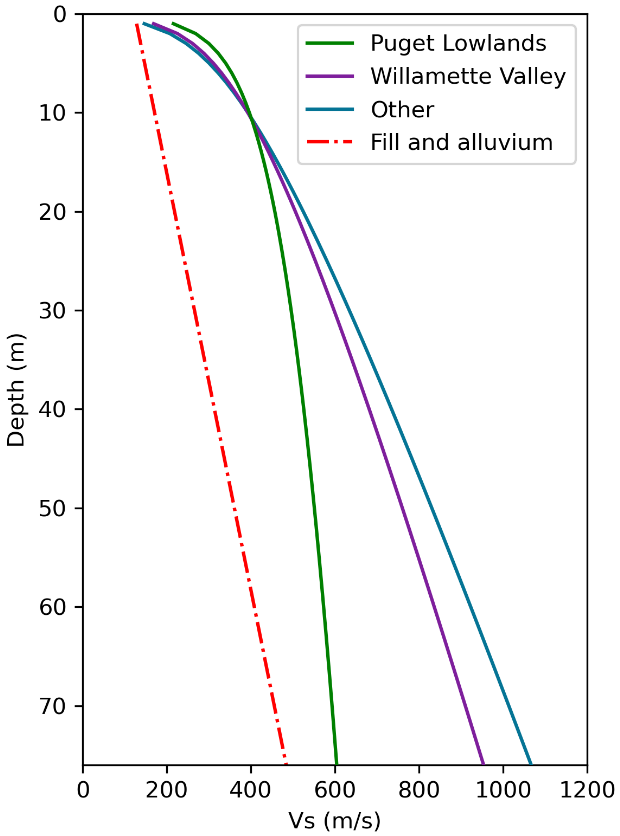

Figure 2 Comparison of predicted Vs profiles for the four geologic domains in our soil velocity model. *Puget Lowlands*, *Willamette Valley*, and *other* sites show a 400 m/s Vs_{30} site. *Fill and alluvium* is shown with Vs_{30} = 185 m/s to match profiles used in earthquake simulation.

Model parameters d_0 and d_1 were fit to minimize error between input and predicted Vs_{30} for all profiles in each geologic domain. Equation 6 was used to modify input Vs_{30} values from Geyin and Maurer (2023) for earthquake simulation development (see **Application to the 2001 M6.8 Nisqually, Washington Earthquake**.) For domains where Vs^{100} is used as a predictor variable, the mean value for each domain was used as a representative value when computing Vs^{*}_{30}. *Puget Lowlands* and *Willamette Valley* sites were modeled with a 1200 m/s Vs^{100}, and 2500 m/s was used for *other*. Fitted values for each geologic domain for Equations 3 – 6 are reported in Table 2. Values reported in Table 2 are slightly revised from those in Wirth et al. (2025a) reflecting changes in predicted profiles when withholding post-2017 WGS Vs profiles for validation adopted in this work.

Results for a reference site of Vs_{30} = 400 m/s (Figure 2) reveal significant differences between the four geologic domains considered here. As a function of depth, glacial soils of the *Puget Lowlands* (Figure 2, green) show rapid near-surface increases in velocity before transitioning to nearly constant velocity, likely due to heavy compaction of the ice sheet of buried advance glaciation deposits. Flood deposits of the *Willamette Valley* (Figure 2, purple) and *other* sites (blue) are expected to be slower in the very near surface before more constantly increasing velocity with depth, with *other* sites reaching higher velocities at depth sooner. Fill and alluvial profiles (Figure 2, red) are plotted for a lower 185 m/s Vs_{30} to match profiles used in our earthquake simulations, and have a linear depth-velocity relationship, gradually increasing in velocity at a trend like that of the *other* sites.

Residuals computed from our predicted profiles and all input Vs profiles used for model fitting are shown in Figure 3 (*Puget Lowlands* and *Willamette Valley*) and Figure 4 (*other* and *fill and alluvium*). Included in Figure 3 are the residuals for both profiles used during model fitting (Figures 3B, E) and blind predictions of our withheld verification dataset (Figures 3C, F). In both Figures 3 and 4, the left panels show measured and predicted velocity profiles as a function of depth for all available sites. For the verification dataset of profiles in the *Willamette Valley* and *Puget Lowlands* collected by the WGS since 2017, mean error is close to zero across all profiles with a similar scatter to those profiles used in model development. We do observe a slight depth-dependent bias in the profiles of the *Puget Lowlands* (Figure 3C, in black), where profiles collected and processed by WGS post-2017 seem to have a slightly different characteristic form compared to the data compiled by Ahdi et al. (2017) and those of Friedman Alvarez et al. (2024). This offset is relatively small and within the range of the velocity model predictions but may reflect a real difference due to the locations these profiles were collected or an artifact due to processing differences.

An example profile for a Vs_{30} = 435 m/s glacial site in Tacoma, Washington is shown in Figure 5 with model predictions from this work (dark blue), the generic PNW soil model of Wirth et al. (2020) (light blue), the basin-centric soil model of Marafi et al. (2021) (purples), and

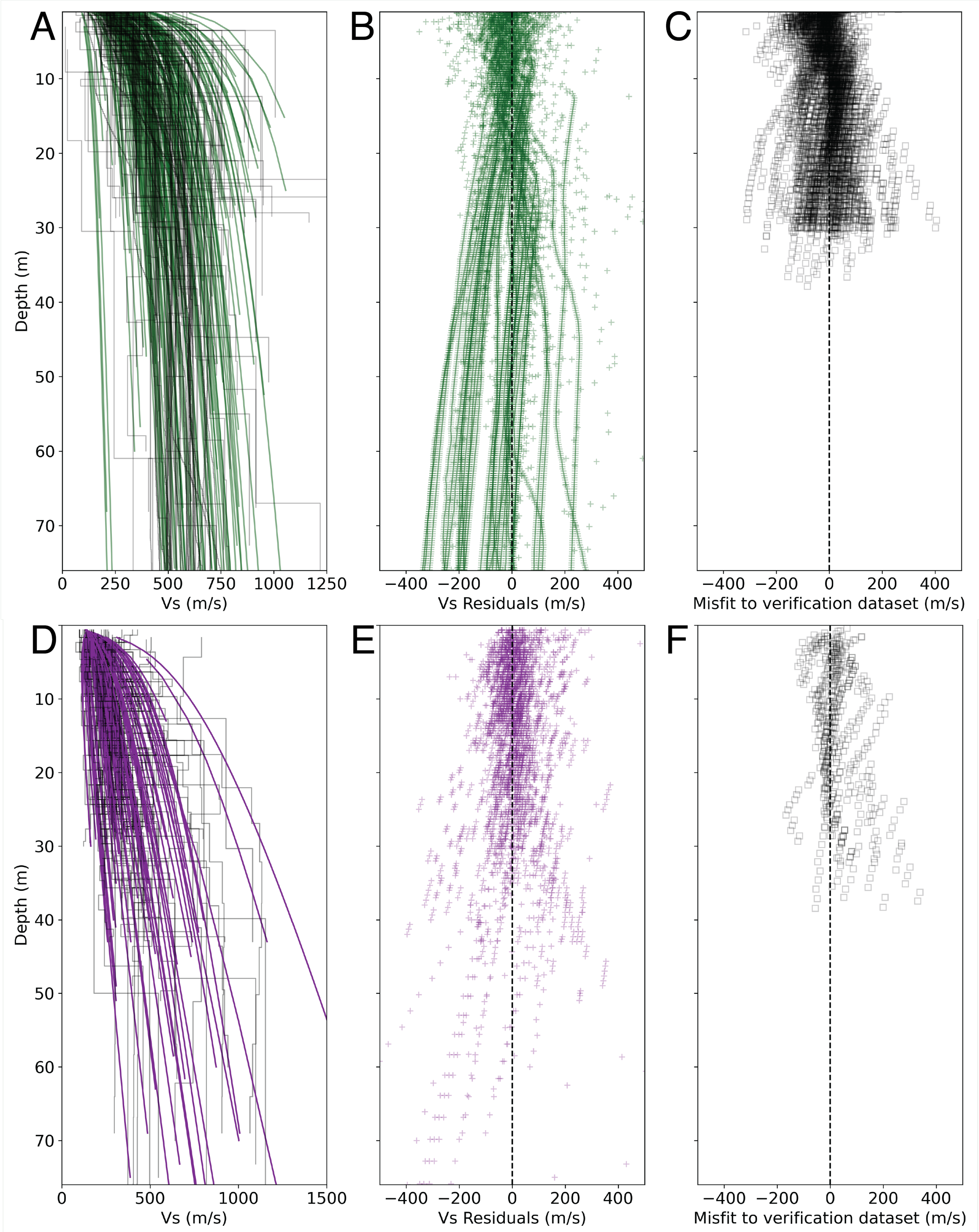

Figure 3 **A, D.** Measured data and predicted velocity profiles (colored) for the *Puget Lowlands* (A – C) and *Willamette Valley* (D – F) geologic domains. **B, E.** Residuals computed from profiles used during model fitting (colored crosses). **C, F.** Residuals of profiles withheld as a 'verification' dataset (black squares) collected by the Washington Geological Survey (2021).

that of Shi and Asimaki (2018) (yellow) for Southern California. Our proposed *Puget Lowlands* SVM closely matches the measured data, with the generic PNW and Southern California models also providing reasonably good fits to the data, while the basin-centric model from Marafi et al. (2021) does less well with respect to com-

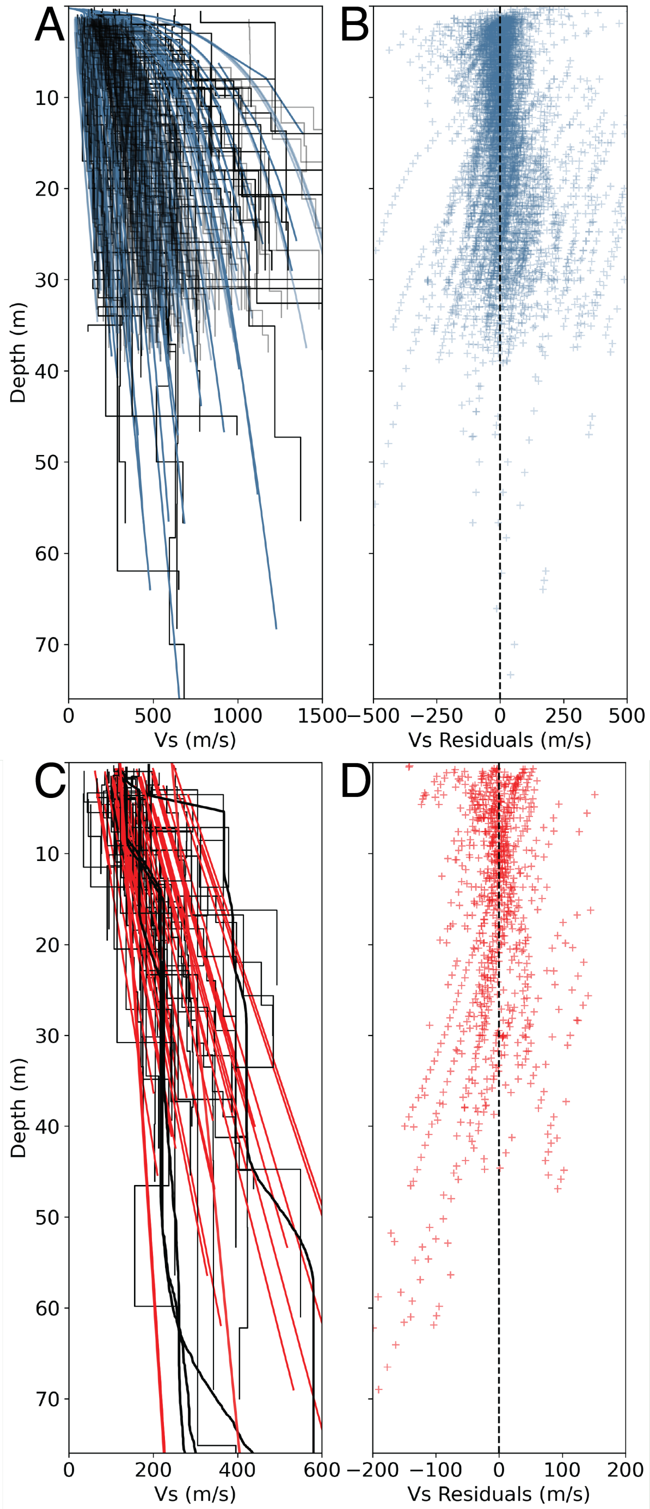

Figure 4 **A, C.** Measured data (black lines) and predicted velocity profiles (blue and red) for the *other* and *fill and alluvium* geologic domains. **B, D.** Residuals computed from all profiles used during model fitting. Note that no testing data was withheld for these two domains.

Domain	A (Vs0)		B (linear component)			C (log curvature)			D (vs30 correction)*		Sigma	
	a0	a1	b0	b1	b2	c0	c1	c2	d0	d1	s0	s1
Puget Lowland	-38.86	0.67	3.28e-3	5.53e-4	-2.35e-6	-3.58e1	1.95e-1	3.06e-2	-26.86	0.115	23.96	0.13
Willamette Valley	111.15	0.13	1.84e-2	2.06e-3	-7.62e-7	-8.98e1	3.64e-1	1.19e-2	2.59	-0.026	0.85	0.30
Fill and Alluvium	-19.11	0.77	1.97	0.02	–	–	–	–	–	–	0	0.22
Other	-0.64	0.36	4.31e-3	-1.99e-3	-2.42e-6	-8.81e+1	3.24e-1	1.98e-2	-21.89	0.07	62.74	0.11

Table 2 Best-fit model parameters for estimating shear wave velocity profiles for the four PNW geologic domains considered in this work.

puted root mean square error (RMSE). These patterns are replicated across all areas in our study; that is, our domain-specific models outperform previous generalized or out-of-region models (Figures 5, 6). To assess model performance across all available profiles, we computed RMSE and the sum of absolute values of residuals, $\Sigma|r|$, for each geologic domain. These errors are shown in Figure 6 and compiled as domain averages in Table 3. In Figure 6, the California model of Shi and Asimaki (2018) is not shown for clarity but performs similarly to the generalized PNW profile of Wirth et al. (2020).

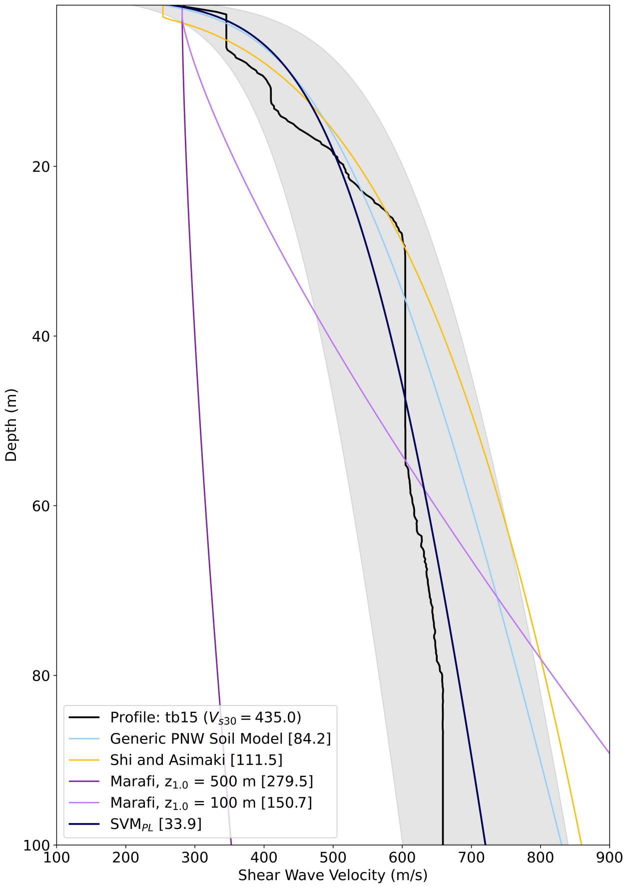

Figure 5 Comparison of the proposed *Puget Lowlands* Soil Velocity Model (SVM_{PL}, dark blue) to the generalized PNW SVM of Wirth et al. (2020) (light blue), the basin-soil model of Marafi et al. (2021) for 500 m (dark purple) and 100 m depths to Z1.0 (light purple), and the Southern California model of Shi and Asimaki (2018) (yellow) for a site measured in the Tacoma, WA (black). The RMSE for each model is shown in square brackets. Grey shading shows the one standard deviation uncertainty in the predicted SVM.

In all but one case, we find the proposed set of SVMs to outperform existing PNW soil velocity models (Table 3) for our error metrics. RMSE and $\Sigma|r|$ are both reduced by the introduction of geologic information and reconsideration of appropriate functional form of velocity as a function of depth, as expected. For all geologic contexts and measurements of error, we find that the Marafi et al. (2021) model performed less well (Table 3) than other models, likely due to the dataset being largely composed of deep geophysical explorations within substantial post-glacial deposits of the Fraser River delta. Additionally, profiles were required to include a shear-wave velocity of at least 1000 m/s (that is, a measured Z1.0) for inclusion. While the Marafi et al. (2021) profiles are a good fit to the subset of PNW velocity data used in that study, our emphasis on shallow (typically < 50 m) behavior and comparison to near-surface profiles leads to dramatic differences between soil models that focus on shallow (SVM and Generic) and deeper (Marafi et al., 2021) characteristics (Figure 5).

5 Application to the 2001 M6.8 Nisqually, Washington Earthquake

To test the impact and performance of the SVM, we ran 3D simulations of the 2001 M6.8 Nisqually, Washington earthquake using seismic velocity models with and without the SVM. In this section, we provide a brief summary of how the Stephenson et al. (2017) seismic velocity model and SVM (this study) were combined in Washington State, but we refer the reader to Wirth et al. (2025a) for additional details.

Using the model 1 Vs_{30} map of Geyin and Maurer (2023), modified by Equation 6, and the proposed SVM profiles described in the **Results** section, we computed shallow Vs profiles for every site in the Stephenson et al. (2017) CVM. We merge the shallow soil profiles with the deeper CVM structure using a set of location specific rules (Wirth et al., 2025a,b). In the Puget Lowland, we follow the soil velocity model Vs profile until the depth at which it exceeds the Vs of the CVM model. At depths greater than this crossover point (typically $\geq$100 – 200 m), we use Vs values from the CVM, which results in a smoothly varying Vs profile with depth. For sites in the Seattle area with artificial fill and Holocene alluvium, we use the soil velocity model Vs estimates at appropriate depths, based on the measured thickness of the fill or alluvium layer (typically < 70 m; Frankel et al., 2007). For all such sites, we assign a value of Vs_{30} = 185 m/s to reflect average fill and alluvium conditions. These fill and alluvium sites are also within the Puget Lowland, so the impedance contrast at the base of the fill and alluvium layer is minimal; it is possible that the impedance contrast is stronger in the real Earth. For all *other* sites, we followed Vs estimates from the SVM to a depth of 50 meters. This depth was selected because very few measured profiles in our *other* category extend beyond 50 meters. At these sites, Vs values were linearly interpolated between 50 m (Vs from SVM) and 100 m (Vs from CVM) depths to minimize any sharp impedance contrasts (see **Discussion** for more details)

Simulations of the 2001 M6.8 Nisqually earthquake were run up to 1.75 Hz with a minimum shear wave velocity of ~150 m/s using the 3D seismic modeling code SW4 (Petersson et al., 2023). We focused on simulated ground motions in the greater Seattle area, due to its range of shallow site characteristics and numerous recordings of the Nisqually earthquake. Recordings of the M6.8 Nisqually earthquake were downloaded from the EarthScope Consortium Web Services (https://service.iris.edu/).

Results show that the addition of the soil velocity model strongly influences simulated ground motions in the Seattle region (Figure 7). Simulations of the M6.8 Nisqually earthquake using the original CVM show correlations between higher shaking intensities and the location of the Seattle and Tacoma Basins (Figure 7A), since basin-scale structure in the Puget Sound region is

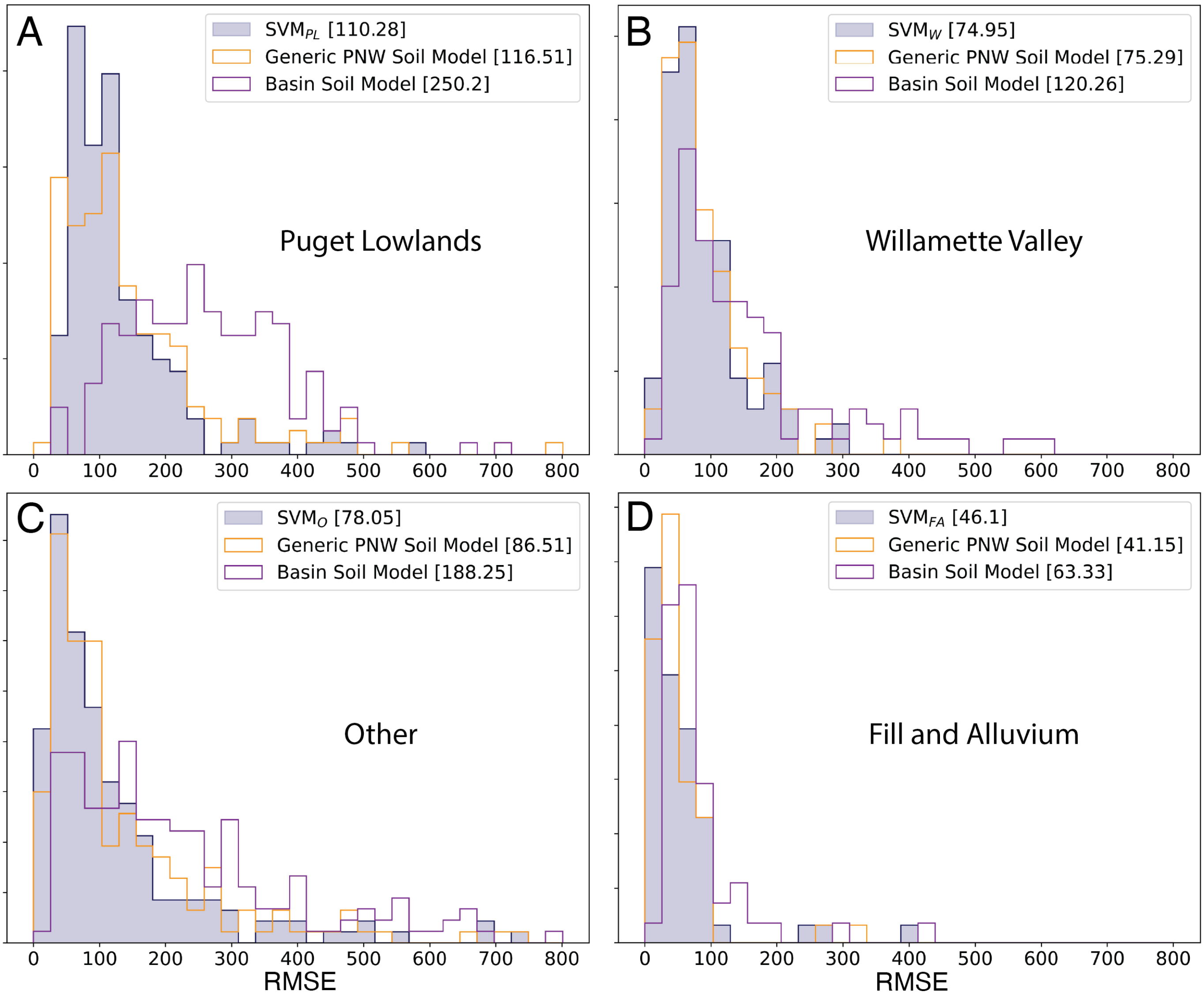

Figure 6 Root mean squared error (RMSE) histograms for all profiles disaggregated by geologic domain, for the proposed soil velocity models (SVMs), generic Pacific Northwest (PNW) soil model, and the basin-soil model.

	SVM (This study)		Wirth et al. (Generic PNW)		Marafi et al. (Basin-centric model)	
	RMSE	$\Sigma\|r\|$	RMSE	$\Sigma\|r\|$	RMSE	$\Sigma\|r\|$
Puget Lowland	108.5	1241.9	116.5	1288	250.2	2862
Willamette	72.7	1798	75.3	1852	120.3	3000
Other	79.1	1630	86.5	1747	188.3	4072
Fill and Alluvium	46.1	339	41.2	358	63.3	491

Table 3 Soil velocity model (SVM) residuals for each considered geologic domain compared to alternative PNW models by Wirth et al. (2020) (generic PNW model) and Marafi et al. (2021) (basin-centric model). For the Marafi et al. profiles, we use Z1.0 values sampled from the Stephenson et al. (2017) seismic velocity model. Reported values are the median for each index computed from all available profiles and all measured velocities as a function of depth. RMSE: root mean squared error; $\Sigma|r|$: sum of the absolute value of residuals. Shading indicates the best performing model for each residual metric.

well represented in the Stephenson et al. (2017) CVM. Earthquake simulations using the CVM+SVM show an additional correlation between higher intensity ground motions and Vs_{30} (Figures 7B – D). This is particularly evident for soft artificial fill and alluvial materials (Vs_{30} < ~ 200 m/s) throughout the Puget Sound area, which coincides with areas of high damage during the Nisqually earthquake (Frankel et al., 2002).

When comparing to recorded data from the M6.8 Nisqually earthquake, we find that the simulations using the soil velocity model proposed here (CVM+SVM) provide a better match to the observations, especially for short-period shaking intensity measures and at low Vs_{30} sites (Figures 8–9). In regard to the SVM mostly impacting high frequencies, this behavior is expected, since the thickness of the soil velocity model is relatively thin (i.e., 100 – 200 m) and therefore is somewhat "invisible" to long-period seismic energy. In general, since

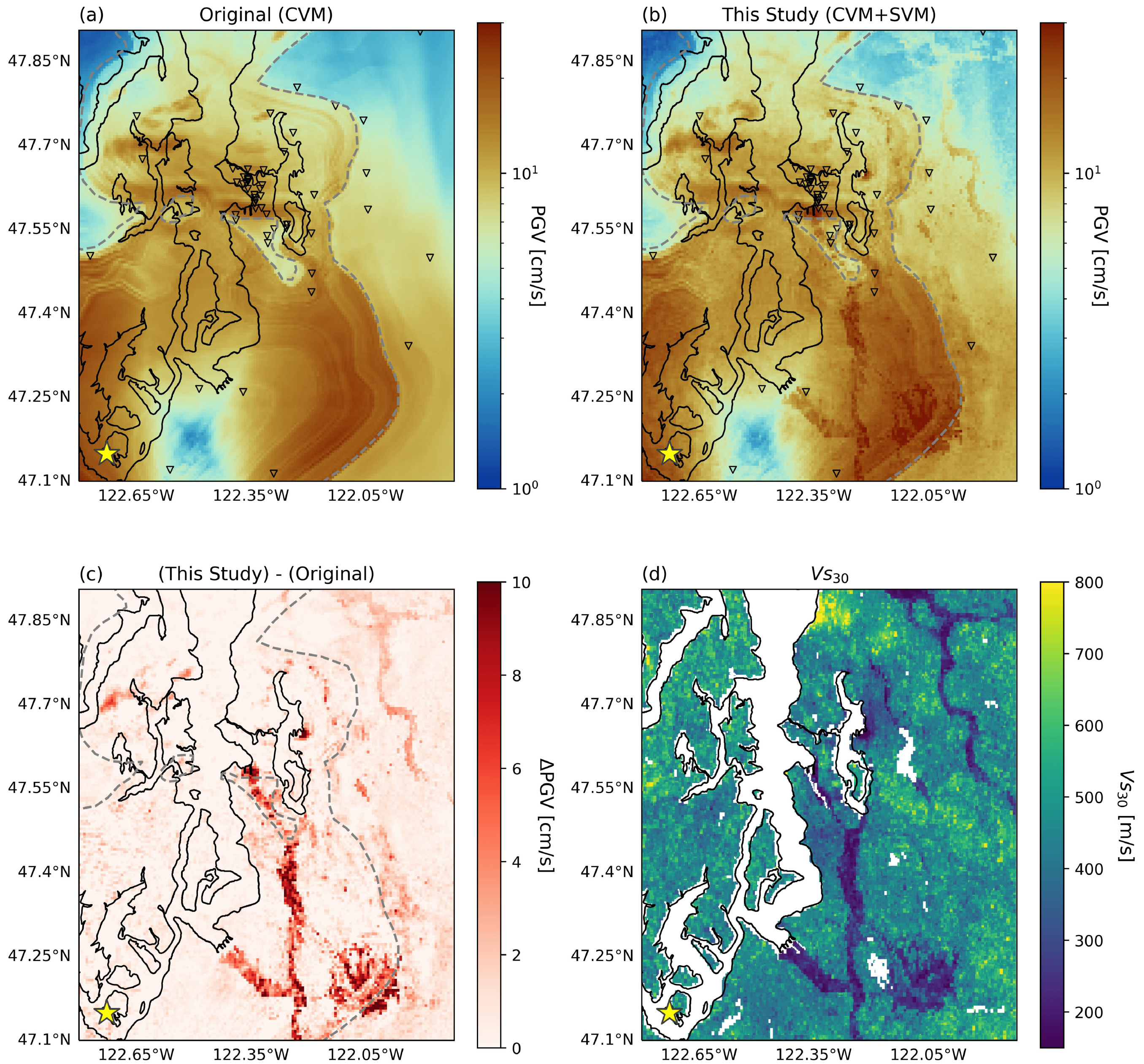

Figure 7 Simulated peak ground velocity (PGV) from the 2001 M6.8 Nisqually earthquake (yellow star) using **A,** the original Cascadia Velocity Model (CVM; Stephenson et al., 2017) and **B,** the modified CVM with a shallow soil velocity model (CVM + SVM; this study). Peak ground velocity is computed using the maximum of the horizontal components. Gray dashed lines outline the extent of the Quaternary sediment in the Stephenson et al. (2017) CVM at 100 meters depth, with the northernmost lobe representing the Seattle Basin and the southernmost lobe representing the Tacoma Basin. **C,** Difference between the PGV values in **B** and **A. D,** Vs_{30} from 'model 1' of Geyin and Maurer (2023).

the Stephenson et al. (2017) CVM had a minimum shear wave velocity of ~600 m/s, we expect to see the most significant differences between the CVM and CVM+SVM at sites with low Vs_{30}. This generally appears to be the case, as we note large changes in Peak Ground Velocity (PGV, up to ~10 cm/s) at sites with Vs_{30} ~200 m/s (Figure 8) and improved fits to period-specific observational data at sites with Vs_{30} < ~ 500 m/s (Figure 9). Similarly, we see that the addition of a soil velocity model has the most noticeable impact on simulated ground motions at frequencies greater than ~0.3-0.5 Hz, which is consistent with the expected impacts of a thin shallow soil layer (Figure 9).

6 Discussion

The proposed soil velocity model (SVM) utilizing basic geologic domain classifications to subdivide the PNW is an improvement over existing soil models in the region (Figure 2, Table 3) and allows for improved earthquake simulation of recorded events (Figures 8–9). Capturing slow, near-surface, shear wave velocity (Vs) structure is critical for earthquake simulations and hazard estimation as near-surface ground response has a significant effect on felt ground shaking amplitudes and is sensitive to both the value and layering structure of velocities. These generalized profiles for distinct geologic domains

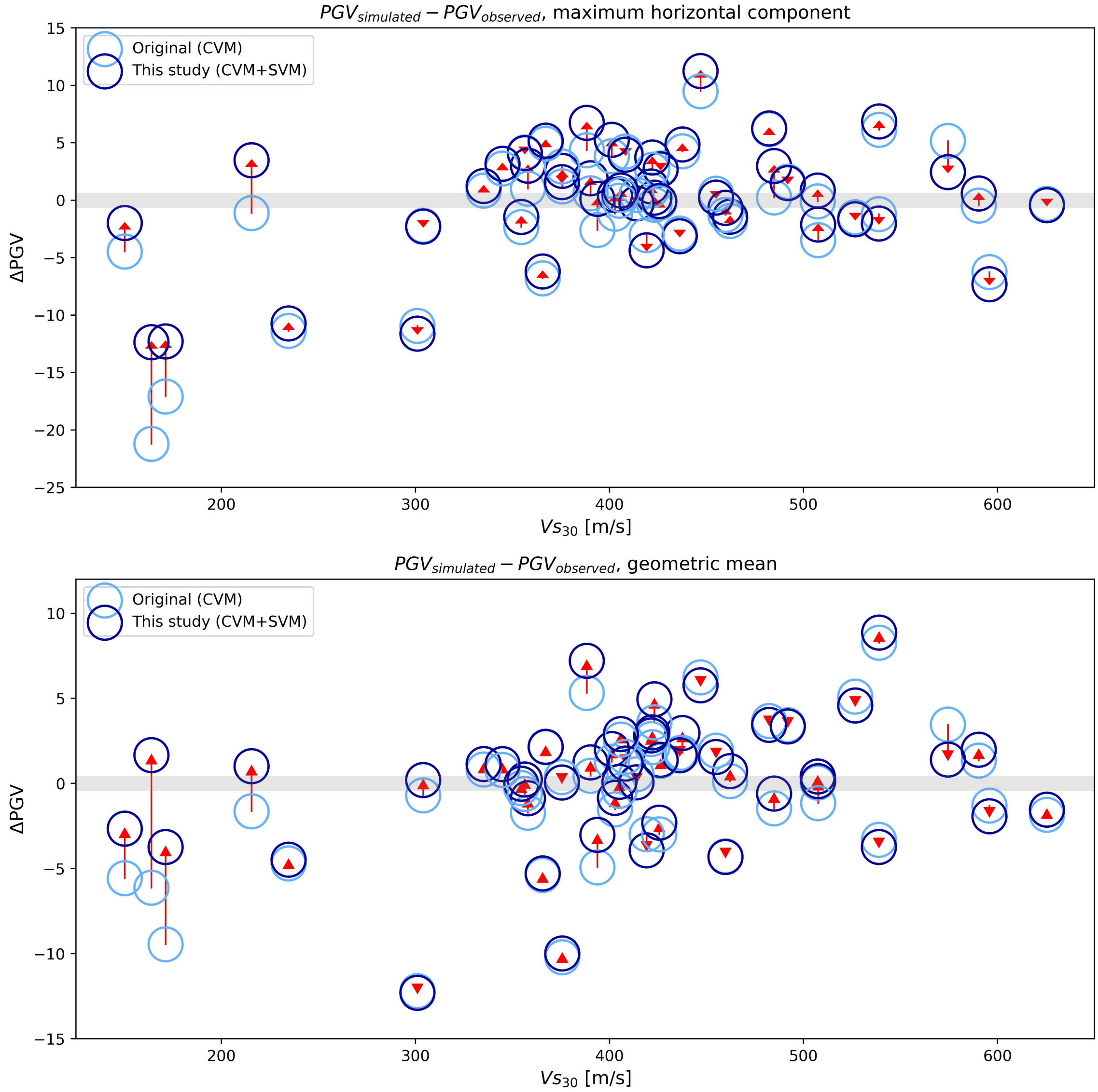

Figure 8 Difference in simulated peak ground velocities compared to observed peak ground velocities (ΔPGV = observed - predicted) from the 2001 M6.8 Nisqually earthquake, as a function of Vs_{30}. ΔPGV is shown using the maximum horizontal component of velocity (upper panel) and geometric mean of the horizontal components (lower panel). A ΔPGV=0 indicates that the simulation results exactly match the recorded observations, while a positive ΔPGV indicates that the simulations underpredict the observational data.

in the PNW can be used for estimating site response at sites without directly measured profiles throughout the region, in addition to use in direct earthquake simulation as demonstrated here with the 2001 M6.8 Nisqually earthquake. While site specific data should be used where possible, these profiles should provide reasonable estimates of surface ground motions for a wide range of conditions in the PNW to quickly assess potential zones of high seismic hazard.

The presented SVMs were developed based on the availability of openly accessible data and grouping into first order geologic domains for practical application. While several hundred Vs profiles were used in this work, a fundamental limitation of these SVMs is data availability and density along several dimensions: geologic, depth, and spatial clustering. We did not attempt any clustering or statistically based sorting of these profiles in deference to using known, mapped, geologic information (i.e. the extent of Puget Lobe glaciation and therefore glacial sediments in the populous Puget Sound region of Washington State). Estimates of Vs_{30} from Ahdi et al. (2017) use much more granular divisions of geology that were not considered in this work due to the increased uncertainty when modeling full

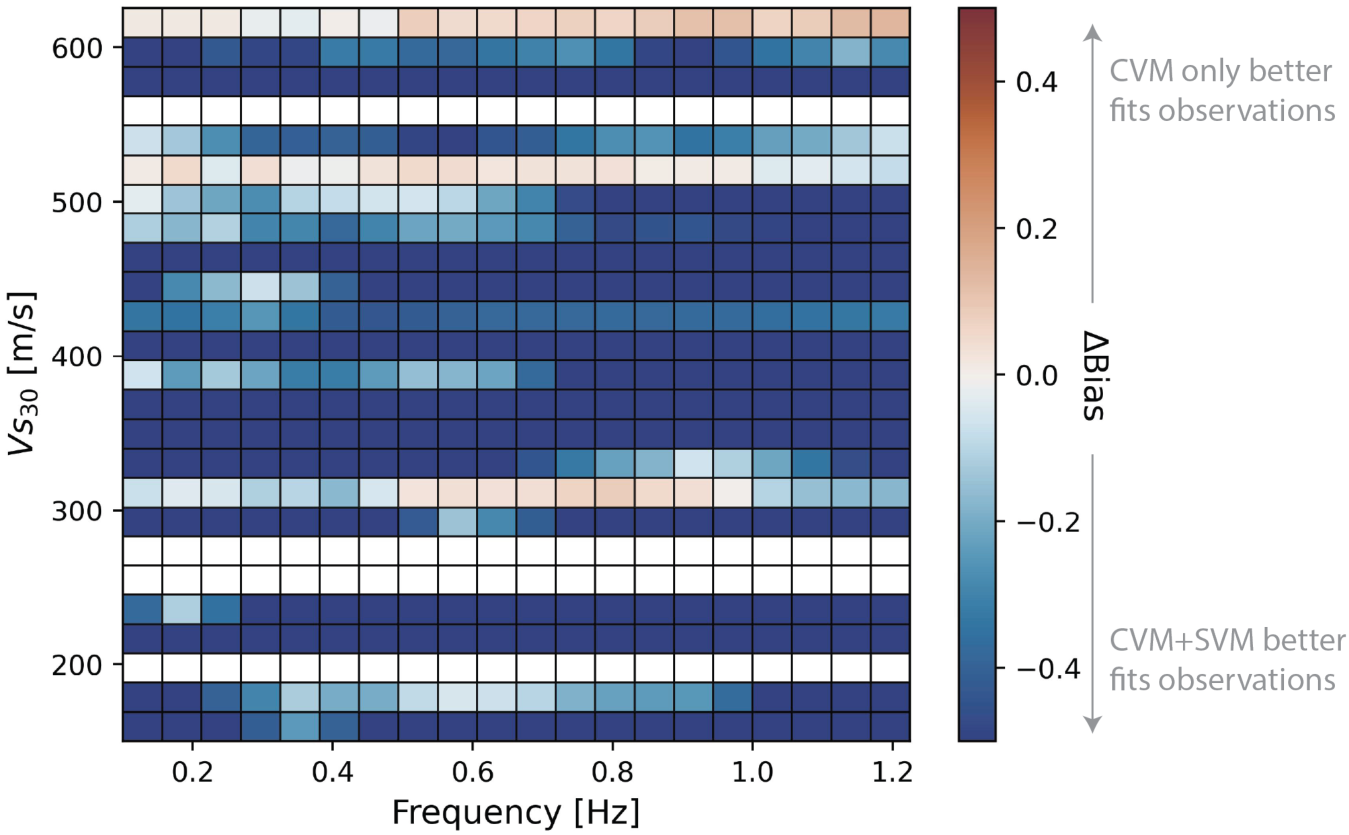

Figure 9 Change in 'bias' when comparing simulated data using the CVM+SVM and CVM-only to recorded ground motions of the M6.8 Nisqually earthquake. Bias was computed as $\ln(FS_{observations}/FS_{synthetic})$, where FS is the maximum horizontal component of the Fourier spectra computed at various frequencies and averaging over octave frequency bins. $\Delta Bias$ is defined as $|Bias_{CVM+SVM}|$ - $|Bias_{CMV}|$. A $\Delta Bias > 0$ indicates that simulations using the CVM only provided a better fit to observations of the Nisqually earthquake, while a $\Delta Bias < 0$ indicates that simulations using the CVM+SVM provided a better fit to the observations. Bias results from individual stations were averaged within each Vs_{30} and frequency bin. Within our study area, if there were no recording stations at a site with a particular Vs_{30} value (e.g., Vs_{30}~275 m/s), $\Delta Bias$ values at all frequencies will be zero (shown as white bins).

profiles with limited data. Data sampling and availability is highly heterogeneous in this study, even within the more spatially limited geologic domains of the *Puget Lowlands* and *Willamette Valley*. Sites within both the Puget Lowlands and Willamette Valley (Figure 1) cluster around the major cities of Seattle and Portland. These data concentrations bias the resulting profiles towards being most representative of a small spatial subset of each of these domains and may introduce errors in other locations. While we did not observe spatially coherent errors when assessing model performance, additional data collection in less well sampled regions (e.g., the northern Puget Lowlands and southern Willamette Valley) may reveal spatial patterns and profile differences not found in this work. The problems of undersampling are magnified in the *other* geologic domain. Sparse regional coverage of Vs profiles outside of the major metropolitan regions limited our ability to capture additional explicit domains (see **Study Region and Geologic Background**) and limits alternative (i.e. various geostatistical) approaches to refining the definition and application of *other* in the PNW. Additional focused geophysical or geotechnical measurements of Vs profiles in one or several sets of distinct geologic domains in the PNW (e.g., the Palouse, alluvium outside of the Puget Lowlands, and thin soils overlying the extensive Columbia River Basalts) could improve profile prediction and reduce uncertainty by differentiating disparate geologic domains within the current *other* category. We also note cross-border modeling of a joint bedrock and soil velocity model of the U.S. and Canada could include explicit characterization of the Fraser River delta soils (e.g., Assaf et al., 2022, 2023), as well as the glacial soils of the surrounding region.

Another data limitation in this work is the depth of most publicly available Vs profiles in the PNW. Median Vs profile depths for our four geologic domains was 29 – 40 m, making the proposed SVM most applicable to the top ~50 m of near surface sediments. While our profile selection decisions, such as removing low-resolution but deep (km scale) profiles, skews our dataset towards shallower depths, the region still lacks a significant number of sites with velocity measurements hundreds of meters below the ground surface. The underlying CVM, built on regional tomographic studies, is best constrained at depths below ~500 m (Stephenson et al., 2017). These disparate datasets create a 'mesoscale' velocity gap in the PNW (depths of ~50 – 500 m) where additional data could help constrain both the SVM and CVM. While the work of Friedman Alvarez et al. (2024)

was critical to the profile development in this work, providing Vs data to hundreds of meters depths, continued data collection and higher-frequency modeling of near-surface structure capturing the velocities in these intermediate depths could improve seismic hazard estimates by filling in this data gap.

When combining a regional geologic velocity model (i.e. the CVM) with the SVM for ground motion simulation, care must be taken at the model interface. In this work we follow the rule-based methods of Wirth et al. (2025b) (see **Application to the 2001 M6.8 Nisqually, Washington Earthquake**), which were designed to minimize the generation of artificial impedance contrasts between the SVM and CVM where they are not well defined, and include impedance contrasts where they are known to exist (e.g., at the base of artificial fill). Modifications to the merged SVM+CVM, or combination of the SVM to a different regional velocity model should be mindful of the potential to impose large velocity jumps at the base of the SVM, particularly in cases where the minimum or surface velocities in the regional model are high (>1 km/s). Further data collection on shallow sediment thicknesses throughout the PNW and development of interface surfaces in Quaternary deposits (e.g., depth of glacial and alluvial sediments) could allow for future model merging constraints with much more realistic transitions.

7 Conclusions

We present a Pacific Northwest soil velocity model (SVM) composed of four distinct profile types based on major geologic domains of the region: the *Puget Lowlands, Willamette Valley, fill and alluvium*, and *other*. These Vs profiles were developed using a compilation of openly available shallow velocity data throughout the region. The resulting profiles are shown to out-perform previous region-specific soil velocity models in matching observed velocity structures. We then modify a regional geologic velocity model (CVM, Stephenson et al., 2017; Wirth et al., 2025a) with the proposed SVM and compare observed ground motions from the 2001 M6.8 Nisqually, WA earthquake to simulations. We show the SVM+CVM modeled ground motions show much better agreement with observations, particularly at soft sites and higher frequencies, than simulations only using the CVM. The SVM thus provides a basis for improved ground motion simulations and higher fidelity hazard estimates throughout the region, as well as providing a suite of soil profiles for use in site response estimation across the Pacific Northwest.

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Data and code availability

Shear wave velocity data used in this work are openly available from Ahdi et al. (2017), Washington Geological Survey (2021), and Friedman Alvarez et al. (2024). All seismic data were downloaded through the EarthScope Consortium Web Services (https://service.iris.edu/), using the UW (Pacific Northwest Seismic Network; University of Washington, 1963) and GS (Albuquerque Seismological Laboratory (ASL)/USGS, 1980) networks. Recorded and synthetic seismograms were processed using ObsPy (Beyreuther et al., 2010). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Competing interests

The authors have no competing interests.

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