Proxy-Based V_{S30} Prediction in Alaska Accounting for Limited Regional Data

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ABSTRACT
The time-averaged shear wave velocity in the upper 30 m (V_{S30}) is commonly used as a parameter representing site conditions for ground motion model development. While it is ideal for shear wave velocity (V_S) profiles to be acquired using in-situ geophysical measurements and to depths greater than 30 m, often times such information is not available at a particular site of interest. As part of the NGA-Subduction project, regional proxy-based models for estimating V_{S30} have been, or are in the process of being, developed for several regions [e.g., the Pacific Northwest (PNW) of North America, Taiwan, Chile] to facilitate V_{S30} estimation at strong-motion accelerometer sites that have recorded subduction-zone earthquakes. The focus of this paper is V_{S30} estimation in Alaska, which presents several challenges. Namely, the region is large and geologically varied, and the available velocity profile data is few in number and regionally clustered, such that no information is available for some important areas within the state. As is done elsewhere in NGA-Subduction, we develop prediction models for the natural log mean and standard deviation of V_{S30} conditioned on secondary information such as surface geology, topographic gradient (slope), and geomorphic terrain categories. Alaska V_{S30} data is taken from 126 measured V_S profiles or V_{S30} values from university research, most of which are clustered in Anchorage, Fairbanks, Seward, Valdez, and areas affected by the 2002 Denali earthquake. As a result of the data sampling problems, we propose alternative approaches for proxy development, whereby: (1) for geologic conditions for which V_S data is available, we validate/calibrate PNW models for application in Alaska; (2) for geologic conditions lacking V_S data, we adopt models for similar geologic conditions from other regions. Sites in Alaska are classified using a five-class schema developed herein that fall under the umbrella of the two aforementioned approaches. Uncertainties assigned to V_{S30} estimates are increased when based on values adopted from approach 2.

1 INTRODUCTION

We summarize methods and recommendations for estimating the time-averaged shear wave velocity in the upper 30 meters of the crust (V_{S30}) for geologic conditions in Alaska. A major initial application of these methods is for estimating site parameters at strong motion accelerograph (SMA) stations that have contributed data to the Next Generation Attenuation-Subduction (NGA-Sub) project (Kishida et al. 2017) and for which geophysical data are not available. Our methodology involves estimating the natural log mean and standard deviation of V_{S30} from secondary information derived from surface geologic maps and digital elevation models, which is generally available across the study region. These maps provide site-specific "proxies", which include surface geology categories, topographic slope, and geomorphic terrain categories.

A crucial element of this effort was the compilation of a database of seismic velocity profiles for the study region, which is termed a profile database (PDB). The profile database for Alaska consists of 126 geophysical profiles and/or V_{S30} values, clustered in Anchorage and a few other major urban areas, and selected sites that were affected by the 2002 Denali earthquake. Because data for Alaska is relatively sparse, we have supplemented the Alaska PDB with selected information from the PDB for the Pacific Northwest Region (PNW) of North America as compiled by Ahdi et al. (2017a). While the scope of that study did not include the development of proxy models for Alaska, we leverage commonalities in geologic groups for proxy model development because of the generally similar tectonic regime and geology.

The proxy development process for Alaska is described here. We propose a mixed approach in which models are derived using local (Alaska) data when justified by data quality and quantity, adopted from a PNW proxy for poorly populated geologic conditions, and (where necessary), adopted from California for certain conditions. We do not utilize models conditioned on terrain classes; we refer the reader to the companion study for the PNW for a discussion of these models (Ahdi et al. 2017a), which found them to have less predictive power than geology-based models.

We use the assembled geophysical data and proxies to populate the NGA-Sub project site database for ground motion recording sites in Alaska. We follow protocols that mirror similar efforts for NGA-West 2 and NGA-East (e.g., Seyhan et al. 2014; Parker et al. 2017) with some modifications.

2 PREVIOUS STUDIES

Proxy-based models can be categorized in different manners. One is on the basis of region of applicability, with global models distinguished from local models. The principal global model is that of Wald and Allen (2007) and Allen and Wald (2009), which use 30 arc-sec topographic gradient (slope) derived from the Shuttle Radar Topography Mission (SRTM30) digital elevation model (DEM) (Farr and Kobrick 2000). Separate V_{S30} correlations were developed for both active tectonic regions (ATR) and stable continental regions (SCR), neither of which is clearly applicable to Alaska (a subduction region). The ATR relationship was derived using data from California, Italy, and Taiwan; the SCR data is taken from Australia and Tennessee.

Local models are applicable to a particular domain, typically defined on the basis of political boundaries or changes in the predominant crustal structure. For a given domain, a second level of categorization concerns the type of proxies considered for use in the correlation model. These include surface geology, geotechnical descriptors, slope gradient, terrain, and hybrids of more than one proxy. Several recent models use a combination of surface geology and ground slope, an approach introduced by Wills and Gutierrez (2008) and subsequently applied to several regions by others. A similar approach is used in the present work for Alaska and was used in the companion study for the PNW region.

In the broader NGA-Sub project, the site database at this stage uses both local and global models. Local models have been developed as part of NGA-Sub for the PNW (Ahdi et al. 2017a) and Taiwan (Kwok et al. 201x). Such models are under development for Chile, and were employed on the basis of prior work for Japan (Ahdi et al. 2017b). For some other regions, typically having relatively sparse data that caused these regions to not be prioritized for proxy development, we intend to use global models.

3 V_S PROFILE DATABASE

3.1 Database Attributes

We compiled a V_S profile database (PDB) for Alaska that consists of a digitized collection of 90 V_S profiles, with an additional 36 sites for which a measured V_{S30} is available, but not a V_S profile. We also consider as part of this study a separate PDB for the PNW region (Ahdi et al. 2017a), with 917 V_S profiles and 11 sites with a measured V_{S30} value. Profiles are considered when they are based on geophysical testing and extend to a maximum (profile) depth $z_p \geq 6$ m, have known geodetic coordinates (i.e., latitude and longitude), and are derived from geophysical measurement techniques that are considered credible (at least for V_{S30}).

The contents of the Alaska PDB include V_S profile information (site identification number, time-averaged velocities to different depths, profile depth) and metadata related to site location (proxies and their sources). The PDB file for PNW sites is an electronic supplement to Ahdi et al. (2017a), which also contains a more detailed description of the database contents and the data sources. The PDB file for Alaska has not yet been published, but will be presented as part of the NGA-Sub final data reports.

Sites included in the Alaska PDB are predominantly non-SMA sites in Fairbanks (Cox et al. 2012), SMA and other sites that recorded the 2002 Denali earthquake (Kayen et al. 2004), a series of sites in Seward and Valdez (R. Kayen, *personal communication*, 2016), and two SMA sites in Anchorage (SW&AA 1980; Steidl et al. 2004). The Cox et al. (2012), Kayen et al. (2004) and Kayen (*personal communication*) sites were investigated using the non-invasive spectral analysis of surface waves method (88 sites total). The Anchorage sites were investigated using downhole methods.

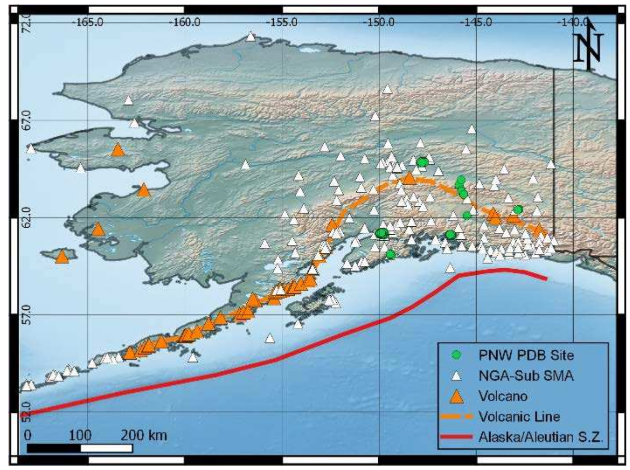

Figure 1. Map of Alaska showing locations of PDB and SMA sites with respect to the volcanic line separating forearc (south) from backarc (north) sites.

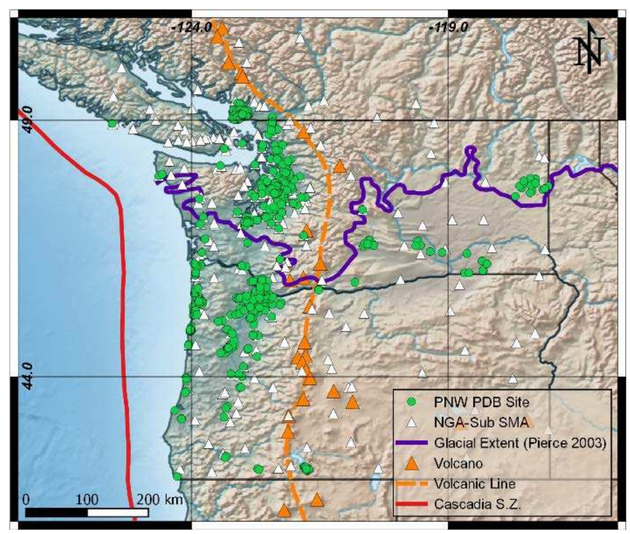

Figure 2. Map of PNW region showing locations of PDB and SMA sites with respect to the glacial extent as mapped by Pierce (2003) and the volcanic line separating forearc (west) from backarc (east) sites. Modified from Ahdi et al 2017a.

A project-level priority was to include as many profiles as possible, and thus discrimination based on geophysical measurement methods was not undertaken with one exception. We do not consider the profiles derived using the CXW method (Poran et al., 1994) to be credible. This method was used to collect data at 36 sites in Anchorage

(Dutta et al., 2000). Our judgment on the suitability of this method draws upon the recommendations of Boore and Brown (1998) and Wills (1998), who caution that V_S profiles derived from this method are biased compared to those derived from invasive methods such as downhole and crosshole. However, we retain V_{S30} values for these sites in the present work, as they do not vary significantly from V_{S30} values obtained from other methods, as determined for sites in Los Angeles (Boore and Brown, 1998).

Figure 1 shows PDB and strong motion sites in Alaska. The PDB sites are concentrated in Anchorage, Fairbanks, Seward, Valdez, and other locations affected by the 2002 Denali earthquake. Most measurements are located within alluvial or basin regions. Figure 2 shows the locations of PDB sites in southern British Columbia, Oregon, and Washington as considered by Ahdi et al. 2017a. Data is less generally clustered than in Alaska, but is especially abundant in Portland, OR, Seattle, WA, and the Fraser River Delta region south of Vancouver, BC.

3.2 V_{S30} Computation

The time-averaged V_S to the maximum profile depth z_p is computed as

$$V_{SZ} = \frac{z_p}{\Delta t_z} \qquad [1]$$

in which

$$\Delta t_Z = \int_0^{z_p} \frac{dz}{V_S(z)} \qquad [2]$$

where Δt_z is the travel time for shear waves to travel from depth z_p to the ground surface. In practice the integral is taken as a summation across depth intervals with constant velocities. When $z_p \geq 30$ m, which occurs for 651 of 1007 PDB sites, V_{S30} is computed by replacing z_p with 30 m. For the sites having $z_p < 30$ m, V_{S30} must be estimated by extrapolation. We select the extrapolation model framework developed by Dai et al. (2013).

4 PROXY ATTRIBUTION

We compiled metadata for PDB sites in Alaska as well as for sites targeted for application of proxies (e.g., NGA-Sub SMA sites). Compiled data includes surficial geologic site conditions, an indicator regarding site location within or beyond the extent of the Cordilleran ice sheet that was present during the late Pleistocene (this applies to all of the sites in Alaska), indicators of site location with respect to the volcanic front separating forearc from backarc regions (for ground motion applications), and topographic slope from the SRTM30 DEM at 30 arc-sec resolution. Geomorphic terrain categories based on procedures in Iwahashi and Pike (2007) (also derived from STRM30 DEM) were compiled and use for proxy development in the PNW, but we did not use this proxy for Alaska, for two reasons. First, much of Alaska was not covered by the Iwahashi & Pike (2007) classification scheme. Second, the PNW study showed that the proxies of a) hybrid geology/slope and b) terrain were highly correlated, with the terrain proxy performing more poorly based on residuals analysis of predicted to measured data.

We considered two compilations of geology maps for Alaska. One is a digital compilation of surface geologic maps by Wilson et al. (2015). We did not give preference to use these maps because of their small scale (1:584,000), which results in limited resolution of Quaternary unit descriptions and unit boundaries. The other compilation is the National Geologic Map Database (NGMDB) of the USGS, which we utilized to look up maps at larger scales, where available. Where large-scale maps are not available in Alaska, the NGMDB reverts to the Wilson et al. (2015) map. The surficial geologic maps delineate locations of Quaternary sediments (e.g., alluvium, till, loess) and outcropping rock units. Maps of relatively large scale typically delineate a more refined age distinction, particularly among Quaternary sediments. Information extracted for each location includes geologic unit, age, and description. In addition to the map information, we record in the PDB and site database (SDB) the surface geologic conditions identified by geologist site visits or as attributed to uppermost layers in a V_S profile where available.

Porter et al. (1983) mapped the extent of the Late Wisconsin Cordilleran ice sheet, which was present during the Late Pleistocene, in the PNW/Rocky Mountains region. Pierce (2003) provides an updated map which was used in this study. As mentioned previously, essentially the entirety of Alaska plots within the glaciated region. The limits for the PNW are shown in Figure 2.

Figures 1 and 2 show our interpretation of the volcanic line separating forearc and backarc regions, with forearc to the south/west and backarc to the north/ east, for Alaska and the PNW, respectively. We drew the volcanic line “by eye” through volcano locations from the Global Volcanism Program (2013). The PDB and SDB files include tags indicating whether sites are located in the forearc or backarc regions (Ahdi et al. 2017a).

5 PNW HYBRID GEOLOGY/SLOPE PROXY

Although the focus of this paper is on a proxy-based V_{S30} prediction model for Alaska, the manner by which our work was undertaken was to first develop models for the PNW, and then to test the applicability of those models (with modifications as needed) for Alaska. For this reason, in this section we review the proxy development process for the PNW, then in Section 6 we explain in detail the Alaska model development.

The 928 PDB locations in the PNW were grouped to identify features that produce distinct V_{S30} distributions, a process described in detail in Ahdi et al. (2017a). Assuming a log-normal V_{S30} distribution, we represent data distributions within groups by their mean V_{S30} (taken as the exponent of the natural log mean, and denoted $\mu_{\ln V}$, which has units of m/sec) and log standard deviations ($\sigma_{\ln V}$, dimensionless). Within each group, we consider the mean trend of V_{S30} with 30 arc-sec topographic gradient.

The collection of PNW PDB sites fall in 124 distinct geologic units. Most sites are located on Quaternary sediments. Our initial grouping was judgment-based, in consideration of lithological unit descriptions, depositional environment, and age; this resulted in 42 categories. For data within individual categories and various combinations of categories, moments $\mu_{\ln V}$ and $\sigma_{\ln V}$ were computed and a mean trend with topographic gradient (s) was evaluated as:

$$\overline{\ln(V_{S30})} = c_0 + c_1 \ln(s) \quad [3]$$

where V_{S30} is in m/sec, slope gradient s is expressed as a decimal (meters per meter), and c_0 and c_1 are regressed coefficients. The gradient effect is considered statistically significant when null does not fall within the 95% confidence intervals for c_1.

Statistical F-testing of V_{S30} distributions within and across categories supported combining together many of the 42 categories, such that 18 groups remained (Table 1), each having a geologic description and a unique set of attributes ($\mu_{\ln V}$, $\sigma_{\ln V}$, and trend with gradient). We did not use geologic age (not shown for brevity) as the primary (first order) group discriminator, which is different from other regional studies utilizing geology for V_{S30} prediction. Rather, our primary discriminator was the description of lithology and depositional environment, which in many cases can be associated with multiple ages (e.g., alluvium,

Table 1. Summary of geology-based and hybrid geology-slope-based V_{S30} proxy for Alaska and PNW. For Alaska, the Class designation indicates the approach used to arrive at the recommended natural log mean model and standard deviation values (Table 2).

Group	Description	Alaska						PNW				
		N	$\mu_{\ln V}$ (m/s)	$\sigma_{\ln V}$	c_0	c_1	Class[1]	N	$\mu_{\ln V}$ (m/s)	$\sigma_{\ln V}$	c_0	c_1
1	Peat	0	161	0.522	*	*	IV	68	161	0.348	*	*
2	Fraser River: overbank silt/clay	0	182	0.395	5.520	0.0506	IV	74	182	0.259	5.520	0.0506
3	Fraser River: overbank sand/silt, sandy/clayey loam, channel deposits	0	198	0.263	*	*	IV	122	198	0.263	*	*
4	artificial fill	4	198	0.314	5.625	0.0762	III	89	198	0.314	5.625	0.0762
5	fluvial + estuarine deposits	0	239	0.867	*	*	IV	31	239	0.578	*	*
6	alluvium & valley sediments	45	323	0.365	5.928	0.0266	I	90	249	0.496	5.976	0.1002
7	flood deposits: sands, fines, floodplain, undifferentiated	2	322	0.243	5.904	0.0275	IV	91	322	0.243	5.904	0.0275
8	lacustrine (incl. glaciolacustrine)	10	326	0.135	6.057	0.0657	II	10	326	0.135	6.057	0.0657
9	beach, bar, dune deposits	0	339	0.647	6.326	0.1264	IV	20	339	0.431	6.326	0.1264
10	fan deposits	37	360	0.338	*	*	II	37	360	0.338	*	*
11	Loess	22	376	0.380	*	*	II	22	376	0.380	*	*
12	glacigenic sediments (drift & outwash)	17	399	0.305	*	*	III	68	399	0.305	*	*
13	flood deposits: channel, gravel, coarse	0	448	0.432	*	*	IV	37	448	0.288	*	*
14	glacial moraines & till	3	453	0.512	*	*	IV[2]	66	453	0.341	*	*
15	undifferentiated sediments & sedimentary rocks	1	455	0.545	*	*	IV	42	455	0.363	*	*
16	terrace deposits & old alluvium	0	458	0.761	*	*	IV	21	458	0.507	*	*
17	volcanic rocks & deposits	1	635	0.995	*	*	IV	14	635	0.663	*	*
18	crystalline rocks (igneous & metamorphic)	0	750	0.641	*	*	IV	5	750	0.427	*	*

[1] Class V assignments specific to the Alaska site database for NGA-Sub include 10 sites on mélange rocks. V_{S30} moments, borrowed from California (Wills et al. 2015) for geologic group KJf, are $\mu_{\ln V}$ = 665 m/s and $\sigma_{\ln V}$ = 0.662 (after inflation by 50% to account for uncertainty).
[2] Group 14 has 66 profiles in the PNW, and 3 in Alaska, which meets our threshold. However, these 3 are closely concentrated and have V_{S30} values that are significantly lower than the mean of Group 14 in the PNW. Thus, we opt not to use these 3 in model development for Alaska.

Group 6, has three age bins—Holocene, Pleistocene, and undivided Quaternary). The lack of further discrimination by age in these cases resulted to some degree from limited data in certain age bins, but to the extent that the data is available, we did not observe age to have predictive power for V_{S30} within these bins.

Site location within or beyond the extent of the Cordilleran ice sheet did not affect V_{S30} beyond the classifications present in Table 1. Site location within or outside of basins also did not carry predictive power (Ahdi et al., 2017a).

Our proposed model for the PNW provides estimates of $\mu_{\ln V}$ and $\sigma_{\ln V}$ conditional on geologic group number and, in some cases, gradient s. For groups without provided values of c_0 and c_1, the mean should be taken as the gradient-independent $\mu_{\ln V}$ value from Table 1. For other groups, the mean is taken from Eq. 3 using the coefficients in Table 1. For both model types, $\sigma_{\ln V}$ is provided in Table 1.

6 ALASKA HYBRID GEOLOGY/SLOPE PROXY

The range of geologic conditions at PDB sites in Alaska is much more limited than those for the PNW, due to data concentrations in a few locations. Nearly all Anchorage sites are founded on overconsolidated sediments overlying variable thicknesses of clay of the Bootlegger Cove Formation (Updike 1985). These sites receive various alluvial, fan, lacustrine, and glacial till/moraine geologic classifications on the NGMDB maps. In Fairbanks, all sites were mapped as alluvial, fan, or loess deposits. At other locations in Alaska, geologic maps generally have lower resolution (smaller scale), and as such many sites are mapped simply as alluvial, fan, or undifferentiated sedimentary deposits.

In general, the geologic conditions at PDB sites in Alaska can be associated with the same categories provided in Table 1, which were originally developed for the PNW. Accordingly, in many cases groups created for the PNW can be applied to Alaska sites. While the geologic conditions present at strong motion sites are much more diverse than those for PDB sites, Table 1 covers the range of conditions presented in the Alaska portion of the NGA-Sub SDB; for example, the Bootlegger Cove formation is classified in Group 8 (glaciolactustrine sediments). Exceptions include mélange rocks (10 sites in the Alaska SDB) and tidal-flat deposits (one site in the Alaska PDB), which are assigned V_{S30} moments from proxies developed for California (i.e., Wills et al. 2015).

In developing guidelines for assigning V_{S30} to sites in Alaska, we developed an approach that is adaptable to groups with varying amounts of data. Where data is available and the velocities from Alaska are judged to be distinct from those in the PNW, we use an Alaska-derived model comparable in form to those for PNW (but different coefficients). This applies to Group 6 (alluvium) only and is denoted Class I. Where data is present but limited (at least three profiles), we test applicability of PNW models using residuals analysis. In some of these groups, the proxy estimates for PNW include Alaska data due to their similarly (Group II), in others they do not use Alaska data but the group data across regions nonetheless appear to be similar (Group III). Additional groups accommodate cases with no Alaska data (IV and V).

The aforementioned residuals of log mean V_{S30} for candidate groups were calculated as:

$$R_i = \ln\left(V_{S30}\right)_i - \overline{\ln\left(V_{S30}\right)_i} \qquad [4]$$

where $\ln(V_{S30})_i$ is the natural log of the V_{S30} calculated from V_S profile i, and $\overline{\ln\left(V_{S30}\right)_i}$ is the proxy-based natural log mean for profile i. If the mean +/– the standard error of the residuals encompassed zero, that group's bias with respect to the PNW model was deemed to be statistically insignificant for Alaska data and the PNW model was adopted. Table 2 shows candidate groups that were tested in this manner, and resultant classes into which each group was placed for the purpose of V_{S30} assignment.

Table 2. Summary of classes for V_{S30} proxy development for Alaska based on number of profiles N in each geologic group.

Group	N	Bias, $\bar{R}$ (m/s)	Dispersion, $\sigma_{\ln V}$	Standard error	Class
4	4	0.249	0.573	0.287	III
6	45	0.384	0.254	0.038	I
8	5	0.013	0.127	0.057	II
10	32	-0.086	0.211	0.037	II
11	14	-0.073	0.259	0.069	II
12	17	-0.012	0.309	0.075	III
14	3	-0.840	0.217	0.125	IV[1]

[1] See Note 2 from Table 1.

To summarize the recommended approach, the classes for V_{S30} moment assignment are as follows:

I. Use good quality Alaska data when available to develop Alaska-specific model (i.e. Group 6 – alluvium)
II. Use models developed jointly with PNW and Alaska data, as published in Ahdi et al. (2017a); use these moments after checking the bias of the residuals and verifying that they are statistically insignificant (i.e. Groups 8, 10, 11)
III. Borrow as-published PNW proxy, but check the significance of bias of residuals; if bias insignificant, use the original $\sigma_{\ln V}$. (i.e. Groups 4 and 12).
IV. Borrow as-published PNW proxy without checking residuals due to lack of data; inflate $\sigma_{\ln V}$ by 50% (all other groups).
V. Borrow as-published proxy model from other regions and inflate sigma by 50%. (e.g. one PDB site on Qi, tidal-flat deposits, will borrow V_{S30} moments from Wills et al. 2015)

7 RECOMMENDATIONS FOR V_{S30} ASSIGNMENTS

It is well-established that best practices in site characterization for seismic analysis include direct measurement of seismic velocities, preferably extending to firm materials such as rock. Site parameter V_{S30} can be readily computed from the V_S profile, or in the case that the profile depth is < 30 m, estimated from shallower profiles. The proxy relationships developed in this paper are recommended when seismic velocity measurements are unavailable and it is necessary to estimate V_{S30}. For application to V_{S30} assignments in the NGA-Sub site database, we adopt protocols similar to those outlined in Seyhan et al. (2014), but modified to represent the proxies developed and used in this study. The Alaska-specific V_{S30} assignment protocols are:

0. Assign mean V_{S30} as computed using profile with z_p > 30 m. Standard deviation taken as $\sigma_{\ln V}$ = 0.1 per Seyhan et al. (2014).
1. For sites with a V_S profile that extends to depth z_p < 30 m, estimate V_{S30} using the Dai et al. (2013) methodology. The associated $\sigma_{\ln V}$ can be taken as the square-root sum of variances associated with the depth extrapolation (σ_e^2) (Eq. 4) and 0.1^2, as follows:

$$\sigma_{\ln V} = \sqrt{\sigma_e^{\,2} + 0.1^2} \qquad [5]$$

2. Estimate V_{S30} and its uncertainty using the models presented here. Take the natural log mean and standard deviation from Table 1, except when coefficients c_0 and c_1 are given in Table 1, in which case take the mean using those coefficients with Eq. 3. Table 1 reflects class assignments I to V and their impact on uncertainty.

8 SUMMARY AND CONCLUSIONS

A large majority of seismic recording stations in Alaska lack geophysical measurements, which necessitates the estimation of site parameters from suitable proxies to facilitate the development and application of ground motion models and site amplification models. In this paper, we focus on the development of proxies for estimation of parameter V_{S30} for sites in Alaska, the immediate application of which will be in the NGA-Subduction project.

The main challenge that was faced in developing these models is the lack of widely variable data availability across geology groups in the study region. We propose and implement an approach that uses data to directly derive models that are justified by relatively abundant data; uses data to validate models borrowed from elsewhere where data is limited but finite; and simply borrows models for similar geologic conditions without validation when data is absent (but with inflated standard deviations to reflect the additional uncertainty this entails).

The proposed procedures have been implemented for all SMAs in Alaska that have produced usable recordings from subduction events for the NGA-Sub project. The V_{S30} assignments will be published in a forthcoming database that will encompass all NGA-Sub sites.

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