Geotechnical Characterization and Evaluation of Site Amplification at Selected PNSN Strong Motion Sites, Seattle, Washington

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ABSTRACT

The 28 February 2001 moment magnitude (**M**) 6.8 Nisqually, Washington, earthquake was recorded by more than 70 strong motion sites within the Pacific Northwest Seismic Network (PNSN) and National Strong Motion Program (NSMP). To allow evaluation of the shallow site response effects on the recorded Nisqually ground motions, as well as those of future earthquakes, we have characterized the shear-wave velocity (V_S) structure down to depths of 100 to 300 ft at the 32 PNSN and NSMP sites, which recorded the highest ground motions around the Puget Sound region, using the Spectral-Analysis-of-Surface-Waves (SASW) technique.

The near-surface geology of the Puget Sound region is dominated by a complex interbedded and discontinuous sequence of glacial and non-glacial deposits and this is reflected in the V_S profiles. Most of the surveyed strong motion sites are underlain by glacial till (Qvt) with the remaining sites on Holocene alluvium (Qal), glacial recessional (Qvr) and advance outwash deposits (Qva), or manmade fill/modified ground (m). V_S30 (average shear-wave velocity in the top 30 m [100 ft]) values for Qvt and Qvr range from 1,266 to 1,769 ft/sec and 1,139 to 1,826 ft/sec, respectively. These V_S30 ranges correspond to NEHRP Site Class C.

Ground motions in the 2001 earthquake recorded at the 32 sites, as characterized by peak horizontal ground acceleration (PGA), ranged from 0.04 to 0.31 g. Two sites, SEW and SP2, only 2,600 ft apart in Seward Park, Seattle, at a hypocentral distance of about 80 km, recorded significantly different PGA values of 0.17 and 0.31 g, respectively . SP2 is underlain by Qvt and SEW by colluvium and Blakely Formation. In contrast, the closest station to the earthquake (hypocentral distance of 57 km) is underlain by Qvr and recorded a maximum PGA of only 0.07 g. In general, ground motions were highest at sites underlain by lower velocity materials (e.g., outwash) relative to stiffer sites such as the glacial Qvt. Apparently the ground motions at short to moderate periods (0.1 to 0.5 sec) are strongly affected by near-surface geology and topography as exemplified by the two Seward Park sites.

INTRODUCTION

The Seattle, Washington, metropolitan area and surrounding Puget Sound region have been the most seismically active region in the Pacific Northwest in historical times. Damaging intraslab (intraplate) earthquakes such as the 1949 moment magnitude (**M**) 6.8 Olympia, 1965 **M** 6.6 Seattle-Tacoma, and most recently, the 2001 **M** 6.8 Nisqually earthquakes have struck the Puget Sound region (Langston and Blum, 1977; Baker and Langston, 1987; Noson et al., 1988; Ludwin et al., 1991; PNSN Staff, 2001; Ichinose et al., 2004; 2006). However, the earthquake effects in these past events have been minimized by their relatively deep origins (40 to 60 km). In the past two decades, geologic evidence for large prehistoric crustal earthquakes (**M** ≥ 7) in the Puget Sound region suggests that the maximum severity of seismic hazards has not been experienced in historic times. Additionally, paleoseismic data indicate that Cascadia subduction zone earthquakes of approximate **M** 9 in size have also occurred at least 19 times in the past 10,000 years (Goldfinger et al., 2010), most recently in January 1700. A future occurrence of a **M** 9 earthquake is inevitable.

The most recent significant earthquake, the 28 February 2001 **M** 6.8 Nisqually event, was recorded by more than 70 strong motion sites within the University of Washington's Pacific Northwest Seismic Network (PNSN) and the U.S. Geological Survey's (USGS) National

Strong Motion Program (NSMP) (Frankel et al., 2001). The earthquake was the result of normal faulting at a depth of 56 km within the subducting Juan de Fuca plate (Ichinose et al., 2004). Its epicenter was about 20 km northeast of Olympia (Figures 1 and 2). Total direct losses in the earthquake amounted to one billion dollars and fortunately no deaths or major injuries resulted from the event. It is by far the best recorded earthquake in terms of strong ground motion in the Pacific Northwest (Figure 1), in large part because of the addition of Advanced National Seismic System (ANSS) stations to the PNSN.

To quantify accurately the earthquake ground-shaking hazard in the Seattle metropolitan area and surrounding Puget Sound region, the effects of unconsolidated and semiconsolidated sedimentary and glacial deposits on ground motion need to be evaluated. Analyses of some of these data indicate that site amplification effects have been significant at strong motion recording sites (e.g., Frankel et al., 2002). To evaluate the effects of the shallow soils on the recorded Nisqually ground motions and future earthquakes, we have characterized the shear-wave velocity (V_S) structure to depths of 100 to 300 ft at 31 PNSN and NSMP sites and one temporary USGS station (SEW) around the Puget Sound (Figures 2 and 3) using the Spectral-Analysis-of-Surface-Waves (SASW) technique (Stokoe et al., 1994). These 32 sites of the 70 plus PNSN and USGS strong motion stations exhibited the largest ground motions recorded in the 2001 earthquake. This study is a continuation of our efforts to evaluate the near-surface site amplification of earthquake ground motions in the Puget Sound region (Wong et al., 1999a; 1999b; 2003). The study was funded by the U.S. Geological Survey under a National Earthquake Hazard Reduction Program (NEHRP) external grant.

PREVIOUS STUDIES

Several studies have been performed to estimate the strong ground shaking from future earthquakes in the Seattle and Puget Sound areas (Cohee et al., 1991; Silva et al., 1998; Wong and Silva, 1998; Frankel and Stephenson, 2000; Hartzell et al., 2002; Frankel et al., 2007). Site response has been evaluated by Silva et al. (1998), Frankel et al. (1999), and Hartzell et al. (2000). Williams et al. (2000) observed that sites with the lowest measured V_S correlate with highest ground motion amplification based on an analysis of recordings from 13 portable seismic stations in the Seattle area. Frankel et al. (2002) noted that the NEHRP class D and C sites that recorded the 2001 Nisqually mainshock and aftershock show similar spectral amplification indicating linear soil response. Amplifications at spectral periods of 0.2 to 1.0 sec for all 35 seismic stations they evaluated generally increase with decreasing V_S30. However, large amplifications at 1 to 2 sec periods with similar V_S30 are observed for sites in the Seattle Basin indicating the long-period amplification may be due to deeper sediments and surface waves.

A number of studies have been performed in the Seattle metropolitan area to provide the basic data to quantify the site effects on the ground motion hazard in the region. Prior to the 2001 earthquake, Williams et al. (1999) measured V_S and P-wave velocity (V_P) to a depth of about 130 ft at 13 portable seismograph sites using seismic refraction/reflection. This study was followed by additional surveys and currently the number of sites measured by the USGS totals 37 (e.g., Williams et al., 2001).

In an earlier (1997-1998) related study funded by NEHRP, near-surface geologic, geophysical, and geotechnical data were compiled for the Seattle metropolitan area and evaluated (Wong et al., 1999a; 1999b). These data included surface geology maps, depth to bedrock maps, water resource studies, V_S measurements, water well logs, and significant geotechnical and geophysical studies. A primary focus of the data compilation effort was to

collect information from deep borings to characterize the general stratigraphy across the Seattle area. Geologic cross-sections from 7.5-minute surface geologic quadrangles, groundwater resource studies, and major geotechnical projects such as tunnels were collected to aid in the subsurface characterization. Locations of these data were plotted atop surficial geologic maps. As part of the study, *in-situ* V_S measurements using the SASW method were performed at nine sites in April 1998 by the University of Texas at Austin (UTA) and URS (Wong et al., 1999a; 1999b).

In a second NEHRP-funded study (2000 to 2001), all V_S data that had been collected to date including the USGS data, 109 surveys at a total of 71 sites, were digitized and augmented with a small amount of data made available due to new cooperative efforts among geotechnical consulting firms as part of Project Impact (Wong et al., 2003). An objective of this task was to compile as complete a V_S digital database for the Seattle metropolitan area as possible.

Palmer et al. (2004) developed a statewide NEHRP site class map based on a V_S database compiled by Bilderback et al. (2004) and downhole V_S surveys performed in 8 boreholes drilled throughout the State including 3 holes in the Seattle area. The Seattle V_S database from Wong et al. (2003), including the results of this study, were incorporated into the statewide database (Bilderback et al., 2004).

A 3-D geologic model of the Seattle area has been developed by the Pacific Northwest Center for Geologic Mapping Studies based on tens of thousands of exploration points (website: http://geomapnw.ess.washington.edu). The database compiled as part of this effort includes depths, thicknesses, material types, geologic unit, depth to the water table, and other subsurface properties and information. Although V_S data are not available at this time, CPT data can be accessed.

PUGET SOUND NEAR-SURFACE GEOLOGY

The Puget Sound region is located within the Puget Lowlands, a structural and topographic basin between the Cascade Range to the east and the Olympic Mountains to the west (Troost and Booth, 2008). The Quaternary geology of the Puget Lowlands is dominated by the deposits from seven glacial advances with the most recent advance and retreat called the Vashon stade from 17,400 to 16,400 years B.P. (Troost and Booth, 2008). The near-surface geology is dominated by a complex interbedded and discontinuous sequence of glacial and non-glacial deposits. Most of the surveyed strong motion sites are underlain by Qvt with the remaining sites on Holocene alluvium (Qal), glacial recessional (Qvr) and advance outwash (Qva and Qvlc) deposits, or manmade fill/modified ground (m) (Table 1).

The Vashon stade consisted of proglacial lacustrine silt and clay, advance outwash sand and gravel, Qvt, ice-contact deposits, and recessional deposits including outwash sand and gravel and lacustrine silt clay. The Vashon advance outwash (Qva) and proglacial lacustrine deposits are called the Esperance Sand Member and the Lawton Clay member (Qvlc) of the Vashon Drift, respectively (Troost and Booth, 2008). The following unit descriptions from youngest to oldest are summarized from Troost and Booth (2008) for the Seattle area. Qal varies in thickness from 10 to 100 ft in river and stream valleys and consists of sand, silt, gravel, and cobbles. Qvr consists of stratified sand and gravel deposits in outwash channels with thicknesses ranging from 3 to 20 ft. Qvt is a compact diamict of silt, sand, and subrounded to well-rounded gravel, glacially transported and deposited under ice. Qvt is very dense and typically 3 to 33 ft in thickness. Qva is a well-sorted sand and gravel

deposited by streams issuing from advancing ice sheets and is widespread in its distribution and locally may be up to 200 ft thick. Qvlc is a laminated to massive silt, clayey silt, and silty clay that has been deposited in lowland proglacial lakes. The deposits exceed 100 ft in thickness. Qpog are pre-Olympic glacio-lacustrine deposit that consist of silt and clay (Palmer et al., 2004). Thicknesses range from 23 ft to more than 108 ft.

The depth to bedrock in the Seattle area as evaluated by Troost and Booth (2008) varies from zero at Alki Point to more than 1,800 ft. The Blakeley Formation (Tb), which is exposed at Alki Point and over a wide area in southeastern Seattle including Seward Park, consists of marine sedimentary and volcaniclastic rocks.

SASW METHODOLOGY

The V_S structure at each site was measured using the SASW technique. The SASW method is widely accepted and has been applied to numerous soil and rock sites (Stokoe et al., 1994; 2004). In particular, the SASW method has often been applied to the problem of characterizing materials for near-surface site response analysis (Rosenblad et al., 2001; Wong and Silva, 2006). The SASW method has been validated at numerous sites in blind comparisons. For example, downhole, OYO suspension, and SASW V_S profiles were compared at Yucca Mountain (Stokoe et al., 2003). The SASW method is cost effective and well-suited for *in situ* testing.

The SASW methodology is a non-destructive and non-intrusive seismic method. It utilizes the dispersive nature of Rayleigh-type surface waves propagating through a layered material to estimate the V_S profile of the material (Stokoe et al., 1994). In this context, dispersion arises when surface-wave velocity varies with wavelength or frequency. Dispersion in surface-wave velocity arises from changing stiffness properties of the soil and rock layers with depth. This phenomenon is illustrated on Figure 4 for a multi-layered solid. A high-frequency surface wave, which propagates with a short wavelength, only stresses material near the exposed surface and thus only samples the properties of the shallow, near-surface material (Figure 4b). A lower-frequency surface wave, which has a longer wavelength, stresses material to a greater depth and thus samples the properties of both shallower and deeper materials (Figure 4c). Spectral analysis is used to separate the waves by frequency and wavelength to determine the experimental ("field") dispersion curve for the site via phase unwrapping. An effective/superposed-mode inversion that takes into account ground motions induced by fundamental and higher-mode surface waves as well as body-waves (i.e., a full wavefield solution) is then used to match theoretically the field dispersion curve with a one-dimensional (1D) layered system of varying layer stiffnesses and thicknesses (Joh, 1996). The 1D V_S profile that generates a dispersion curve, which best matches the field dispersion curve is selected as the site profile. The 1D geometry is an important assumption. Departures from this geometry, such as when velocity layers are dipping, can result in considerable variability in the dispersion curves and hence multiple interpretations.

SASW measurements involve generating surface waves at one point on the ground surface and recording them as they pass by two or more locations. All measurement points are arranged along a single radial path from the source. Successively longer spacings between the receivers and between the source and first receiver are typically used to measure progressively longer wavelengths. The distance between the source and first receiver (d) is typically kept equal to the distance between receivers in order to mitigate against near-field effects. Measurements are performed with several (typically 7 or more) sets of source-

receiver spacings. Phase plots from surface wave propagation between the receivers are recorded for each receiver spacing. From each phase plot, the phase velocity of the surface wave can be calculated at each frequency from (Joh, 1996):

$$V_R = f \cdot \frac{360}{\phi} \cdot d \qquad (1)$$

where V_R is the phase velocity in ft/sec or m/sec, f is the frequency in Hertz (cycles per sec), ϕ is the phase angle in degrees (at frequency f), and d is the distance between the receivers in the same length units as used to represent V_R. From this calculation, a plot of phase velocity versus frequency, called an individual dispersion curve, is generated. This procedure is repeated for all receiver spacings used at the site and typically involves significant overlapping in the dispersion data between adjacent receiver sets. The individual dispersion curves from all receiver spacings are combined into a single composite dispersion curve called the experimental or field dispersion curve that contains literally hundreds of individual dispersion measurements. Once the composite dispersion curve is generated for the site, an iterative forward modeling procedure is used to create a theoretical dispersion curve to match the observed curve (Joh, 1996). The stiffness profile that provides the best match to the observed dispersion curve is presented as the V_S profile at the site.

SASW SURVEYS

From 12 to 21 November 2003, a total of 32 strong motion sites were surveyed (Table 1; Figure 2). The stations were selected based on two criteria: (1) their apparent site amplification capability based on the 2001 Nisqually data, and (2) to improve the amount of data of specific surficial units in our V_S database (e.g., Qvt). The stations included 25 ANSS stations operated by the University of Washington as part of the PNSN, 6 USGS NSMP stations, and one temporary station (SEW) that is part of the Seattle Urban Seismic Array (Carver et al., 2005) (Figure 2; Table 1). A 33rd site, Volunteer Park in Seattle where the USGS had drilled a 500-ft deep borehole and performed downhole V_S and V_P measurements, was also profiled but those results are not reported herein. The majority of the sites are located in the Seattle metropolitan area but also include stations in Bremerton, Olympia, and Puyallup (Figure 2).

The source used in the SASW surveys was the National Science Foundation's Network for Earthquake Engineering Simulation (NEES) mobile vibrator called "Thumper" (Figure 5). Thumper, housed and operated by UTA, is a moderate to high-frequency vibrator. Some important characteristics of Thumper are: mounted on a Ford F650 truck, total weight of about 9,900 kg, and two vibration orientations (field transformable in a few hours), vertical or horizontal. The maximum force output is about 27 kN over the frequency range of 17 to 225 Hz. The force output decreases outside of this frequency band. The relatively low-force output (27 kN) also makes Thumper an excellent vibrator for testing in urban environments where disturbance or possibly damage to existing above-ground and below-ground facilities might occur.

Given the urban environment, most of the SASW surveys were conducted on streets, parking lots, school fields, and parks (Figure 6). We attempted to perform the surveys as close as possible to the location of the strong motion instrument but, in some cases, we were as far as 500 ft away due to logistical constraints. Mark Products L-4C 1 Hz seismometers were used in the surveys (Figure 6). The SASW data were analyzed and V_S profiles

estimated as described above. Typical dispersion curves and associated V_S profiles resulting from forward modeling for two test locations are shown in Figures 7 and 8. Figure 7a shows the experimental and theoretical dispersion curves for the Maple Valley (MPL) site. It can be seen that maximum experimental wavelengths (λ_{max}) as long as 500 ft were measured, allowing determination of the V_S profile for the site to a depth of approximately 250 ft (Figure 7b). Figure 8a shows the dispersion curves for the SEATAC Fire Station (7030) site. In this case, a λ_{max} of almost 600 ft was measured, allowing determination of the V_S profile for the site to a depth of approximately 300 ft (Figure 8b). It should be noted that the V_S profile for a site is typically developed only to a depth equal to the maximum measured wavelength divided by two ($\lambda_{max}/2$) because of the lack of layer resolution at depths greater than this depth. In a few cases, multiple V_S profiles at a site were determined because of lateral variability visible in the dispersion curve.

SASW RESULTS

SASW surveys reached depths ranging from 100 to 290 ft (Figures 7 to 39). The 32 strong motion sites were classified by NEHRP categories based on the V_S30 estimates obtained from the SASW results (Table 1). In the following discussion, the profiles are grouped generally by area and hypocentral distance to the 2001 earthquake. Identification of surficial units at each strong motion were taken primarily from Troost and Booth (2008). The goodness-of-fit of the modeled dispersion curve to the observed curve for each site is qualitatively rated in Table 2.

Olympia-Tacoma

The closest strong motion stations to the 2001 Nisqually earthquake were located in the Olympia-Tacoma area: Camp Murray (MURR), Halvorsen Residence (7008), Highway Test Lab in Olympia (2101), and the University of Puget Sound (UPS) (Table 1; Figure 2). Although the four Olympia-Tacoma stations are at similar hypocentral distances to the 2001 earthquake, 57 to 60 km, the PGA values range over a factor of three from 0.06 to 0.22 g (Table 1). Site response effects must be a significant factor although possibly not the sole factor in amplifying the ground motions at these strong motion sites near the epicenter.

MURR in Tillicum and 7008 in Olympia are the two closest strong motion stations to the 2001 earthquake at a hypocentral distance of 57 km (Figure 2). Yet MURR only recorded a modest peak horizontal ground acceleration (PGA) of 0.07 g. The site is underlain by sand- and gravel-dominated Qvr. The V_S profile suggests the Qvr extends to a depth of about 150 ft, where rock with a V_S of 3,200 ft/sec is encountered (Figure 9a). A thin layer of soil and 20 ft of weathered Qvr form the uppermost portion of the site. The 7008 site (PGA 0.16 g) is characterized by a thin 10- to 25-ft-thick soil layer underlain by a 1,000 ft/sec layer of Qpogl that overlies Qvt at 85 ft (Figure 9b). Given that high-frequency energy (e.g., PGA) is dominated by upgoing waves at these two stations, site effects are probably more important rather than basin effects.

2101 was the first strong motion station installed in Washington in 1948. It recorded the 1949 and 1965 earthquakes. Based on our SASW survey, the site consists of a thin 10-ft-thick layer of fill over Qal that extends to a depth of at least 120 ft, with V_S from 560 to 700 ft/sec (Figure 9c). In 1978, Shannon & Wilson and Agbabian Associates (1978) performed a crosshole seismic survey to a depth of 440 ft (only top 200 ft shown in Figure 9c). The survey yielded a V_S starting at 350 ft/sec in the fill and reaching 1,000 to 1,200 ft/sec (Figure

9c). The crosshole results show somewhat higher V_S values than the SASW results but are consistent with the site being a deep soil site.

The survey at the UPS strong motion site shows a profile where soil and weathered Qvt extends to a depth of about 20 ft with V_S increasing from about 500 to 1,350 ft/sec and then two layers of dense Qvt (V_S > 1,850 ft/sec) to almost 240 ft depth (Figure 9d).

Pierce County

There are three strong motion stations in Pierce County east-southeast of the 2001 earthquake: PCFR, PCEP, and PCMD (Figure 2). PGA values recorded at these sites ranged from 0.13 to 0.21 g (Table 1). All three sites show similar V_S profiles with gradients starting at the surface increasing to more than 2,000 ft/sec (Figure 10). PCFR and PCMD are Qvt sites and PCEP is underlain by Qvr. Depths of more than 250 ft were reached at two of the three sites (PCFR and PCEP) (Figure 10) because of the relatively stiff Qvt and Qvr underlying the sites and that long receiver spacings were utilized due to the availability of open space. At PCMD, the receiver spacing was limited. Rock-like V_S was reached at a depth of about 95 ft at PCEP (Figure 10b). All three Pierce County sites are NEHRP Site Class C sites (Table 1).

Bremerton

Three strong motion stations were profiled in Bremerton: Kitsap County Airport (KIMR), Bremerton Fire Station (7034), and Tahyua Lake (GNW) (Figure 2). PGA values at these three sites only ranged from 0.16 to 0.19 g for hypocentral distances of 69 to 74 km (Table 1). KIMR is a Qvt site and the V_S increases from 1,200 to 2,900 ft/sec to at least a depth of 270 ft (Figure 11a). Because of limited space, we were only able to survey to a depth of 140 ft at 7034 (Figure 11b). The site is characterized by a 20-ft-thick layer of weathered Qvt followed by denser Qvt with a V_S of about 2,100 ft/sec. GNW is one of only two rock sites surveyed. Weathered igneous rock was exposed at the surface. A V_S gradient is observed in the top 70 ft, reaching a hard rock V_S of 6,000 ft/sec (Figure 11c).

South Seattle-Renton

Four stations, the SeaTac Fire Station (7030), Benson Hill School (RBEN), Maple Valley Substation (MPL), and Hazelwood School (RHAZ) were surveyed (Figure 3). SeaTac recorded a PGA of 0.19 g, twice that of RBEN and MPL although it is slightly closer to the hypocenter (Table 1). About 20 ft of fill is observed at SeaTac underlain by Qvr with 1,300 ft/sec to a depth of 170 ft and rock (Qvt?) with a V_S of 2,800 ft/sec (Figure 8). RBEN, a Qvt site, shows a weathered layered with a V_S gradient and a uniform V_S of nearly 2,000 ft /sec (Figure 12a). MPL, also a Qvt site, shows an increasing V_S gradient down to about 150 ft depth where firm rock is reached with a V_S of 3,000 ft/sec (Figure 7). The velocity contrast at a depth of 170 ft may be the source of the amplification at SeaTac (Figure 8). However, in a similar fashion, RHAZ recorded a low PGA of only 0.05 g despite having a very strong velocity contrast at a depth of 80 ft (Figure 12b). The site is 10 km further than SeaTac to the 2001 earthquake.

West Seattle

In both the 1965 and 2001 earthquakes, West Seattle suffered comparatively higher levels of damage compared to other areas in the Puget Sound region. This damage pattern is surprising because West Seattle is located on an upland of consolidated glacial deposits

without any apparent soft soils or ground failure (Booth et al., 2004). Hartzell et al. (2000) and Booth et al. (2004) concluded that abrupt changes in depth to bedrock, basin edge effects or localized trapping of seismic waves may be the causes for the observed heightened amplification in West Seattle.

SASW surveys were performed at Holy Rosary School (HOLY), the West Seattle Fire Station #29 (7032), Kimball School (KIMB), and Seattle Fire Station #28 (7027) (Figure 3). HOLY, 7032, and KIMB have similar V_S profiles with V_S < 2,000 ft/sec in the top 100 to 150 ft (Figure 13). HOLY is underlain by Qpogl as observed in a borehole (Palmer et al., 2004). KIMB is a Qvt site and 7032 is underlain by Qva.

V_S profiles for HOLY and KIMB were also obtained by Palmer et al. (2004) using the downhole technique (Figures 13a and 13c). The HOLY downhole V_S profile shows a gradual gradient from 955 ft/sec at 10 ft depth to 1,633 ft/sec at a depth of 146 ft. Both V_S profiles are similar, with the SASW showing slightly the higher velocities (Figure 13). The downhole V_S profile for KIMB is similar to the SASW V_S profile down to about 100 ft, except for a 10-ft-thick high-velocity layer that appears in the downhole profile at depths between 36 to 49 ft (Figure 13c). The PGA values at HOLY, 7032, and KIMB were very similar, ranging between 0.15 to 0.17 g at hypocentral distances of 77 to 80 km (Table 1) possibly reflecting their similar V_S profiles.

7027 can be characterized as a rock site (Tb) with a thin layer of soil (Figure 13d). A velocity gradient from 2,200 to 3,600 ft/sec is observed in the top 110 ft with a large jump to hard rock at nearly 7,000 ft/sec. The PGA recorded at 7027 was only 0.08 g compared to the nearby KIMB station (0.17 g) or the Seward Park stations (see below) (Figure 3; Table 1) possibly reflecting its hard rock site conditions.

Seward Park

Possibly the most significant SASW measurements were at the two Seward Park sites, SEW and SP2 because of the obvious site response effects that were observed. SP2 recorded the highest PGA in the 2001 earthquake at 0.31 g at a hypocentral distance of 81 km (Table 1). The nearby SEW station (2,600 ft away) recorded a PGA of 0.17 g the same value recorded by KIMB at the same hypocentral distance. SP2 is located adjacent to Lake Washington about 110 ft above the shoreline on a hill slope of about 30 degrees. SEW is located on a small berm about 20 ft above the shoreline. Comparison of the two V_S profiles, at least the top 100 ft, shows no apparent strong differences (Figure 14). The maximum depth was limited at SP2 due to space restrictions. Multiple profiles were interpreted at SEW probably due to dipping layers or lateral heterogenerity. A V_S profile for SEW based on S-wave seismic refraction from Williams et al. (1999) shows similar trends albeit 25% higher velocities.

At SEW, a velocity contrast is encountered at the colluvium/Tb contact at a depth of 35 ft as was observed by Williams et al. (1999) (Figure 14a). A velocity contrast of almost a factor of two is observed at a depth of 70 ft at SP2 and then another velocity step at 100 ft (Figure 14b). SP2 is underlain by Qvt and possibly by Tb at depth. Both sites exhibit shallow velocity contrasts that will amplify high-frequency ground motions, e.g., PGA. An examination of response spectra of the horizontal component time histories shows that the spectra of three of the four records are very similar. Only the east-west component of SP2 is significantly higher although the spectral shape is similar to the other spectra. The shallow

V_S profiles are not different enough to explain the significantly higher PGA at SP2. A possible explanation is that the hillside topography is amplifying the ground motions at SP2.

Seattle

SASW surveys were performed at four stations in Seattle: Queen Anne Hill (QAW), Lawton School (LAWT), the ATM Building on the campus of the University of Washington (SEA), and the NOAA offices at Sand Point (NOWS) (Figure 3). These stations are underlain by a variety of deposits, yet a narrow range of PGA values from 0.07 to 0.11 g were recorded at these stations for hypocentral distances of 83 to 89 km (Figure 1). The QAW V_S profile exhibits a fairly stiff profile with an unusually low velocity inversion at depths between 35 to 55 ft (Figure 15a). LAWT exhibits a V_S gradient starting at 400 ft/sec for the Lawton clay (Qvlc) increasing to nearly 1,800 ft/sec at about 180 ft depth (Figure 15b). The SEA V_S profile exhibits a thin 10-ft-thick soil layer underlain by Qvt with a relatively uniform V_S around 1,700 ft/sec (Figure 15c). NOWS is a deep soil site overlain by fill. The V_S does not exceed 1,400 ft/sec at least down to 180 ft (Figure 15d). The comparatively low PGA recorded at NOWS (0.09 g; Table 1) may have been caused by the higher material damping and downward reflective capability of the 25 ft of engineered fill to energy propagating up through the softer weathered and unweathered Qvt (Figure 15d).

Bellevue-Redmond

East of Seattle, the Wilburton Center (WISC), Alcott School (ALCT), Leota School (LEOT), and East Ridge School (EARN) strong motion sites were profiled (Figure 3). PGA values for the four sites ranged from 0.04 to 0.11 g for a hypocentral distance range of 87 to 101 km (Table 1). WISC reportedly a Qvt, site shows a strong velocity contrast with rock at a depth of 40 ft (Figure 16a). ALCT is underlain by Qvr and exhibits a uniform V_S of about 1,500 ft/sec down to a depth of at least 160 ft (Figure 16b). LEOT, which is also a Qvt site, shows a profile with increasing V_S down to a depth of nearly 140 ft (Figure 16c). Finally, EARN is underlain by Qvr and exhibits a slightly increasing V_S gradient (Figure 16d).

Other Stations

Four strong motion stations outside of Seattle were surveyed: the Brookside School (BRKS) in Bothell and three substations operated by the Bonneville Power Administration (BPA) at Raver (RAW), Echo Lake (ELW), and Monroe (MBPA) (Figure 2). BRKS is a Qal site with a low V_S (< 1,000 ft/sec) down to about 100 ft depth where a V_S contrast is encountered (Figure 17a). RAW is underlain by Qvr and shows a steady increase in V_S with depth and a number of velocity contrasts including large contrasts at 120 ft depth (firm rock) and 220 ft depth (Figure 17b). The high V_S at a depth of 220 ft indicates that a hard rock interface (V_S ~4,000 ft/sec) is encountered. Such a V_S profile suggests significant potential amplification and the relatively high PGA of 0.17 g at this distance (82 km) is consistent with that observation (Table 1). ELW shows Qmw probably to a depth of 26 ft underlain by 1,800 ft/sec material to 81 ft and then a jump to rock with a V_S of 2,600 ft/sec (Figure 17c). Finally, MBPA, the most distant station to the 2001 hypocenter evaluated in this study at 119 km away, recorded a high PGA of 0.15 g (Table 1). The site is underlain by fill and shows a steady V_S gradient with a large step to rock at 85 ft depth (Figure 17d). This V_S profile would appear to have the potential for strong PGA amplification.

CORRELATION WITH SURFACE GEOLOGY

In lieu of V_S measurements, surface geology is often used to characterize amplification potential, usually in the form of NEHRP site factors. In Figure 18, we compare V_S profiles as a function of the most common surface geologic units: Qvr, Qvt, and Qva. As observed in the V_S profiles, there is considerable heterogeneity with depth as would be expected in the complex interbedded and discontinuous sequence of glacial and non-glacial deposits.

Nearly all the Qvr sites show a V_S gradient, with many showing soft rock (V_S > 2,000 ft/sec) being encountered at varying depths (Figure 18a). The majority of strong motion sites we surveyed were located on Qvt (Figure 18b). The V_S profiles beneath the Qvt sites are relatively similar with the exception of WISC and RHAZ, which encountered rock at relatively shallow depths. The shallow Qvt appears to be weathered in the top 50 to 70 ft. Only two sites were underlain by Qva, and they are shown in Figure 18c.

Based on the V_S profiles, V_S30 (average shear-wave velocity in the top 30 m) is estimated for each of the 32 strong motion sites (Table 1). V_S30 is used in the recently developed Next Generation of Attenuation (NGA) ground motion models and so it has taken on greater importance in hazard analyses than simply providing the basis for classifying NEHRP site categories. V_S30 values for Qvt and Qvr range from 1,266 to 1,769 ft/sec and 1,139 to 1,826 ft/sec, respectively. (RHAZ and WISC were not included in these ranges because they are thin soil sites.) These V_S30 ranges generally correspond to NEHRP site class C. Williams et al. (1999) measured V_S30 at 5 Qvt sites and three were characterized by values of 2,057 to 2,230 ft/sec higher than measured in this study. They also measured a V_S30 of 1,420 ft/sec at SEW compared to our value of 1,268 ft/sec. Several sites, e.g., BRKS and NOWS, are categorized as NEHRP D with relatively low V_S30 values of less than 1,000 ft/sec (Table 1). Station 2101 is borderline site class D with a V_S30 of 614 ft/sec.

In general, V_S30 probably does a reasonable job of reflecting site response effects in the Puget Sound region with the significant exception where strong velocity contrasts are encountered ("thin" soil sites) either in the top 100 ft (30 m) such as at WISC and RHAZ (Figure 18b) or below 100 ft such as at the Qvr sites (Figure 18a) (see following discussion).

In Figure 19, 16th, 50th, and 84th percentile V_S profiles are calculated for Qvr and Qvt. The number of profiles and the corresponding COV are also shown as a function of depth. If WISC and RHAZ were to be removed because they appear to be thin soil sites, the COV for Qvt shows small variability (COV less than 0.20) among the V_S profiles. Similarly for Qvt, the COV is below 0.20 although there are only 6 profiles. Figure 20 shows that the median Qvr and Qvt V_S profiles are surprisingly similar suggesting a single profile could be very representative for Qvr and Qvt in the Seattle Basin.

NISQUALLY GROUND SHAKING AND SITE EFFECTS

Based on an inversion of teleseismic data, Ichinose et al. (2004) modeled the slip plane of the 2001 earthquake to be a N10°W-striking, 30 km long, and 24 km wide plane with a dip of 70°. The hypocenter was at a depth of 56 km. As stated previously, recorded ground motions in the 2001 Nisqually earthquake, as characterized by PGA's, ranged up to 0.31 g. However, SP2 recorded a PGA of 0.31 g at a hypocentral distance of 81 km, in contrast to MURR, the closest station to the earthquake at 57 km, which recorded a PGA of only 0.07 g. Additionally, SEW, 2,500 ft south of SP2, recorded a PGA of 0.17 g.

Figure 21 compares the PGA data from the strong motion stations as a function of surficial unit and NEHRP site class based on the V_S profiles with the three intraslab ground motion attenuation models used in the 2008 USGS National Hazard Maps (Petersen et al., 2008): Youngs et al. (1997), Atkinson and Boore (2003), and Zhao et al. (2006). A **M** 6.8 was input into the models and the 16th, median, and 84th percentile curves are shown. Examination of Figure 21 shows some interesting patterns. In general, ground motions were highest at sites underlain by lower velocity materials (e.g., alluvium, outwash) relative to stiffer sites such as the glacial Qvt. Frankel et al. (2002) also observed: 1) that soft soil sites on fill and alluvium produced large amplifications of the mainshock ground motions at 1 Hz and in most cases, 0.5 Hz; and 2) stiff soils on glacial deposits generally had moderate amplifications at the same frequencies. Apparently the ground motions at moderate to high frequencies (2 to 10 Hz) are strongly affected by near-surface geology and this is exemplified by the two Seward Park sites.

The fall off with distance also is much steeper than the median curve for a **M** 6.8 at a depth of 56 km would predict. The reason for this difference will need to be investigated, although Atkinson and Boore (1997) suggest that Cascadia earthquakes may be characterized by low stress drops.

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Table 1. Surveyed Puget Sound Strong Motion Sites Recording the 2001 Nisqually Earthquake

Station	Location	Surficial Geology	Hypocentral Distance (km)	Maximum Recorded PGA(g)	Maximum SASW Depth (ft)	V_S 30 (ft/sec)	NEHRP Site Class	Comments
MURR	Camp Murray, Tillicum	Qvr	57	0.07	180	1717	C	Firm rock at 145 ft
7008	Halvorsen Residence, Olympia	Qpogl	58	0.16	100	1025	D	
2101	Highway Test Lab, Olympia	m/Qal	59	0.22	120	614	D/E	Deep soil
UPS	University of Puget Sound, Tacoma	Qvt	60	0.06	240	1596	C	Firm rock at 140 ft
PCFR	Pierce County Training Center, Roy	Qvt	62	0.13	270	1458	C	
PCEP	Pierce County East Precinct, Puyallup	Qvr	64	0.21	290	1266	C	Steady V_S gradient
KIMR	Kitsap County Airport, Bremerton	Qvr	69	0.16	270	1769	C	Firm rock at 180 ft
PCMD	Pierce County Mountain Detachment, Eatonville	Qvt	70	0.16	180	1637	C	
7030	SEATAC Fire Station	m	73	0.19	290	1139	D	Firm rock at 170 ft
7034	Bremerton Fire Station	Qvt	74	0.19	150	1518	C	Thin soil over firm rock
GNW	Tahyua Lake, Bremerton	Intrusive rock	74	0.16	180	2207	C	Firm rock at 30 ft, hard rock at 70 ft
RBEN	Benson Hill School, Renton	Qvt	76	0.11	170	1614	C	
HOLY	Holy Rosary School, West Seattle	Qpogl	77	0.10	120	1142	D	
MPL	Maple Valley Substation, Renton	Qvt	78	0.10	250	1280	C	Firm rock at 155 ft
7032	West Seattle Fire Station #29	Qva	79	0.15	180	1075	D	
7027	Seattle Fire Station #28	Tb	79	0.08	140	2265	C	Hard rock at 110 ft
KIMB	Kimball School, Beacon Hill, Seattle	Qvt	80	0.17	100	1686	C	
SEW	Seward Park, Seattle	Tb	80	0.17	100	1268	C	Tb at 85 ft
SP2	Seward Park, Seattle	Qvt	81	0.31	120	1139	D	Firm rock at 100 ft
RHAZ	Hazelwood School, Renton	Qvt	82	0.05	250	1826	C	Hard rock at 80 ft
QAW	Queen Anne Hill, Seattle	Qva	83	0.11	200	1186	C/D	Low V_S zone
LAWT	Lawton School, Magnolia, Seattle	Qvlc	84	0.10	180	1036	D	
RAW	Raver BPA Substation	Qvr	84	0.17	270	1292	C	Firm rock at 120 ft
SEA	ATM Building, UW	Qvt	86	0.07	100	1408	C	
WISC	Wilburton Center, Bellevue	Qvt	87	0.11	170	1584	C	Firm rock at 40 ft
NOWS	NOAA Sand Point, Seattle	m	89	0.09	185	911	D	Deep soil
BRKS	Brookside School, Bothell	Qal	94	0.10	170	756	D	
ELW	Echo Lake BPA Station	Qmw	93	0.06	100	1445	C	Firm rock at 80 ft

Table 1. Surveyed Puget Sound Strong Motion Sites Recording the 2001 Nisqually Earthquake (continued)

Station	Location	Surficial Geology	Hypocentral Distance (km)	Maximum Recorded PGA(g)	Maximum SASW Depth (ft)	V_S 30 (ft/sec)	NEHRP Site Class	Comments
ALCT	Alcott School, Redmond	Qvr	94	0.04	170	1285	C	Deep soil
LEOT	Leota School, N. of Lake Leota	Qvt	100	0.08	140	1382	C	
EARN	East Ridge School, Redmond	Qvr	101	0.07	190	1664	C	
MBPA	Monroe BPA Substation	m	119	0.15	180	1095	D	Firm rock at 85 ft

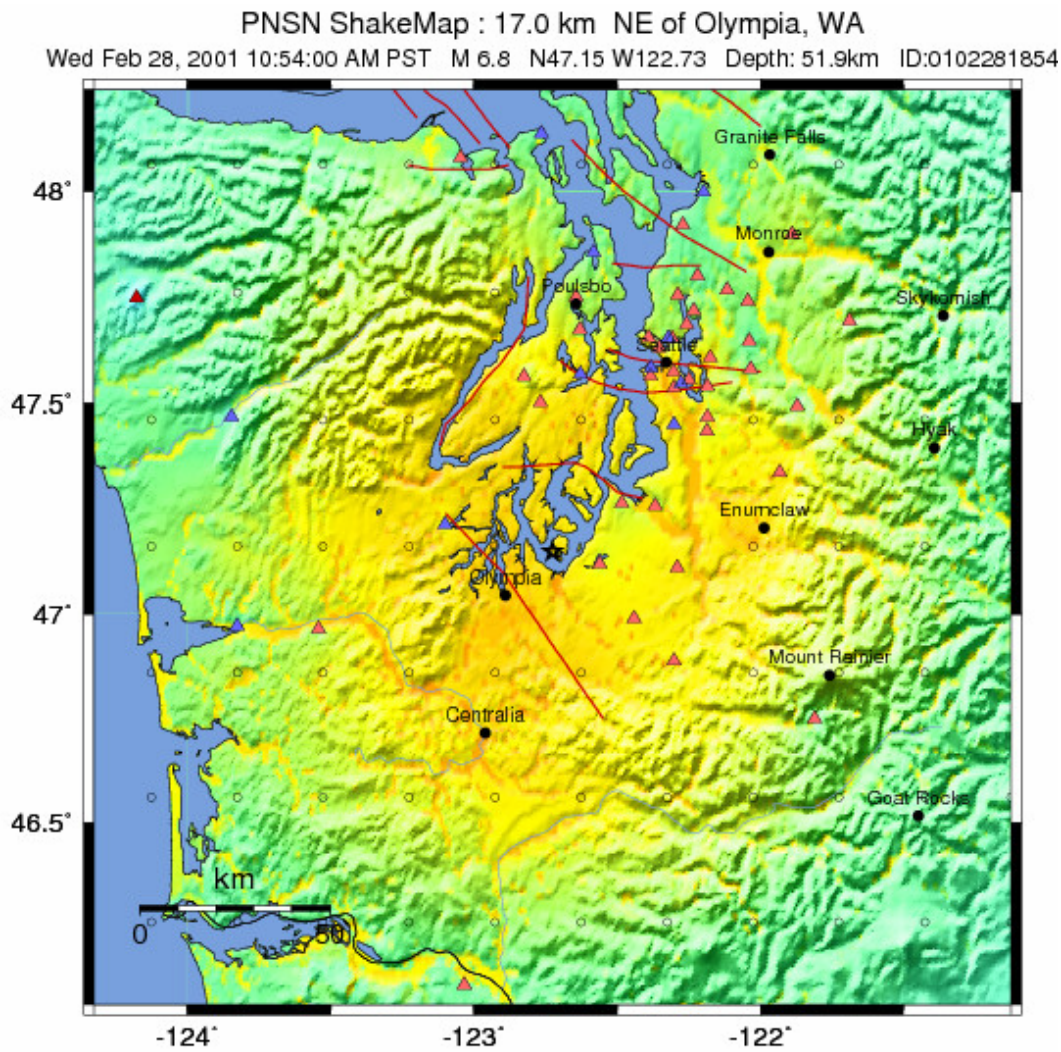
m Fill
Qal Holocene river alluvium
Qmw Mass wastage/colluvial deposits
Qvr Vashon recessional outwash
Qvt Vashon Qvt
Qva Vashon advance outwash (Esperance sand)
Qvlc Vashon advance outwash (Lawton clay)
Qpogl Pre-Fraser glacio-lacustrine silt and clay (S. Palmer)

NEHRP Site Class V_S30
A > 5,000 ft/sec
B 2,500 to 5,000 ft/sec
C 1,200 to 2,500 ft/sec
D 600 to 1,200 ft/sec
E < 600 ft/sec

Table 2. Goodness-of-Fit of Modeled to Observed Dispersion Curves

Site Name	Fit to Dispersion Curve
ALCT	B
7034	B
BRKS	A
HOLY	A
KIMR	A
LAWT	B
LEOT	B
NOWS	A
PCEP	B
PCFR	B
PCMD	B
QAW	A
RHAZ	A
SP2	A
UPS	B
7032	A
WISC	A
EARN	A
MPL	A
MBPA	A
MURR	A
RAW	A
7030	A
SEW	C
ELW	A
GNW	A
7008	B
KIMB	C
2101	C
RBEN	B
7027	B
SEA	C

A: Very good fit to a well-condition dispersion curve
B: Good fit to a dispersion curve showing some lateral variability
C: Dispersion curve shows ranges with high variability



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Source: USGS

Figure 1. ShakeMap of the 2001 **M** 6.8 Nisqually Earthquake. Triangles represent some of the strong motion stations that recorded the event.

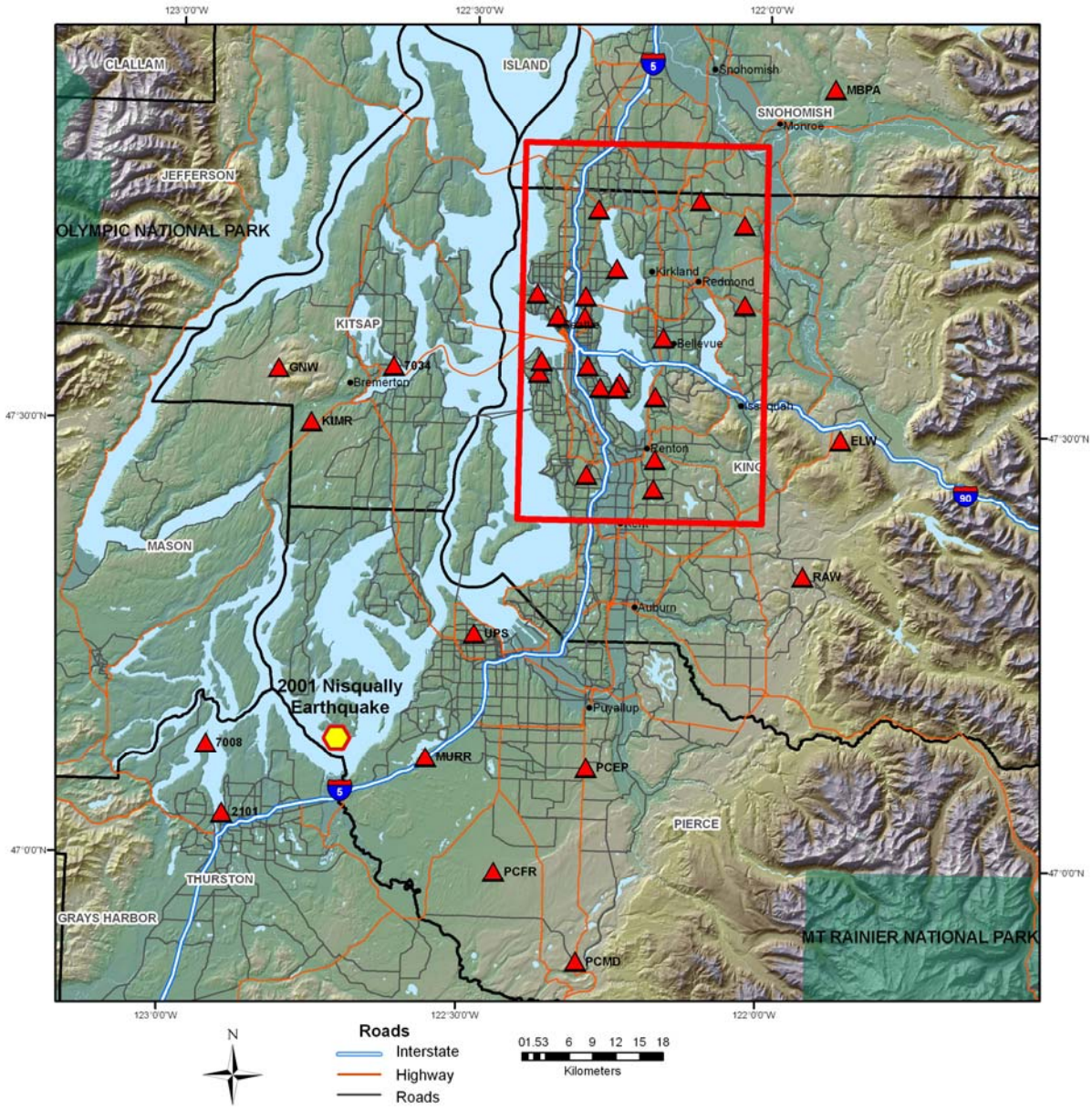


Figure 2. Strong Motion Stations Surveyed in the Puget Sound Region (inset is shown on Figure 3)

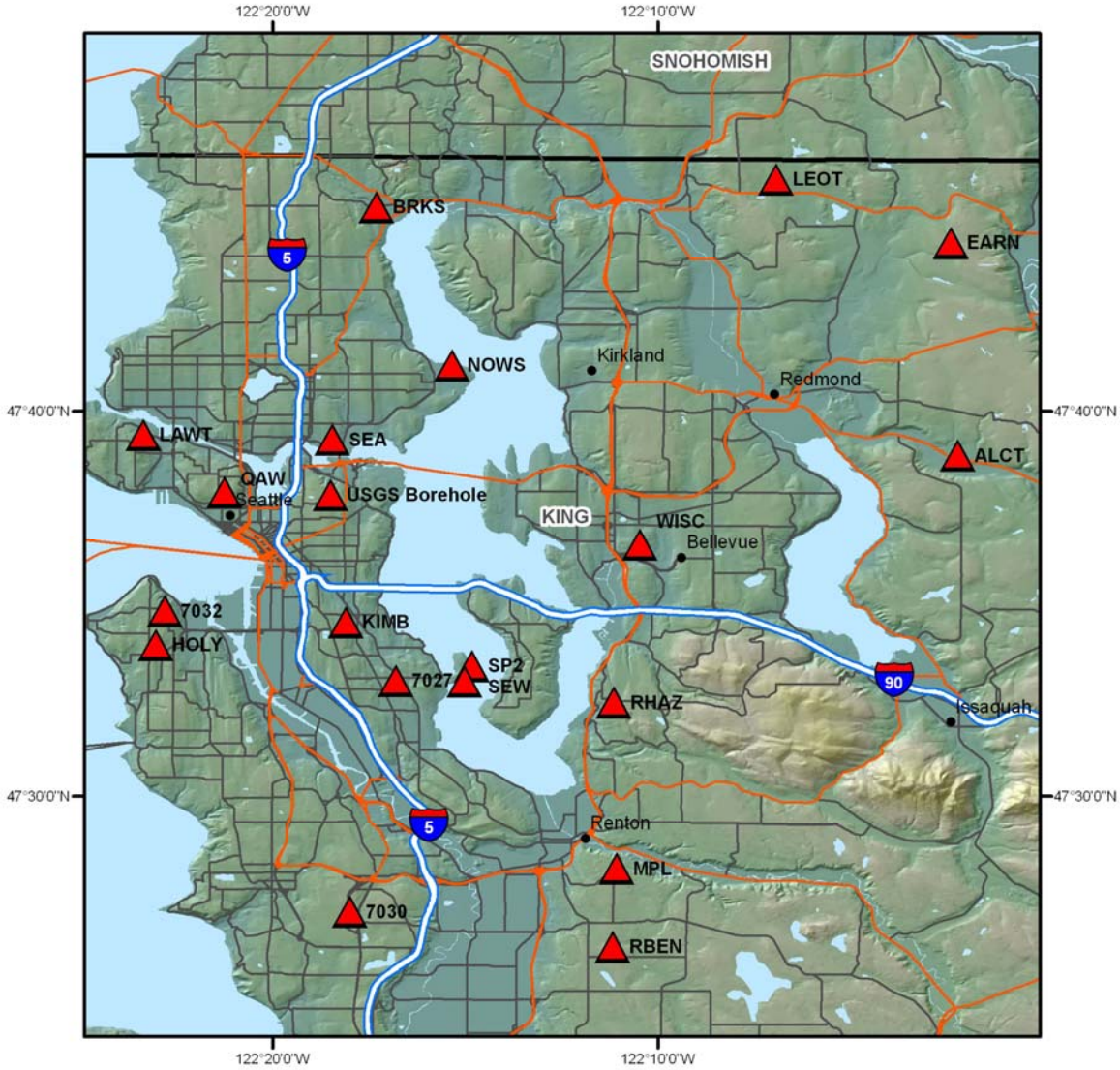


Figure 3. Strong Motion Stations Surveyed in the Seattle-Bellevue Area

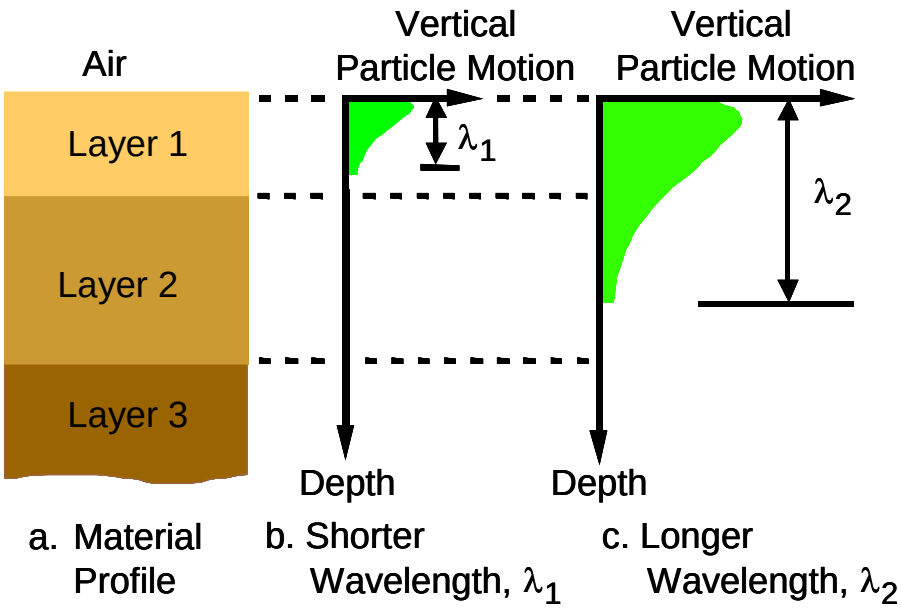


Figure 4. Illustration of Surface Waves with Different Wavelengths Sampling Different Materials in a Layered System, Which Results in Dispersion in Wave Velocities

Figure 5. University of Texas NEES Mobile Vibrator "Thumper" at the University of Washington

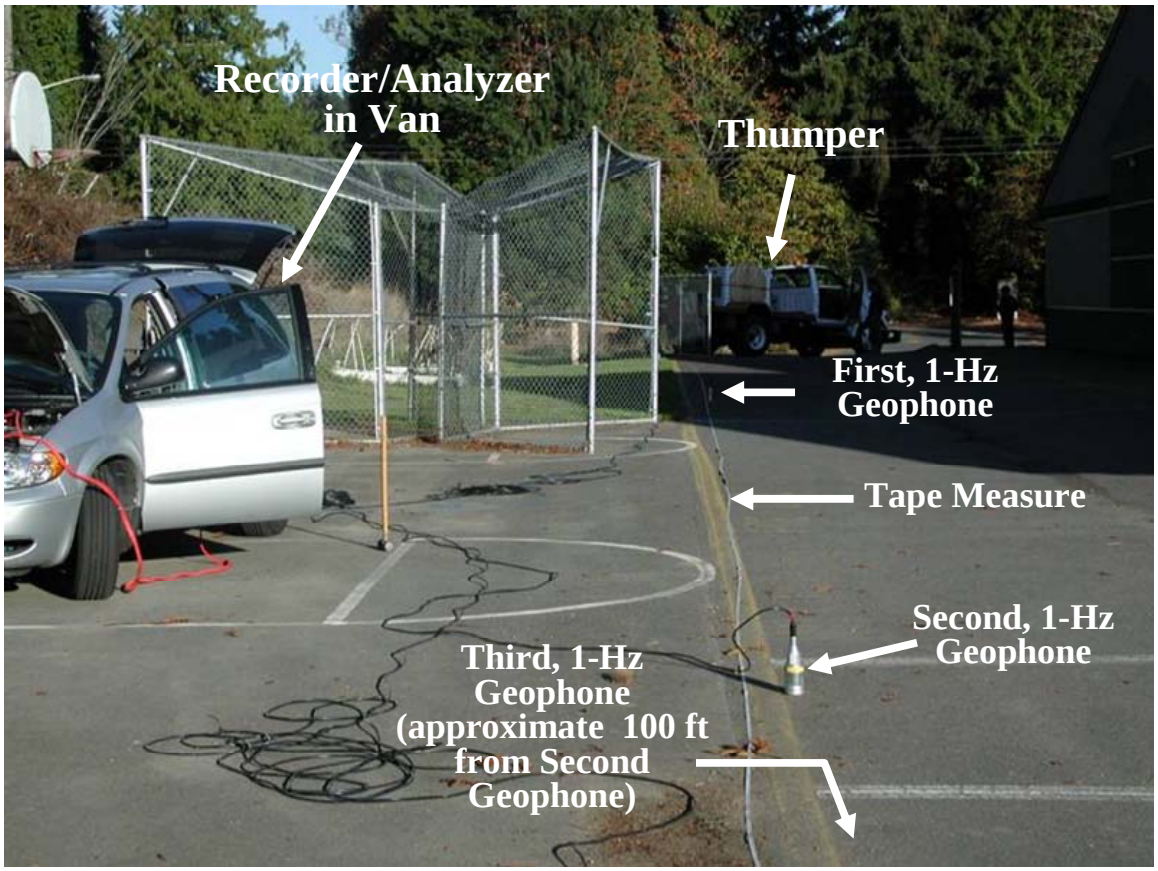


Figure 6. SASW Survey at BRKS. Analysis truck and a 1 Hz vertical seismometer are in the foreground and Thumper is in the far background.

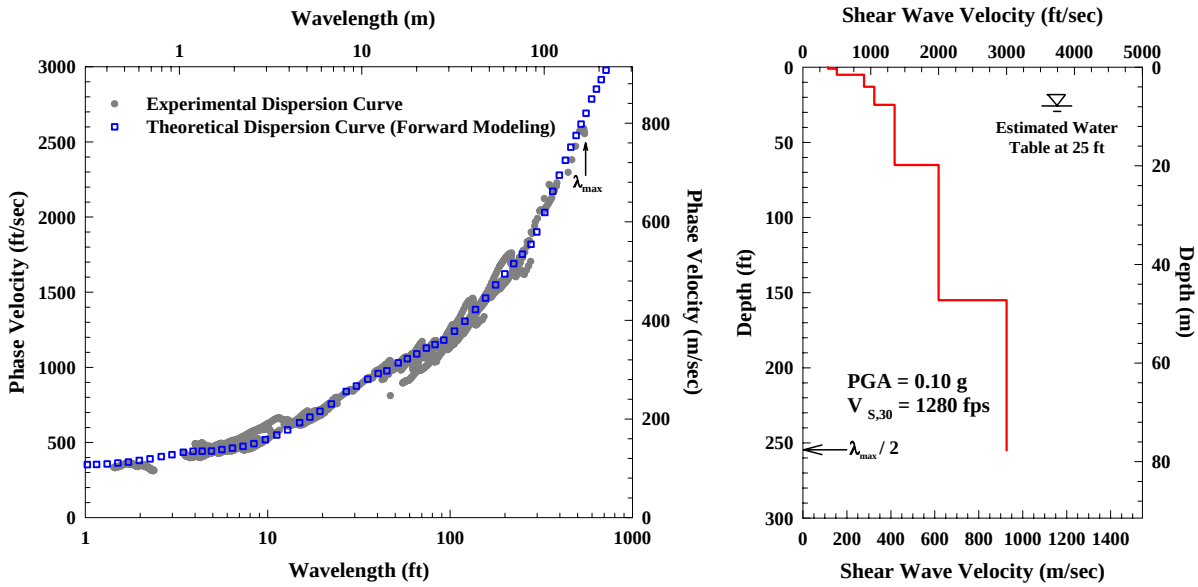


Figure 7. (a) Comparison of the experimental and theoretical dispersion curves, and (b) V_S profile determined from forward modeling for the MPL site. An estimate of the water table is also shown.

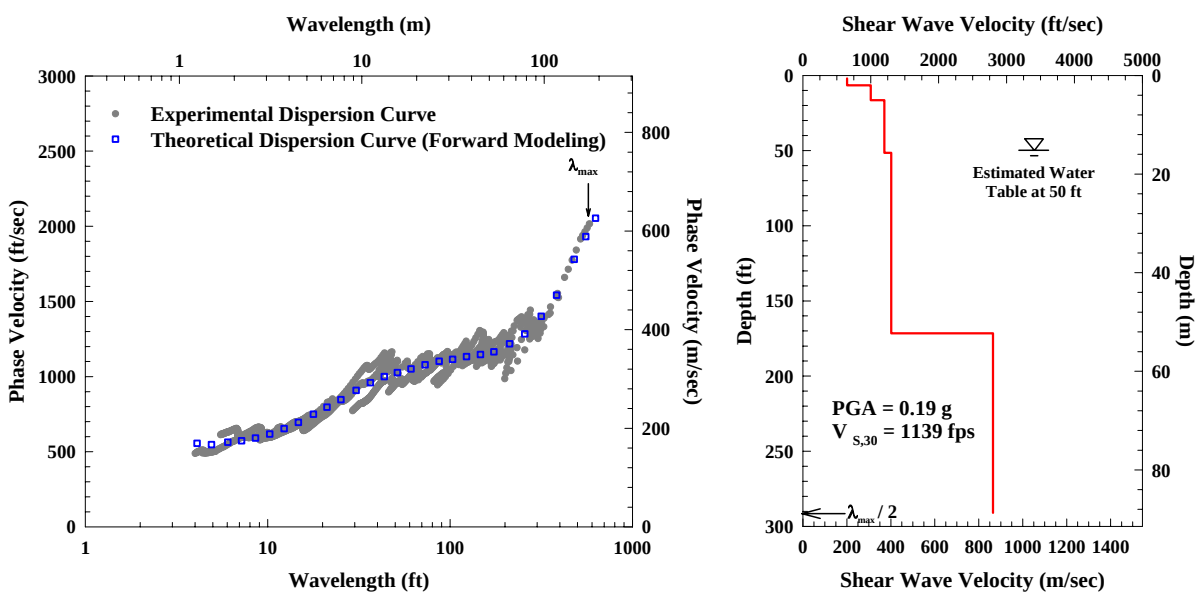


Figure 8. (a) Comparison of the experimental and theoretical dispersion curves, and (b) V_S profile determined from forward modeling for the SEATAC Fire Station (7030).

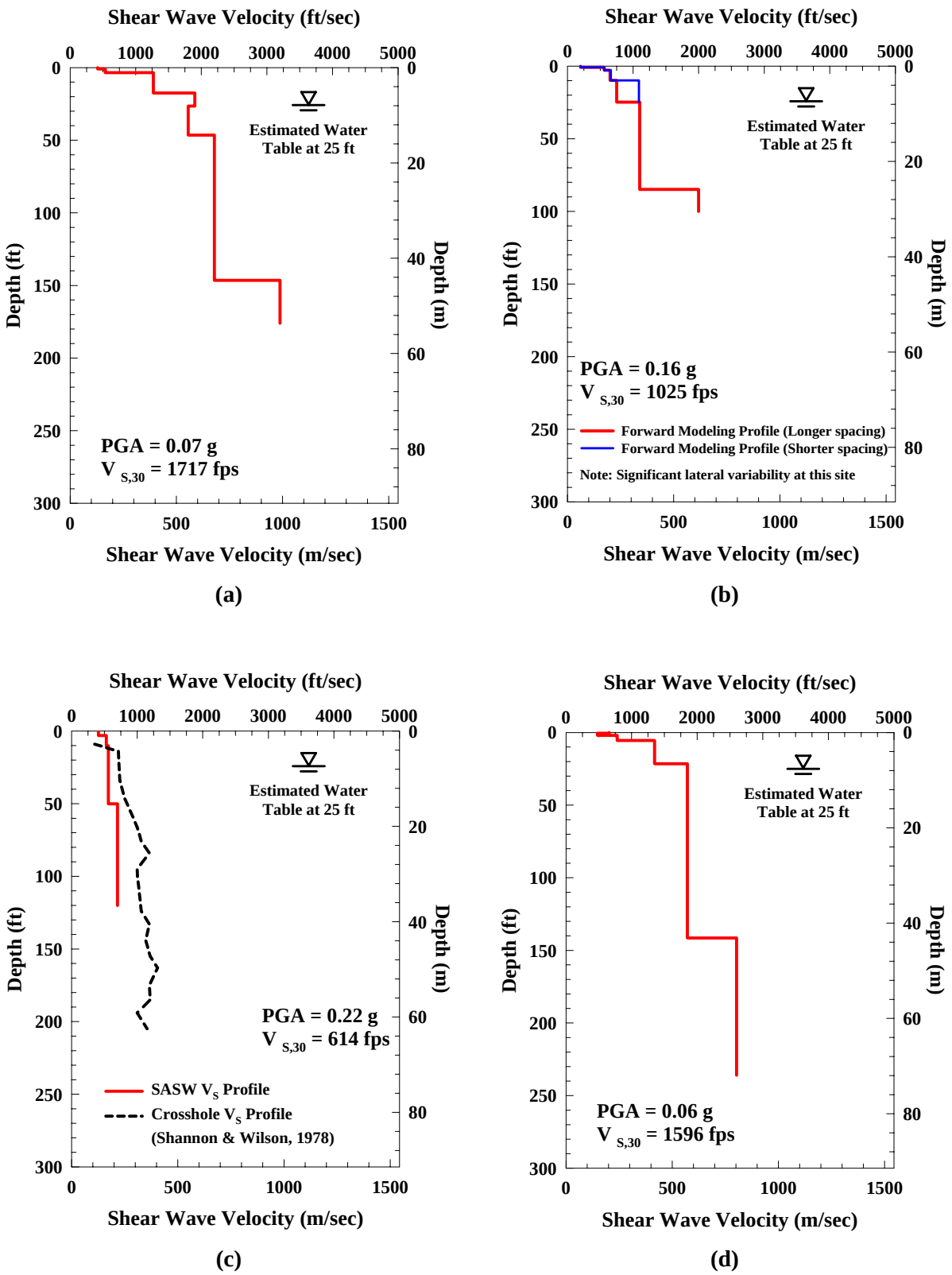


Figure 9. V_S Profiles at a) Camp Murray (MURR); b) Halvorsen Residence (USGS 7008); c) Highway Test Lab (USGS 2101); and d) University of Puget Sound (UPS). The crosshole profile is from Shannon & Wilson and Agbabian Associates (1978).

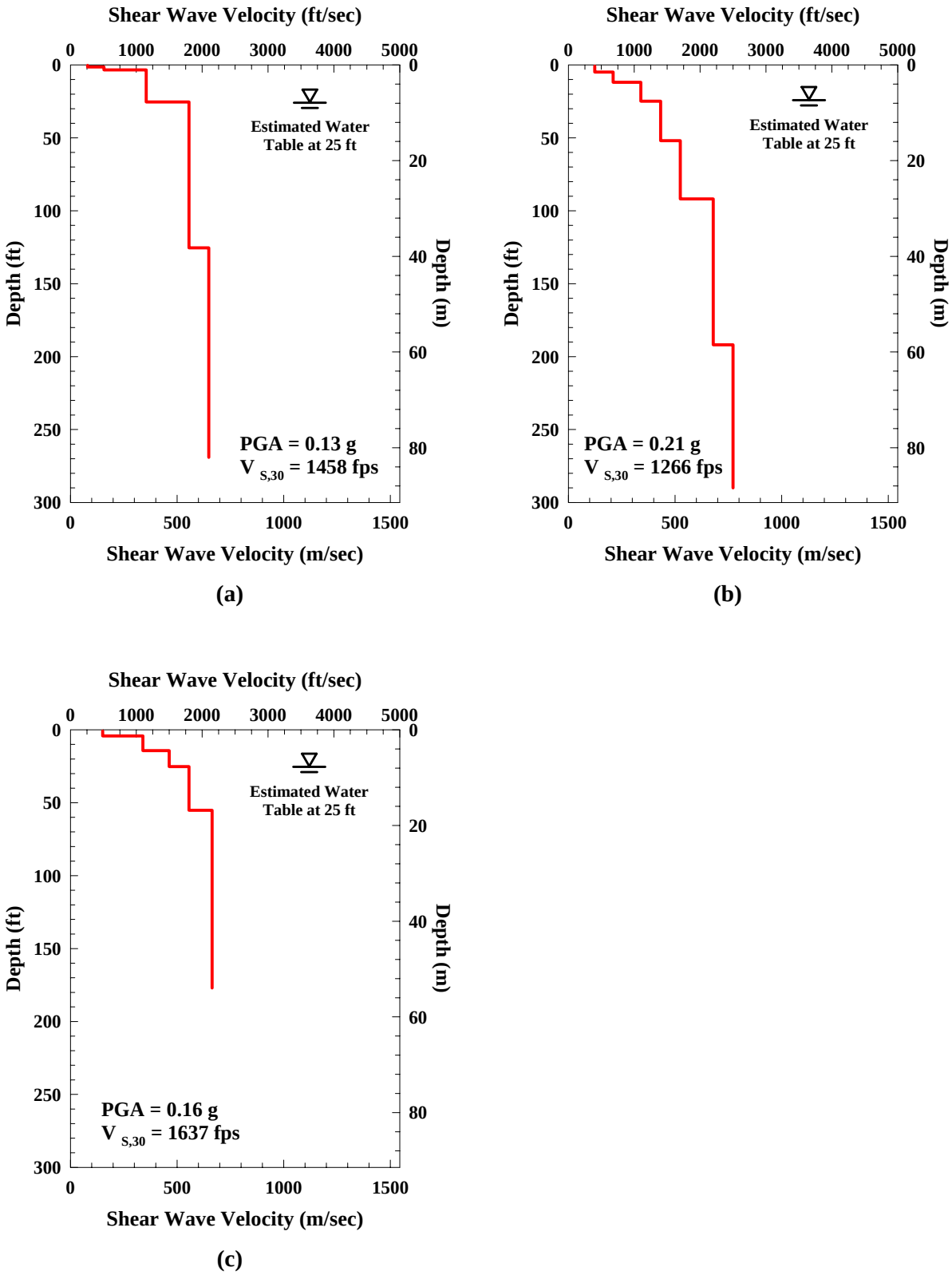


Figure 10. V_S Profiles at a) Pierce County Training Center (PCFR); b) Pierce County East Precinct (PCEP); and c) Pierce County Mountain Detachment (PCMD).

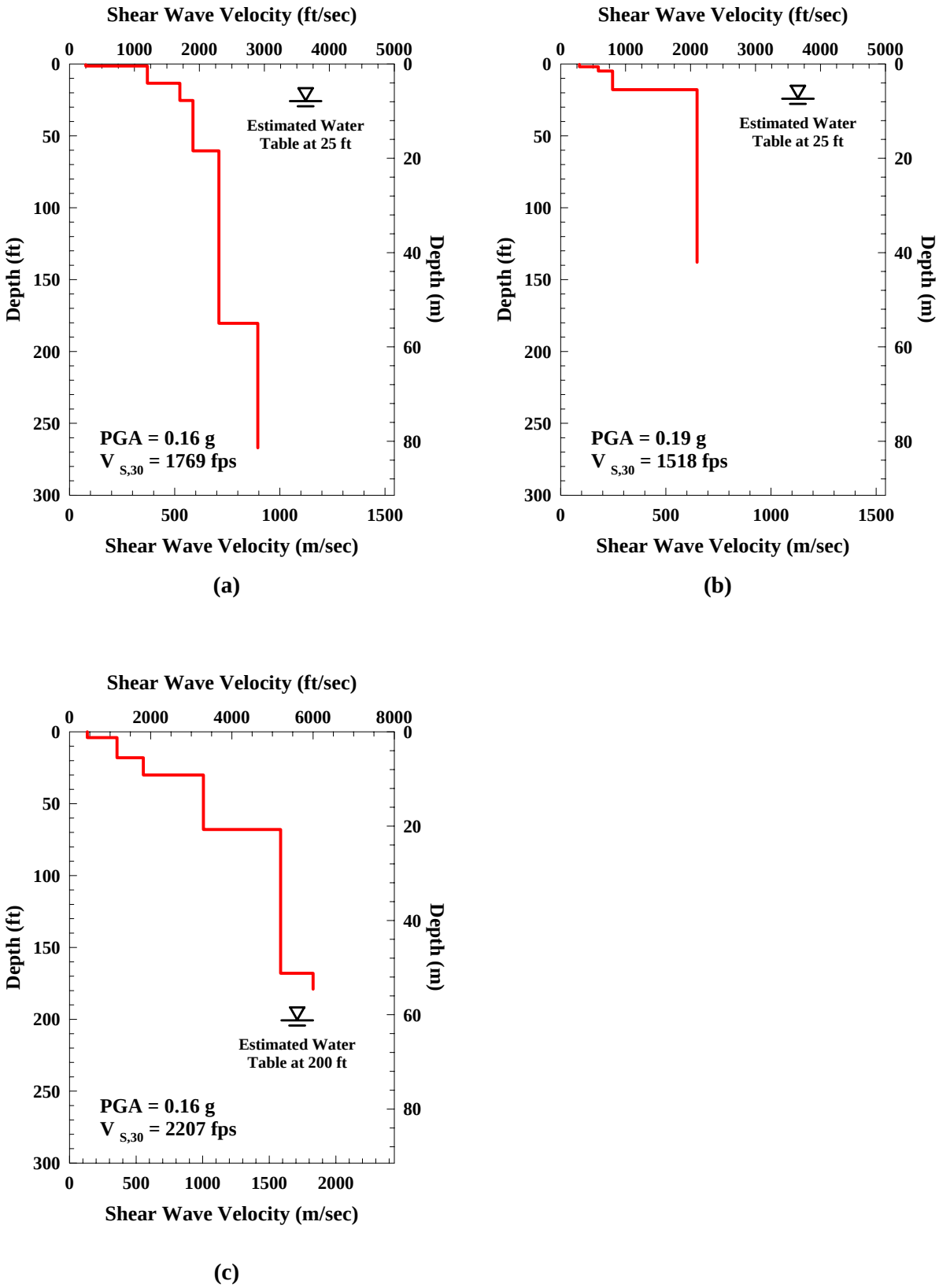


Figure 11. V_S Profiles at a) Kitsap County Airport (KIMR); b) Bremerton Fire Station (USGS 7034); and c) Tahyua Lake (GNW).

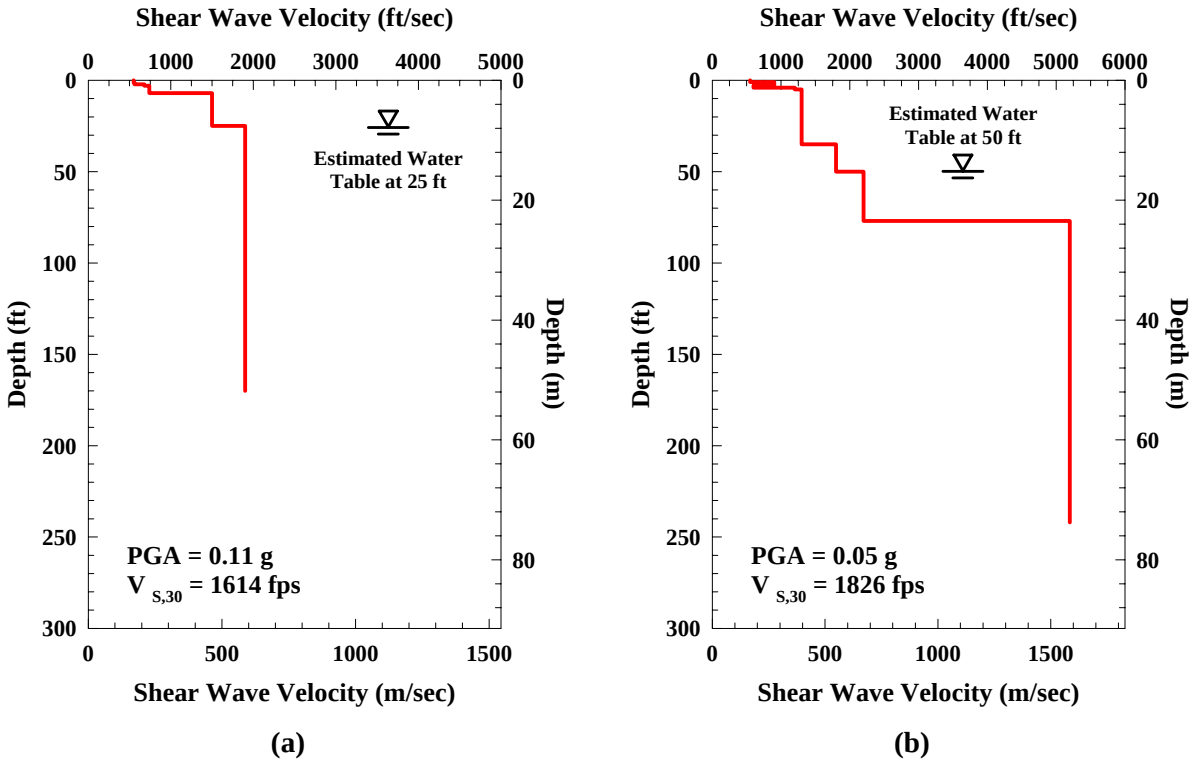


Figure 12. V_S Profiles at a) Benson Hill High School (RBEN); and b) Hazelwood School (RHAZ).

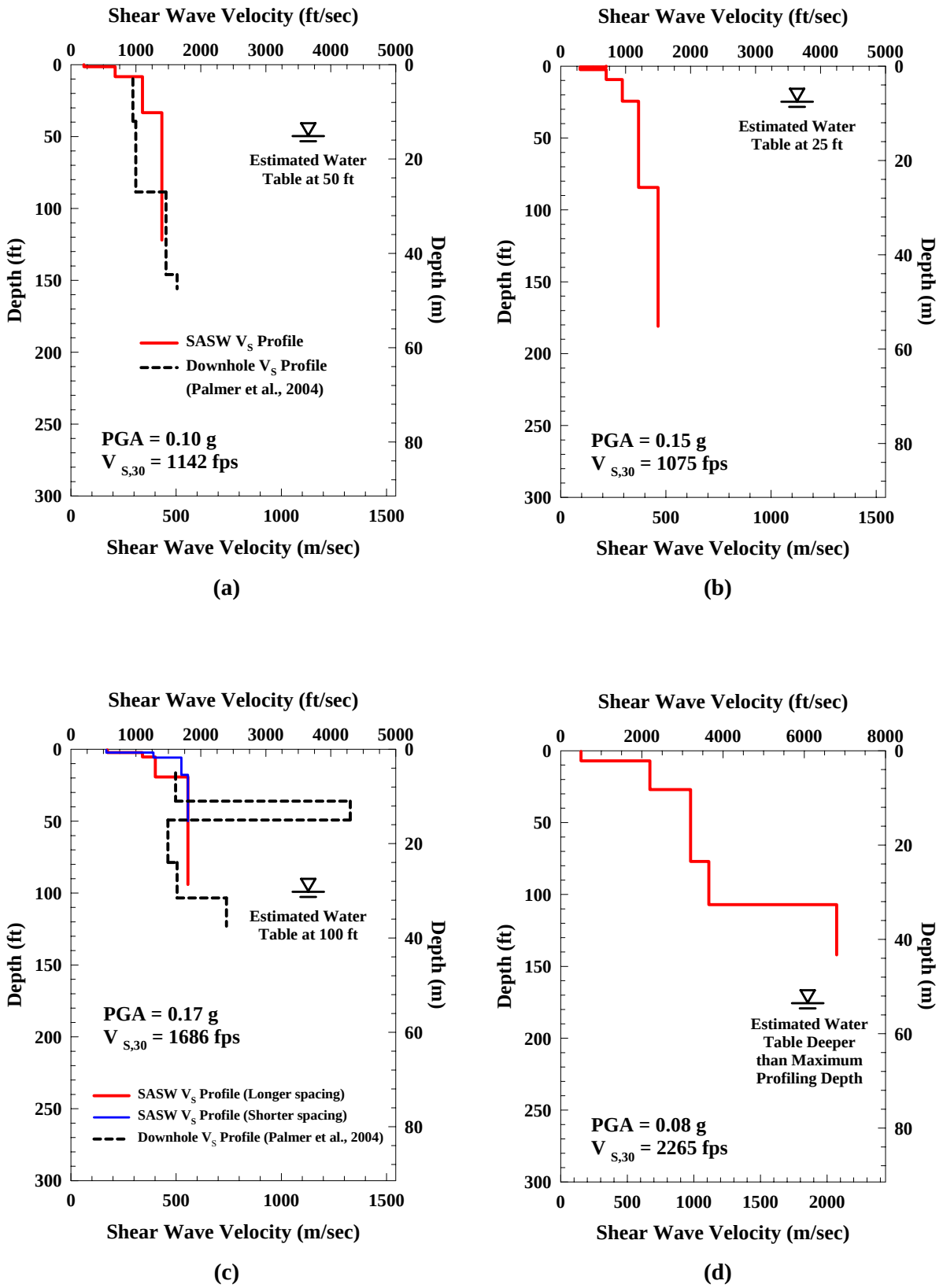


Figure 13. V_S Profiles at a) Holy Rosary School (HOLY); b) West Seattle Fire Station #29 (USGS 7032); c) Kimball School (KIMB); and d) Seattle Fire Station #28 (USGS 7027). Downhole profiles at HOLY and KIMB are from Palmer et al. (2004).

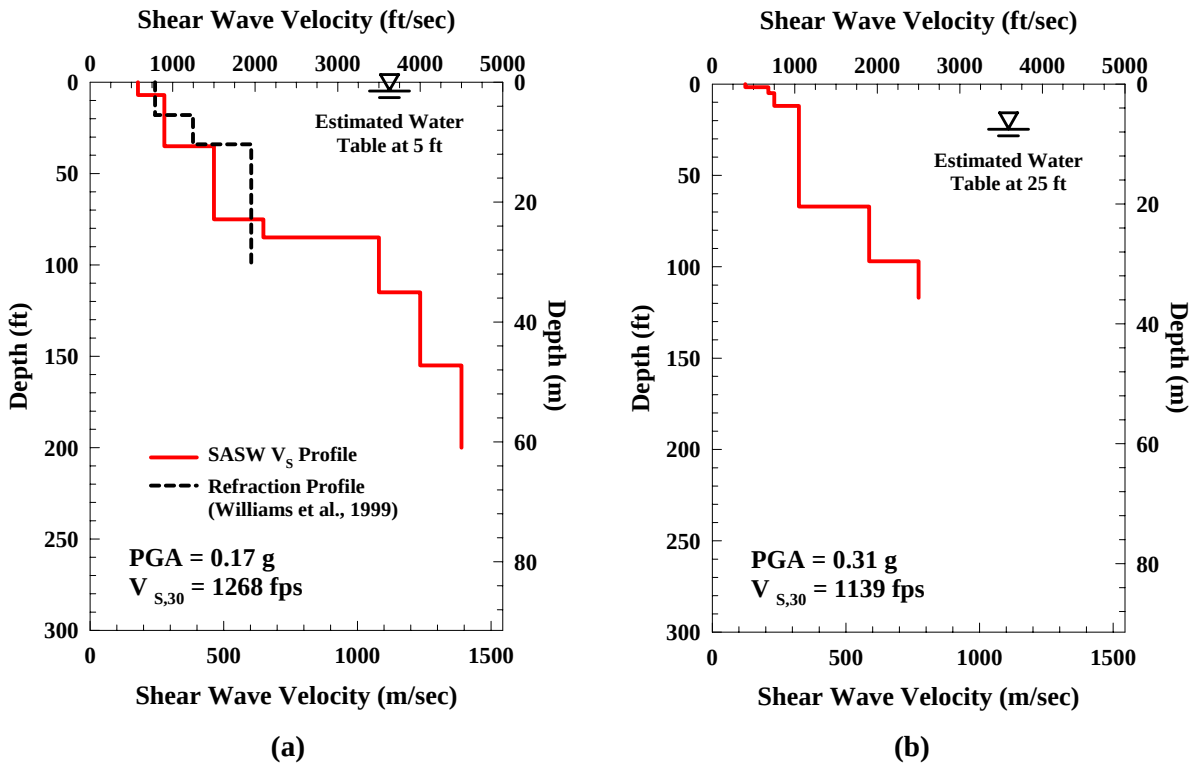


Figure 14. V_S Profiles at a) Seward Park (SEW); and b) Seward Park (SP2). Seismic refraction V_S profile at SEW is from Williams et al. (1999).

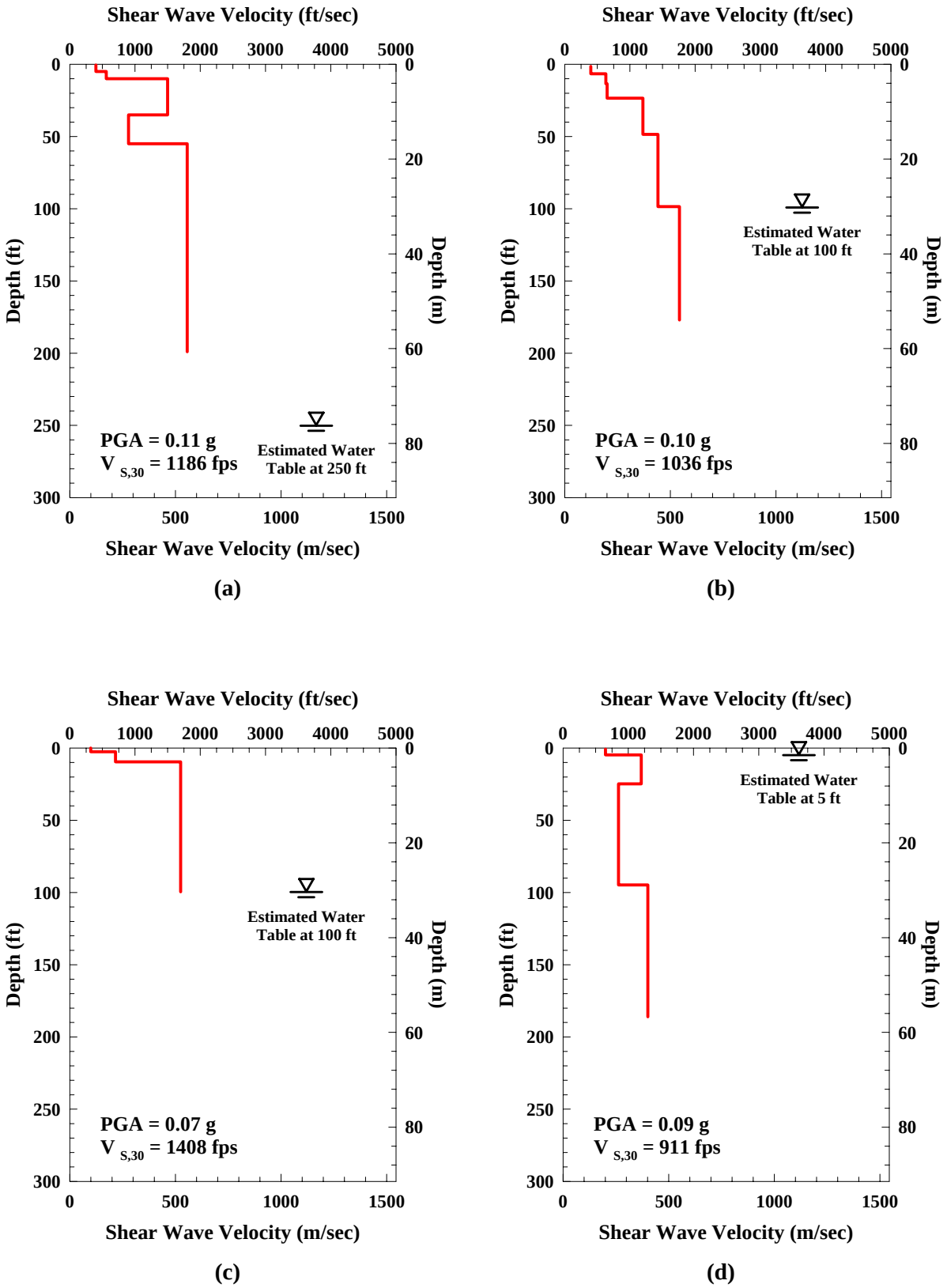


Figure 15. V_S Profiles at a) Queen Anne Hill (QAW); b) Lawton School (LAWT); c) ATM Building, University of Washington (SEA); and d) NOAA Sand Point (NOWS).

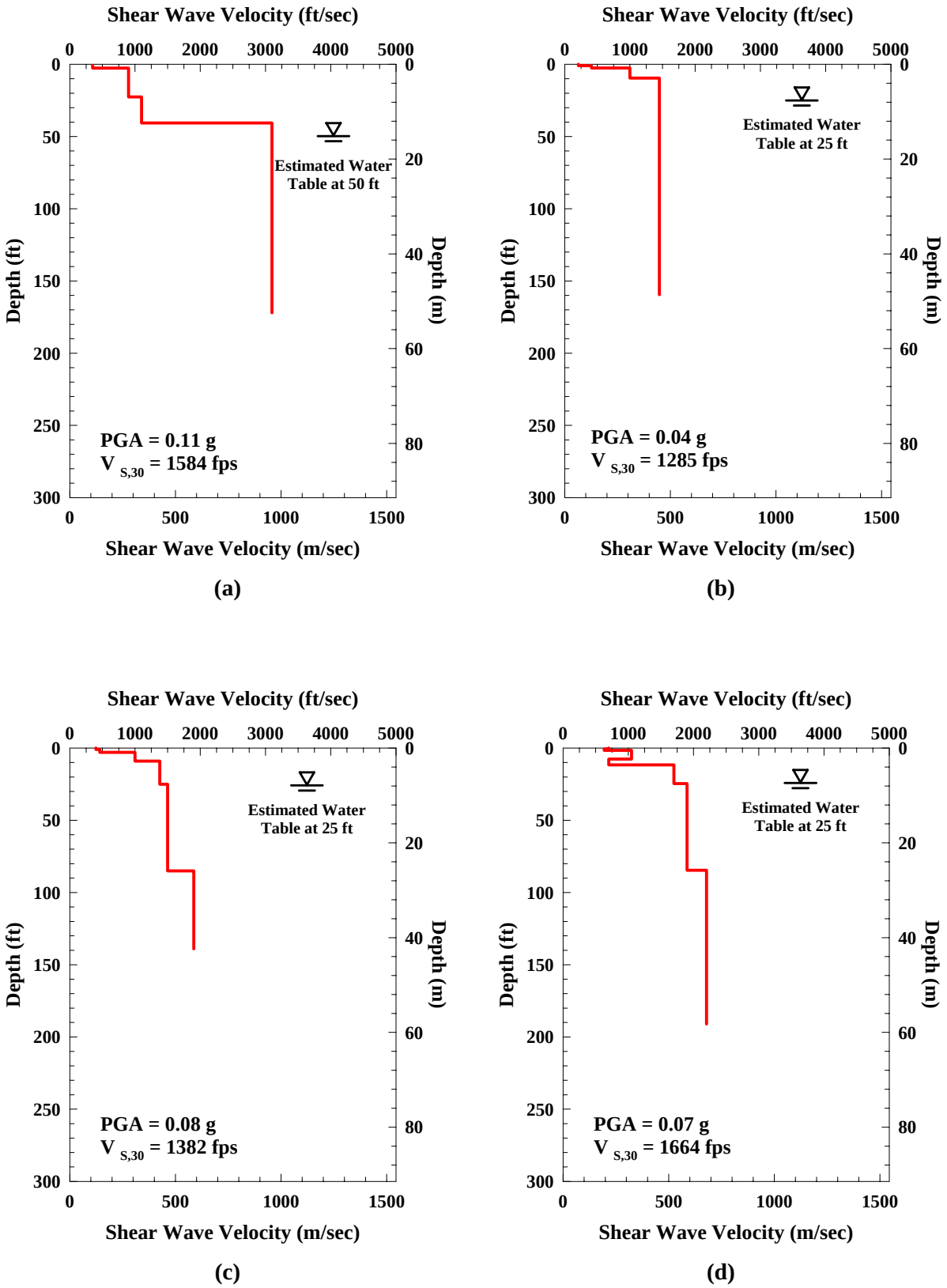


Figure 16. V_S Profiles at a) Wilburton Center(WISC); b) Alcott Elementary School (ALCT); c) Leota School (LEOT); and d) East Ridge School (EARN).

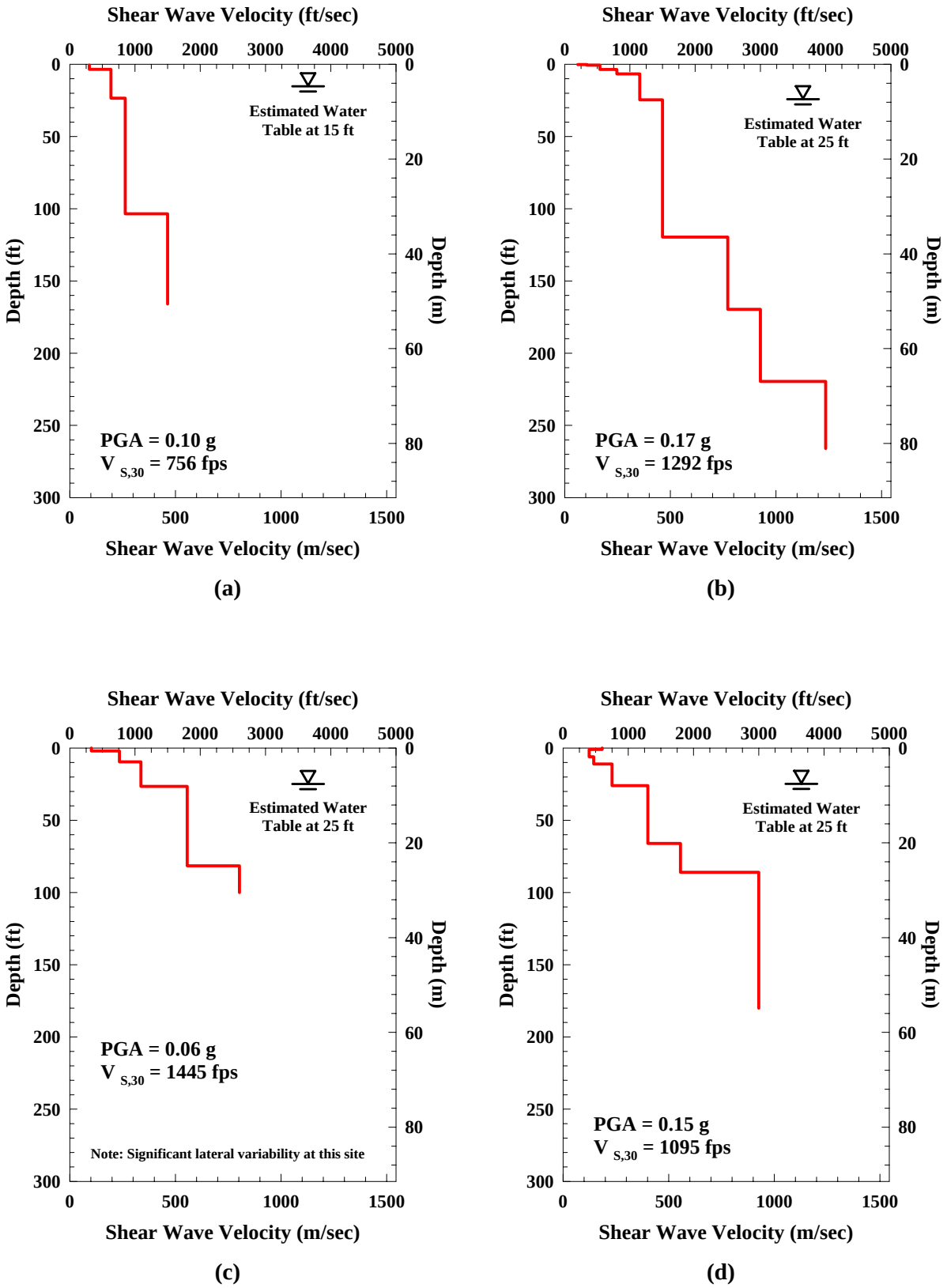


Figure 17. V_S Profiles at a) Brookside Elementary School (BRKS); b) Raver BPA Substation (RAW); c) Echo Lake BPA Station (ELW); and d) Monroe BPA Substation (MBPA).

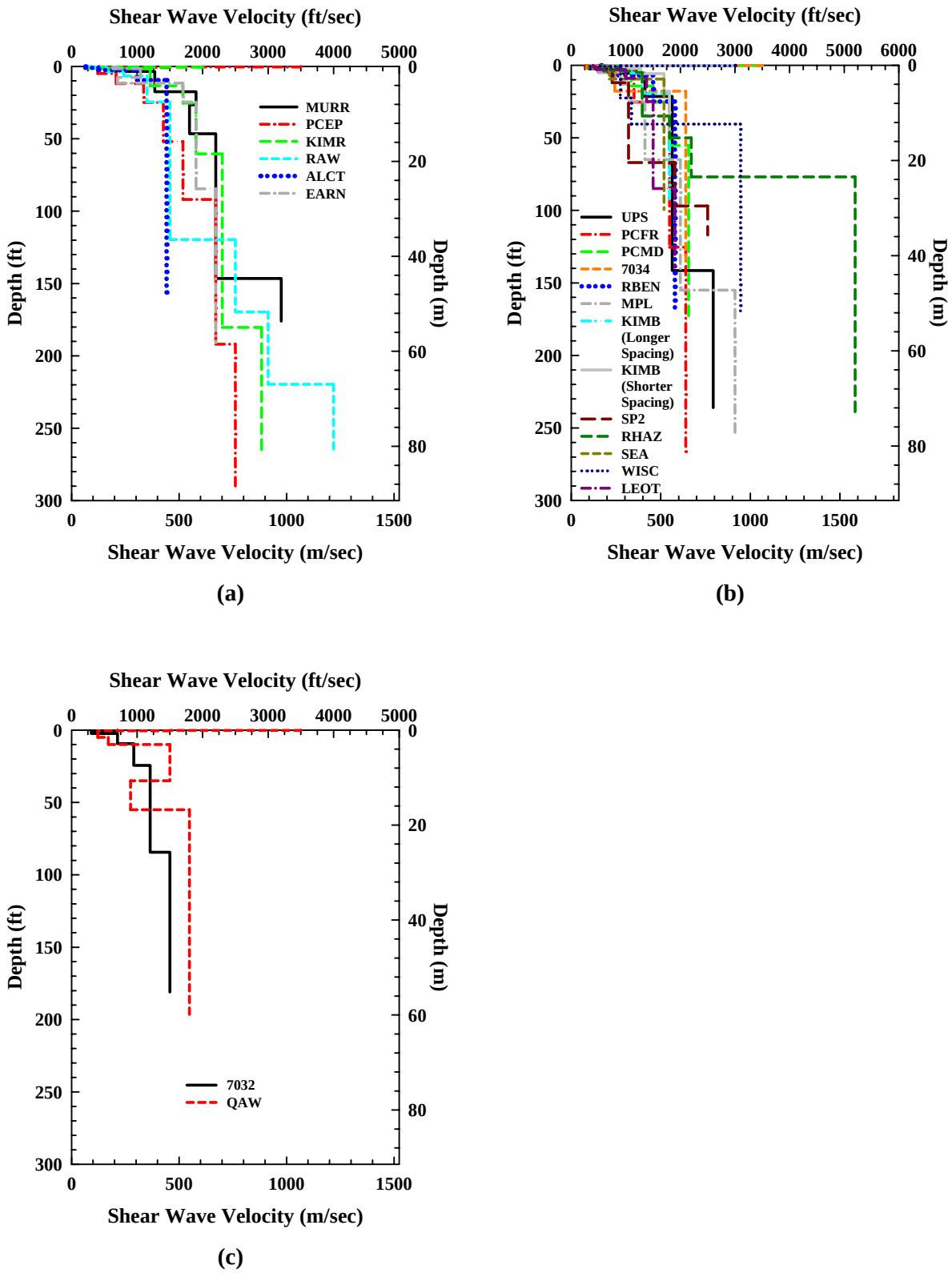
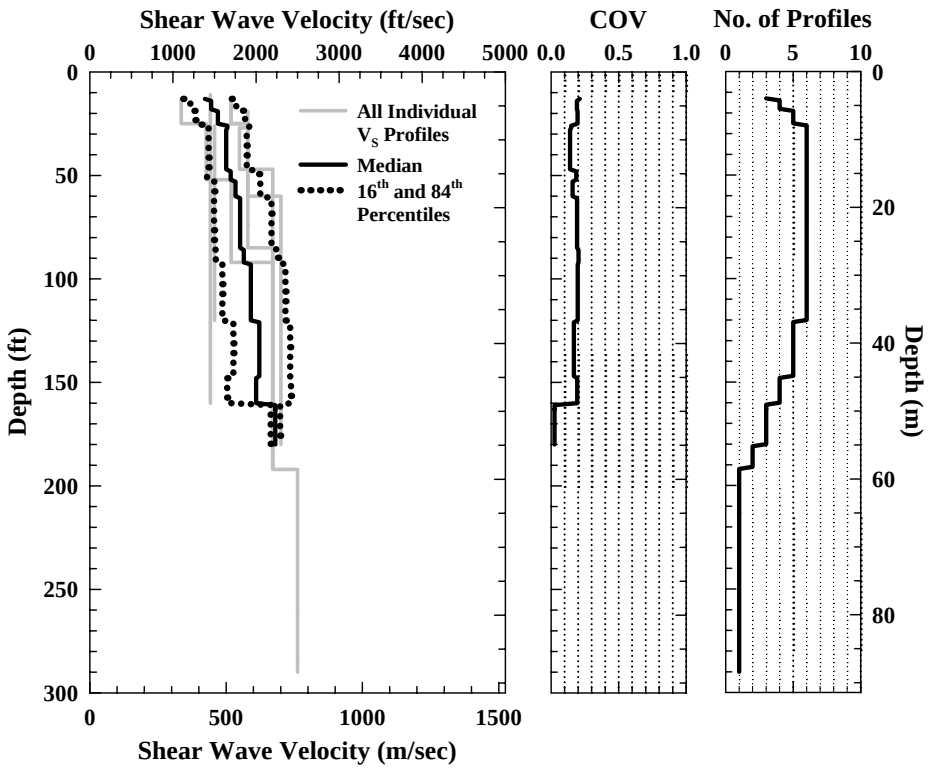
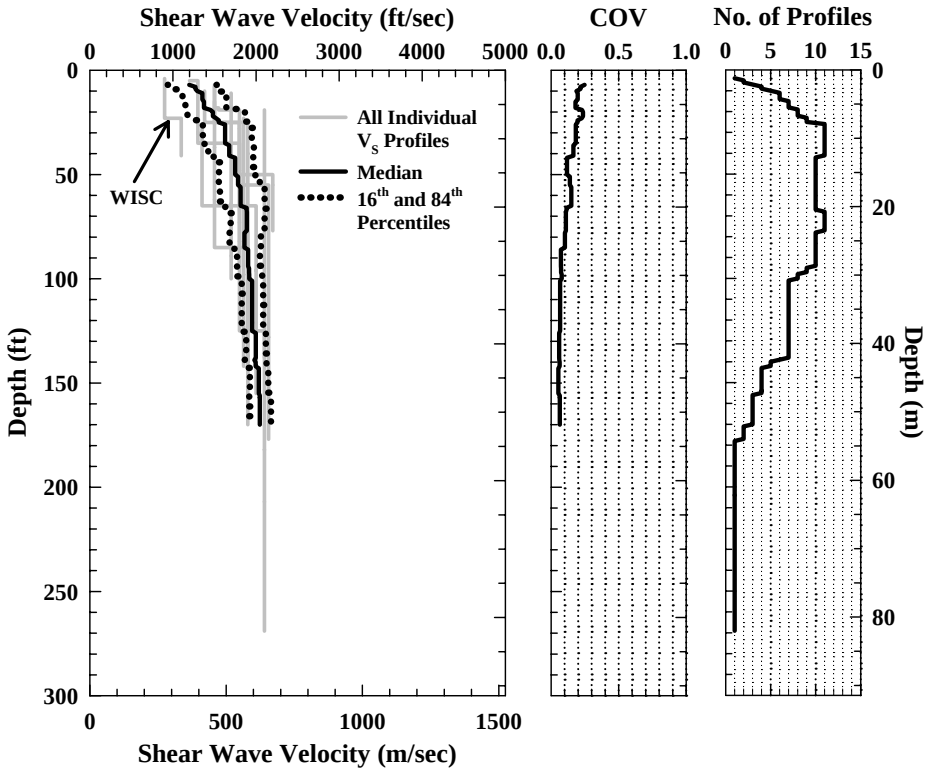


Figure 18. V_S Profiles for a) Qvr; b) Qvt; and c) Qva.



(a)



(b)

Figure 19. Median, 16th, and 8th Percentile V_S Profiles for a) Qvr and b) Qvt.

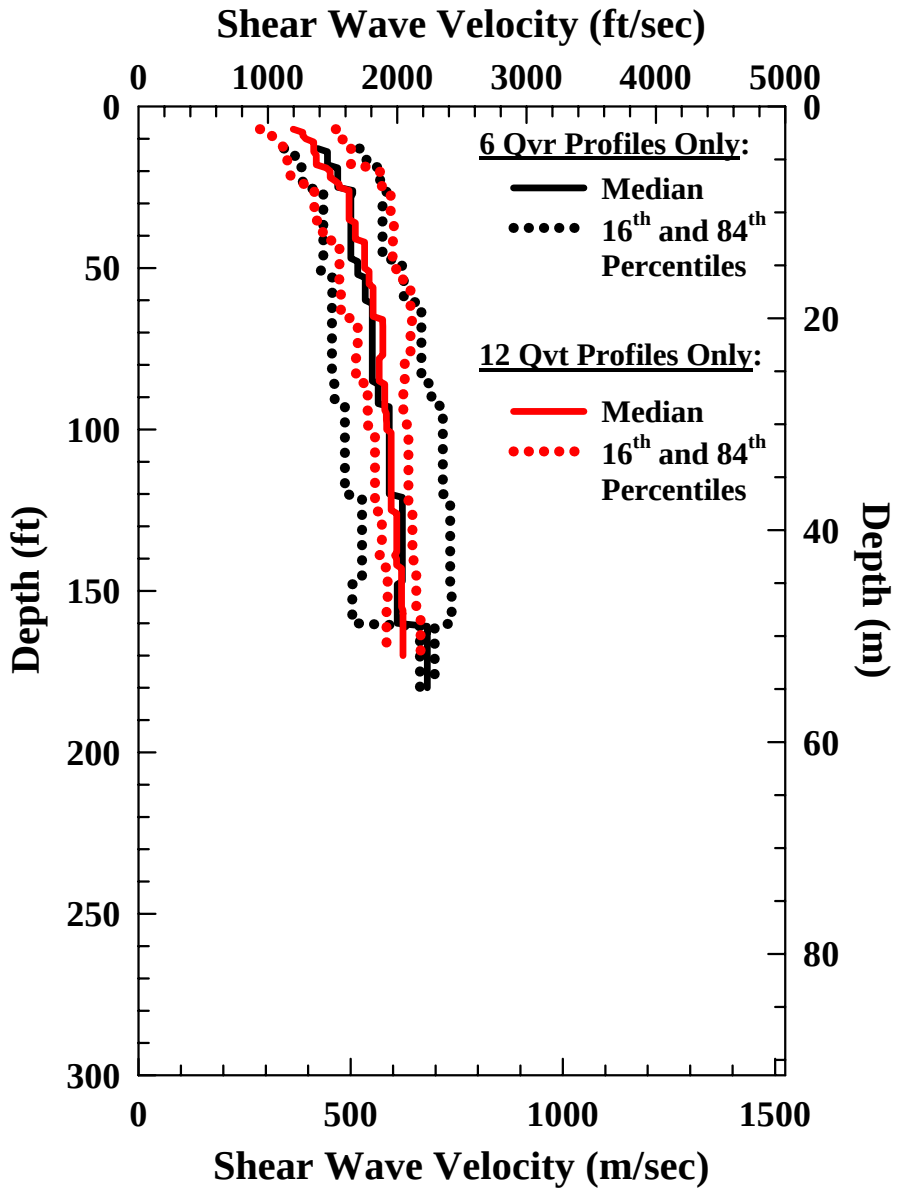


Figure 20. Comparison of Median, 16th, and 84th Percentile V_S Profiles for Qvr and Qvt.

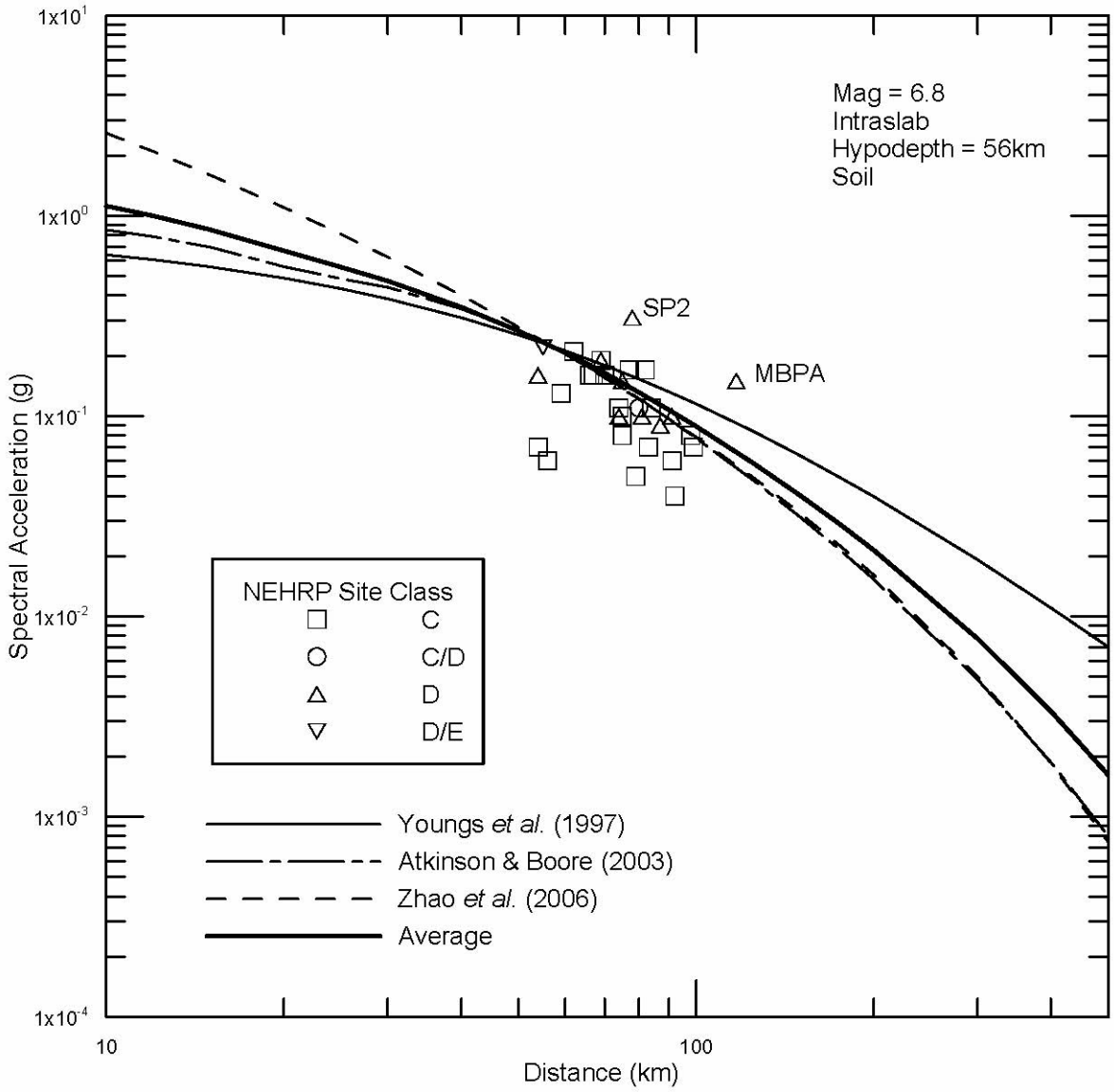


Figure 21. Comparison of Recorded PGA Values With Empirical Intraslab Attenuation Models for Soil. The NEHRP site class of each strong motion station is shown by different symbols.