SEISMIC SITE CHARACTERIZATIONS AT EARTHQUAKE STATION SITES AND COMPILATION OF SITE SPECIFIC INFORMATION IN WASHINGTON AND OREGON

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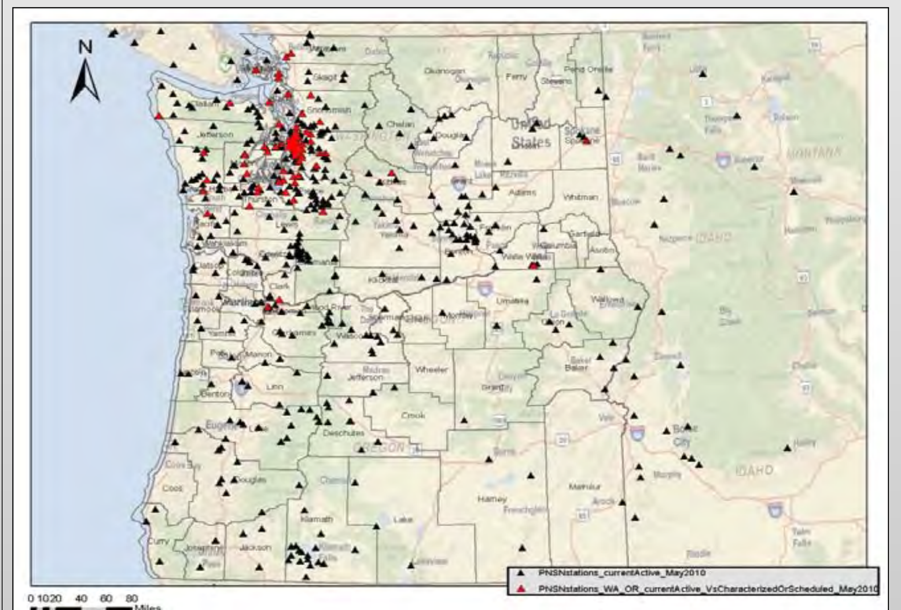
Abstract

In the last 6 years the Washington State Department of Natural Resources, Division of Geology and Earth Resources (WADNR-DGER) has been carrying out shallow seismic site characterizations (with past and ongoing projects funded by the USGS-NEHRP External Grant Program in last 3 years) at about 100 sites to estimate velocity profiles and calculate Vs30m essential for understanding and quantifying soil behavior at earthquake recording station sites and for ShakeMap and HAZUS applications. We have been specifically targeting seismometer sites in Washington and Oregon, and compiling earthquake site-specific information (geotechnical boreholes, water well logs and local geology) in order evaluate the sites qualitatively and/or empirically from previously known estimates. Shallow seismic site characterizations have been carried out using active (Multichannel Analysis of Surface Waves, refraction and downhole seismic) and passive (Microtremor Array Measurements and Horizontal-to-Vertical Spectral Ratio) methods. SPT resistance tests and other borehole soil information (where available) have been extensively used to estimate and correlate shear-wave velocities. We are currently building a shear-wave database in conjunction with the available subsurface database in Washington and will publish the database through the Washington State Geologic Information Portal. Examples of passive and active (or combined) seismic site characterization results and a flow chart for the compilation of site specific information will be presented. The site specific information compiled and generated using seismic methods can be used to improve the seismic hazard maps of metropolitan areas in Washington and Oregon.

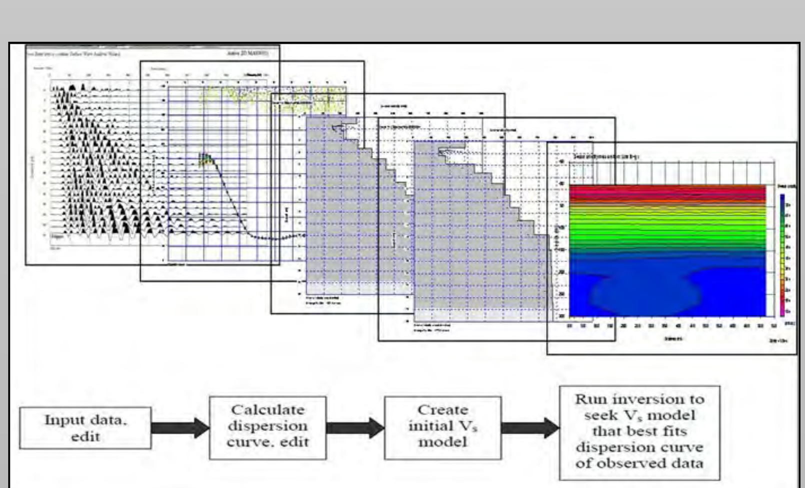
Pacific Northwest Seismic Network (PNSN) Stations and Seismic Characterization Sites



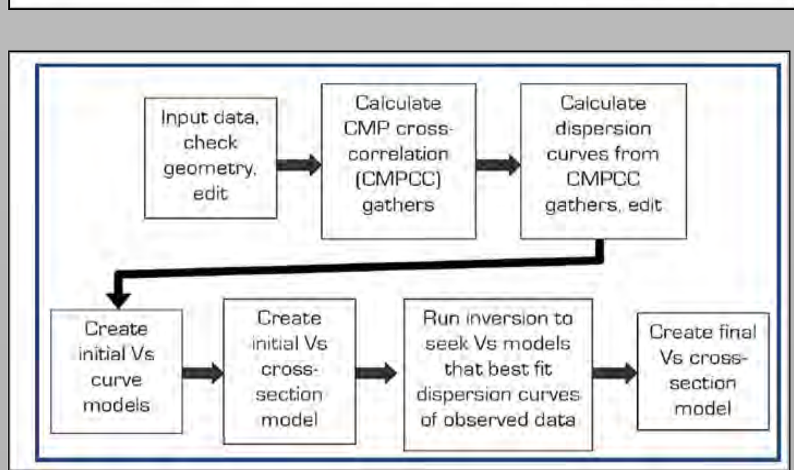
PNSN stations (black-filled triangles) and characterized station sites (red-filled triangles)

Seismic Site Characterization Methods

1 - Multi Channel Analysis of Surface Waves (MASW)



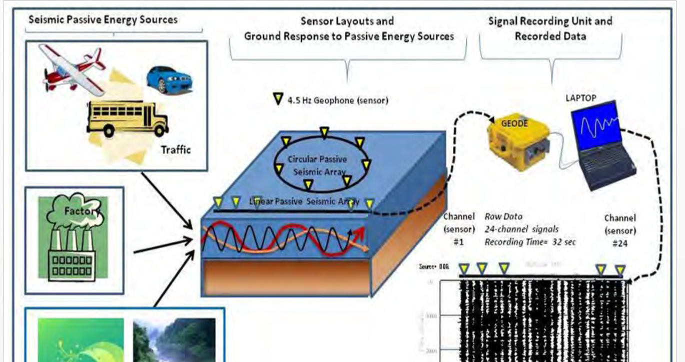
Processing steps for the Multichannel Analysis of Surface Waves (MASW) (Cakir and Walsh, 2010; Geometrics, 2009a).



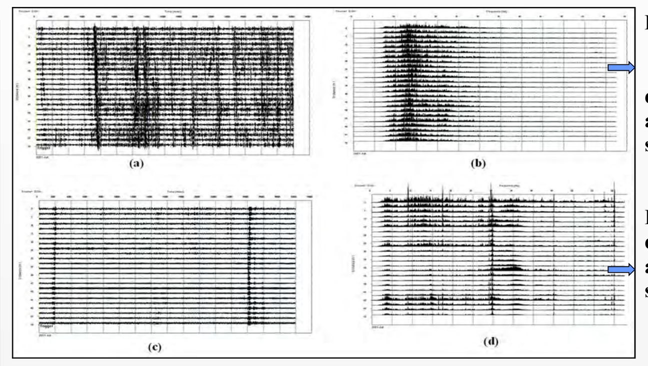
Processing steps for a two-dimensional imaging of the MASW data (Underwood, 2007).

Seismic Site Characterization Methods

2 - Microtremor Array Measurements (MAM)



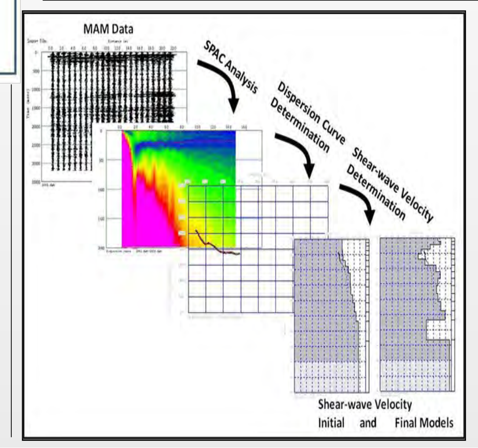
A schematic view for Microtremor Array Measurement (MAM) passive seismic survey and its data (duration=32 seconds) on a 24-channel seismograph (Geode seismograph, Geometrics Inc.); passive seismic signals consisting of cultural and natural noise propagating at various wavelengths (sampling different layered materials) interact with near-surface geology under linear or other (circular, triangular, L-shaped etc.) sensor arrays. The seismograph (data logger, GEODE) receives signals from the sensor array and transfers them to the laptop as a digital signal. An example record of a 32-second 24-channel passive survey (MAM) data set is shown (bottom-right corner).



Recorded MAM data

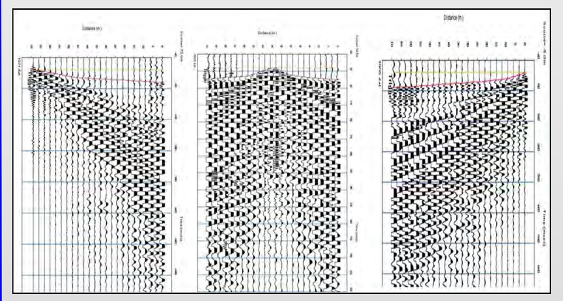
Good-quality MAM data time history (a), and its amplitude spectrum (b)

Poor-quality MAM data time history (c) and its amplitude spectrum (d)

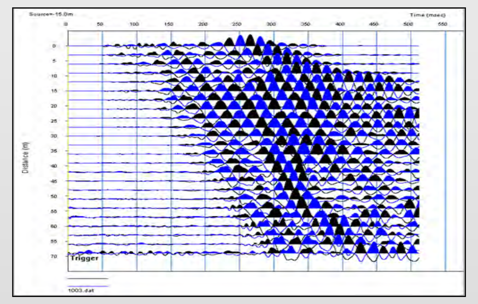


Microtremor Array Measurement (MAM) processing steps: The MAM data having a total of 10 minutes of approximately 20 32-second passive seismic records with a 24-channel seismograph (GEODE) are used as input for Spatial Autocorrelation (SPAC) analysis (originally proposed by Aki, 1957), resulted as a dispersion (frequency vs. velocity) image, which is edited (if needed) for the construction of the fundamental mode dispersion curve. Then a 1-D shear wave velocity (Vs) profile as an initial model is calculated from this dispersion curve. A final Vs profile is generated after an inversion process. The Vs velocity profile is considered as representing the middle part of the array (for example, middle section of the linear array).

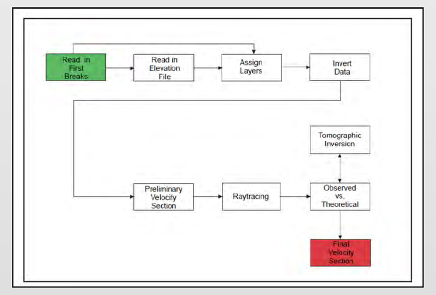
3 - P–wave and S-wave Seismic Refraction



Examples of forward, center and reverse shot gathers. Red lines shows the p-wave first break picks used for the p-wave refraction analysis to estimate subsurface (shallow) Vp profiles by using two-layer or three-layer time term inversion analysis to generate initial Vp model that can be used in tomography process.

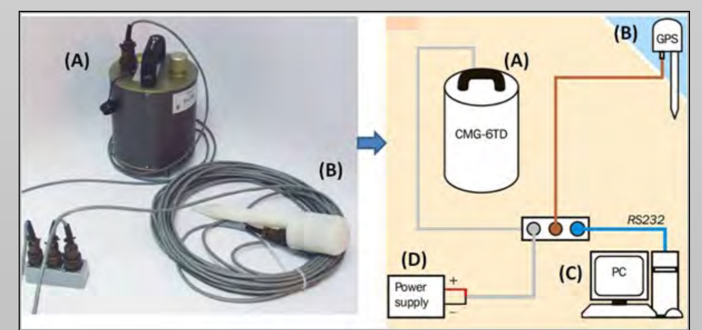


A shot gather with 180°-polarized shear-wave onsets, generated by striking both ends of the wood beam coupled to the ground by parking the front two wheels of the field vehicle on the beam. First onset of the doublets show the arrival times picked for refraction analysis (Cakir and Walsh, 2010).

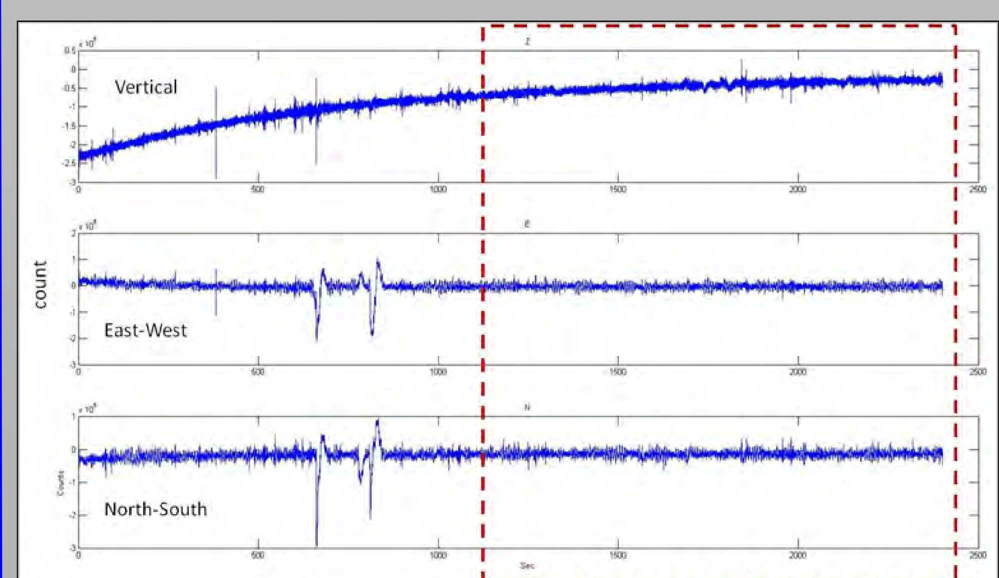


The general flow of the time-term inversion technique (Geometrics, 2009b). To estimate Vp and Vs profiles; a) first-arrival times were picked from the shot gathers and travel-time curves generated from these picks, b) preliminary velocity section were obtained after inverting the travel times curves whose layers visually assigned, c) initial travel time curves were later modified based on running the raytracing, finally d) nonlinear travel time tomography was iteratively run to find the final model until travel time data fits the perturbed initial model (Zhang and Toksöz,

4- Horizontal to Vertical Spectral Ratio (HVRS)



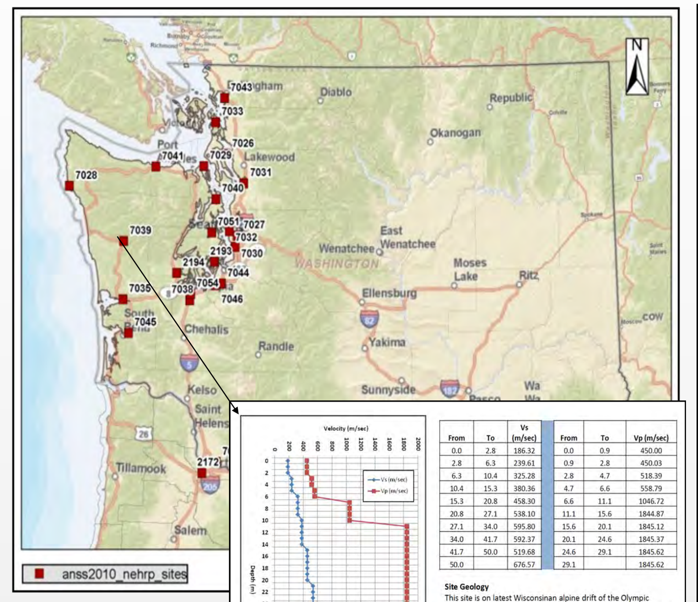
Components of the data acquisition system: (A) Guralp CMG-6TD seismometer, (B) GPS unit, (C) data recording and storage (SCREAM; data acquisition system software running on a Laptop computer), (D) battery. [http://www.guralp.com/products/6TD/]



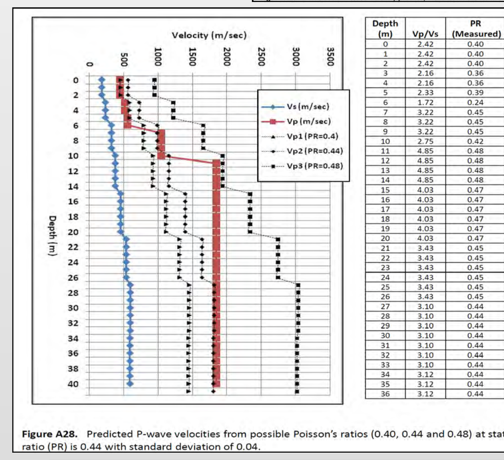
Three-component (E-W, N-S and Vertical) ambient noise recording. Dashed red box shows examples of signals used for the HVSR analysis.

The basic assumptions of the HVSR method are 1) Rayleigh waves in the fundamental mode dominate ambient vibration wave field, and 2) these waves propagate within a nearly homogeneous soft layer (characterized by V_s values smoothly increasing with depth) overlying a rigid bedrock

2010 Seismic Site Characterization Results

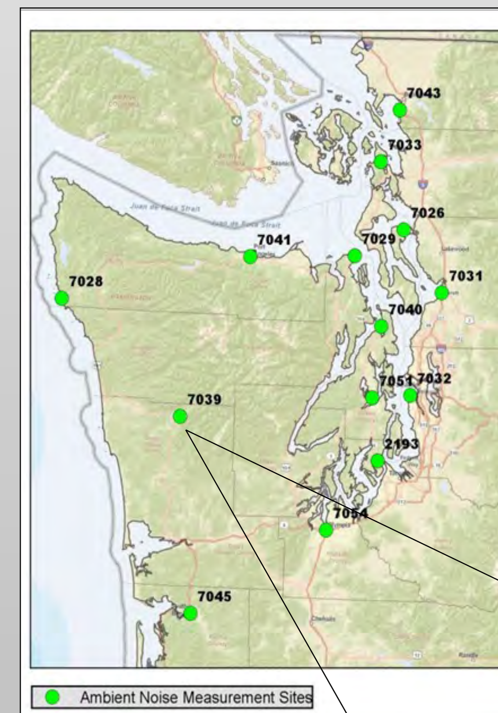


P– and S– velocity (Vp and Vs) profiles, site geology and HVSR at station 7039



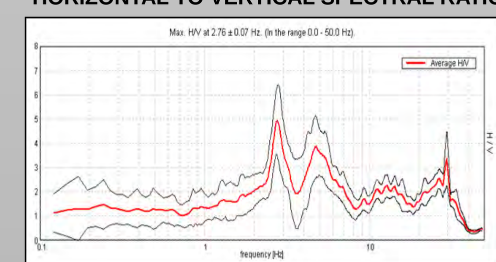
StNum	State	StName	Latitude	Longitude	Conducted Seismic Surveys (*)	Maximum Geophone Spread Length (m)	Vs30 (m/sec)	NEHRP Site Class. (This study)
2172	OR	Portland; Portland State University	45.513	-122.685	1,2,3	69	326	D
2193	WA	Gig Harbor; Fire Station	47.320	-122.586	1,2,3,5	69	416	C
2194	WA	Shelton; Fire Station	47.214	-123.101	1,2,3,4	48	312	D
7026	WA	Stanwood; Camano Island Fire Station No. 1	48.243	-122.455	1,2,3,4,5	69	367	D-C
7027	WA	Seattle; Fire Station No. 28	47.548	-122.277	1,2,3	69	304	D
7028	WA	Forks; La Push Coast Guard Station	47.914	-124.634	1,2,3,4,5	69	271	D
7029	WA	Port Townsend; Fort Worden State Park	48.134	-122.765	1,2,3,4,5	141	386	D-C
7030	WA	Seattle; SeaTac Airport Fire Station	47.451	-122.302	1,2,3	69	244	D
7031	WA	Everett; Fire Station No. 2	47.997	-122.199	1,2,3,4,5	69	538	C
7032	WA	West Seattle; Fire Station No. 29	47.584	-122.389	1,2,3,4,5	69	333	D
7033	WA	Anacortes; Fire Station	48.512	-122.613	1,2,3,4,5	69	204	C
7035	WA	Aberdeen; Fire Station	46.972	-123.826	1,2,3,4	69	154	E
7038	WA	Tumwater; Fire Station Hdqtrs	46.985	-122.910	1,2,3	69	312	D
7039	WA	Quinault Lake; Ranger Stations	47.468	-123.847	1,2,3,4,5	48	359	D-C
7040	WA	Port Gamble; Museum	47.856	-122.583	1,2,3,4,5	69	285	D
7041	WA	Port Angeles; Fire Station	48.115	-123.437	1,2,3,4,5	69	339	D
7042	WA	Vancouver; USGS, Cascades Volcano Observatory	45.611	-122.496	1,2,3,4	69	455	C
7043	WA	Bellingham; Fire Station No. 2	48.720	-122.498	1,2,3,4,5	69	317	D
7044	WA	McChord AFB; Fire Station	47.136	-122.482	1,2,3,4	115	404	C
7045	WA	Raymond; Fire Station	46.685	-123.734	1,2,3,4,5	69	171	E
7046	WA	Camp Murray	47.120	-122.565	1,2,3,4	69	513	C
7051	WA	Bremerton; New Fire Station No. 1	47.570	-122.631	1,2,3,5	69	466	C
7054	WA	Olympia, Centennial Park	47.039	-122.899	1,2,3,5,6	69	193	D or D-E

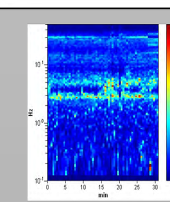
(*) 1=MASW, 2=MAM, 3=P-wave refraction, 4=S-wave refraction, 5=Ambient noise measurement, 6=Downhole seismic

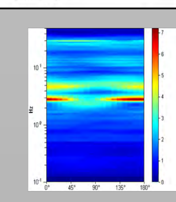


StNum	First Maximum fundamental frequency (f0) (Hz) peak on H/V spectrum	Secondary Maximum fundamental frequency peak (f1) on (Hz) H/V spectrum	Calculated Depth (m) and Average Vs (m/sec) (using fundamental f0)	(Calculated Depth (m), <Vs> (m/sec)) using secondary f0 (=f1)	Parameters (V_0 (m/sec), x)	Sediment Cover (m) from Geology / Geophysics/ Sediment Thickness Map (STM) (or MASW (m)	Vs30m (Active and/ or passive seismic surveys)
2193	0.32	7	(467, 598)	(16, 452)	(170, 0.25)	488 (STM)	416
7026	0.23-3	5-5.5	(723, 665) – (509, 610)	(13, 267) – (12, 261)	(170, 0.25)	732 (STM); Stiffer soil at 11m (MASW)	367= (Vs30m); 234=(Vs12m)
7028	3.1 - 4.1	NA	(24, 301) (17, 280)	NA	(170, 0.25)	Stiffer soil at 24 and 16m (MASW)	271
7029	0.23	9	(723, 665)	(7, 235)	(170,0.25)	732 (STM)	386
7031	0.25	NA	(585, 631)	NA	(170,0.25)	457 (STM)	538
7032	0.26	1.1	(615, 639)	(92,405)	(170,0.25)	91 (STM)	333
7033	0.59	2.2	(208, 492)	(38, 331)	(170,0.25)	30 (STM)	204
7039	2.83	NA	(27, 309)	NA	(170,0.25)	Change to stiffer soil at 27m (MASW)	359
7040	0.52	NA	(246, 512)	NA	(170,0.25)	244 (STM)	285
7041	2.69	NA	(29, 313)	NA	(170,0.25)	183m (STM); Stiffer soil at 29m (MASW)	339
7043	7.27	0.6	(8,246)	(204,489)	(170,0.25)	~30m (STM); Stiffer soil at 8m	317
7045	1.6	NA	(57,363)	NA	(170,0.25)	Very sharp peak on H/V	171
7051	0.45	NA	(298,536)	NA	(170,0.25)	274	466
7054	0.4-0.8	~20	(348,556) - (140,447)	(2,138)	(170, 0.25) (110, 0.4)	122 (STM)	193 = (Vs30m); 122=(Vs2m)

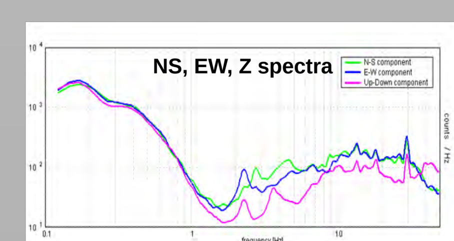
HORIZONTAL TO VERTICAL SPECTRAL RATIO







H/V HISTORY DIRECTIONAL H/V



$$f_0 \cong \frac{\langle V_s \rangle}{4h}$$

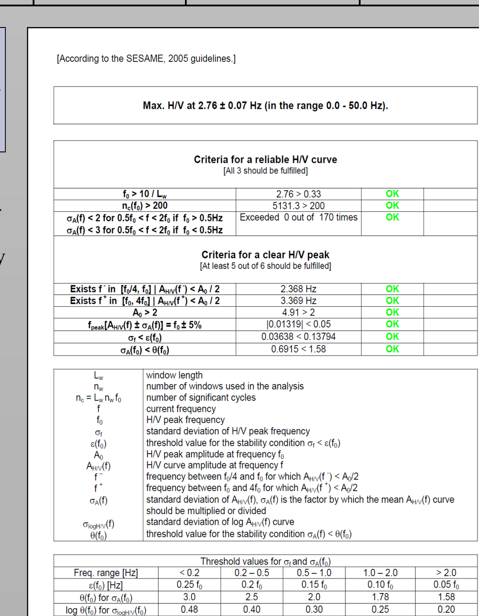
$$\langle V_s \rangle \cong 4 f_0 h \cong 4 f_0 \left\{ \left[\frac{V_0(1+x)}{4 f_0} + 1 \right]^{\frac{1}{1-x}} - 1 \right\}$$

$$h \cong \left[\frac{V_0(1-x)}{4 f_r} + 1 \right]^{\frac{1}{1-x}} - 1$$

Ibs Von Seht and Wohlemberg (1999) proposed a simple approximate relationship between the resonance frequency f_r and the thickness of the soft sedimentary layer *h*

V_0	x	Soil Material Type
210	0.20	Compact soil
170	0.25	Sand(s)
110	0.40	Reworked or very recent soil (such as landslide)

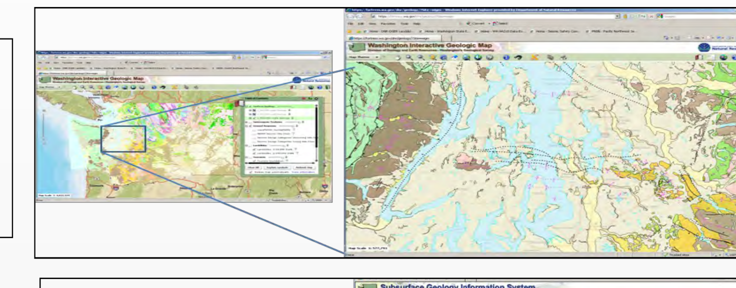
For fast and rough estimations of the sediment cover thickness (h) (Eq. 2) and average velocity (<Vs>), Albarello et al also reported three indicative couples of V_0 and *x* values (Table 1). We used V_0 and *x* values of 210 m/sec and 0,25, respectively, for the estimations of the <Vs> and *h* at each site



Example for Compilation of Site-Specific Information

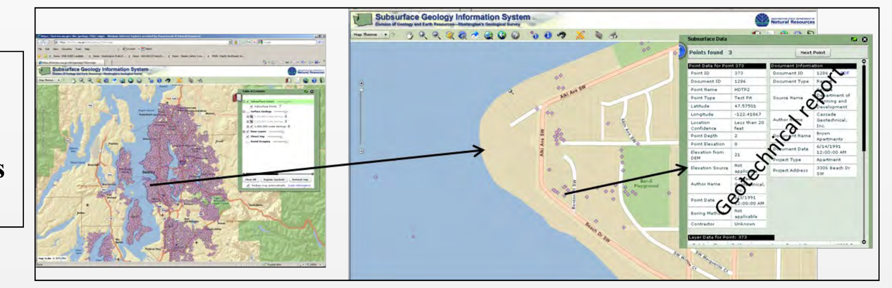
Surface Geology

WA-DNR Geology and Earth Resources



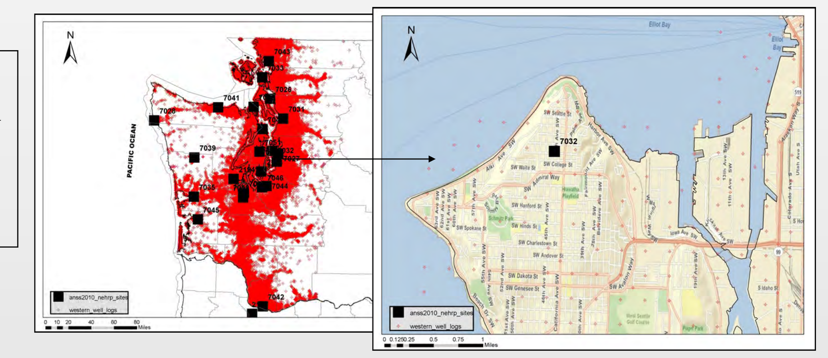
Subsurface Geology

WA-DNR Geology and Earth Resources



Water Well Logs

WA-Department of Ecology



Conclusions

1– We have characterized over 100 sites in Washington and recently our focus is on characterizing ANSS and other earthquake recording sites in Washington and Oregon.

2– We have conducted various seismic surveys to estimate shear-wave velocity profiles at each site and calculated Vs30m and NEHRP site classifications in Washington. These Vs30 values and site classifications are useful parameters for ShakeMap, attenuation relationships for intraslab and/or crustal earthquakes in the Pacific Northwest.

3– Growing online available data such as geotechnical boreholes, well logs and interactive maps of the surface and subsurface geology can now be effectively used for site effect studies at earthquake recording sites.

4– Multichannel surface wave analysis is a power tool to estimate Vs profiles, results found from this analysis are consistent with others (e.g., Wong et al, 2011)

5– HVSR method can be used to estimate depth to bedrock for thick sediment covers, in which shallow seismic energy cannot penetrate - in case of no close by deep borehole information, interpretation of HVRS fundamental frequency peaks should be carefully made using supportive geologic and geophysical data.

References

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Acknowledgments

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