NATURAL RESOURCES

REPORT ON SITE CLASS ASSESSMENTS FOR THE WASHINGTON STATE SCHOOL SEISMIC SAFETY PROJECT

by Loyd T. West, Travis Neilson, and Corina Forson

WASHINGTON
GEOLOGICAL SURVEY
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ABSTRACT

School facilities are a top priority for seismic risk assessment in the State of Washington. To identify potential seismic vulnerability at schools, the Washington Geological Survey (WGS), in coordination with the Office of the Superintendent of Public Instruction (OSPI), began implementing a comprehensive strategy that couples detailed engineering screenings by structural engineers with a site-specific site class assessment. Determining site class is a critical step in seismic hazard analysis and seismic design. Although a statewide site class map exists for the State of Washington, it is based on surficial geology and cannot account for local subsurface variability. In 2018, WGS conducted site class assessments at 94 school campuses and five fire stations that were located within one mile of a school. Of these 99 total sites, 29 have measured site classes that differ from those predicted by the statewide site class map. For several of these sites, the use of the predicted site class would have led to significant under- or over-estimation of earthquake-induced ground motions. This could have led to seismic designs and seismic retrofit or upgrade costs that were either too conservative (and therefore unnecessarily expensive) or not conservative enough (resulting in buildings not being constructed to code). These findings demonstrate the importance of site-specific site class measurements.

INTRODUCTION

The State of Washington ranks second in the nation for seismic risk (FEMA, 2017). School buildings are a key vulnerability in Washington's seismic preparedness. There are more than 4,400 K–12 permanent public school buildings in Washington. A third of these school buildings were constructed using building codes that do not incorporate current seismic hazard standards (Goettel and Dengel, 2014). Very few of these buildings have been assessed for their seismic safety. In the 2017–2019 Washington State capital budget, the Washington Geological Survey (WGS) was allotted funds to conduct seismic assessments across Washington State. This effort, known as the School Seismic Safety Project (SSSP), aims to address the seismic vulnerability of Washington's school buildings.

The seismic assessments conducted as part of the SSSP consisted of two parts: (1) a detailed engineering analysis; and (2) a soil seismic site class assessment, including a limited review of the geologic hazards that could affect each school campus. Site class indicates the degree to which underlying soils will amplify seismic waves. The site class measurements were used to obtain a more accurate estimate of potential ground shaking at each site. This report provides an overview of the methods and results of the 2017–2019 SSSP site class assessments.

PROJECT OVERVIEW

The 2017–2019 SSSP builds on earlier efforts (Walsh and Schelling, 2011; Cakir and others, 2017). In 2010 and 2017, WGS personnel conducted site class assessments at a total of 51 school campuses and worked with a group of volunteer structural engineers who evaluated 156 structures on the campuses. The results were delivered to the Federal Emergency Management Agency (FEMA) and the Office of the Superintendent of Public Instruction (OSPI), added to the OSPI Information and Condition of Schools (ICOS) database, and integrated into pre-disaster planning. In 2011, the Washington State Seismic Safety Committee published a report (*The Washington State School Seismic Safety Pilot Project—Providing Safe Schools for Our Students*) that was a case study for Aberdeen and Walla Walla School Districts (Walsh and Schelling, 2011).

In 2018, WGS evaluated the expected seismic performance of 222 school buildings on 94 campuses and five fire stations located within one mile of a school (Fig. 1). The schools and fire stations were evaluated using the methods established by the pilot study. The WGS contracted structural engineers to conduct seismic screenings using the Tier 1 checklist from the American Society of Civil Engineers 41-17 (ASCE, 2017a), as well as FEMA 154 Rapid Visual Screenings for each school building (Reid Middleton, 2019). The Tier 1 screenings are used to identify and catalog structural and nonstructural deficiencies that may pose a hazard to those inside and outside the building during an earthquake. The Rapid Visual Screenings are a

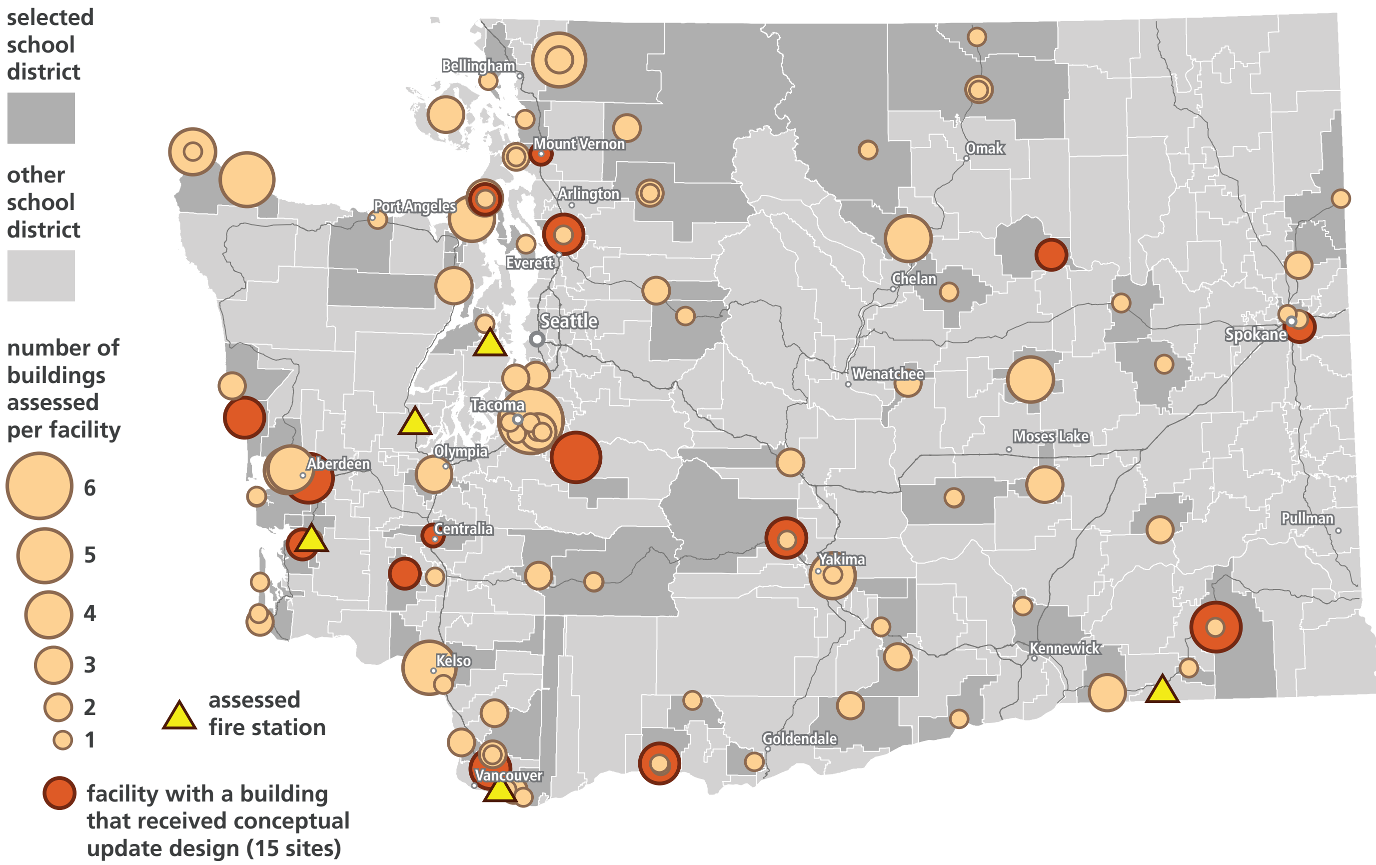


Figure 1. Map showing the location of the 94 school campuses (representing 222 school buildings) and five fire stations assessed for this project. Fifteen of the buildings received conceptual update designs to determine the most cost-effective way to update the building.

preliminary screening tool used to rank buildings based on their seismic risk. At each site, WGS geologists and geophysicists measured the time-averaged shear wave velocity in the upper 30 m (100 ft) of ground (a value known as Vs30)(BSSC, 2004; 2015). This measurement was used to determine the site class at each location. The results were entered into OSPI's ICOS statewide database (Dorn and others, 2014) and the individual screening reports distributed to each school and district.

The Washington State legislature has elected to continue funding the SSSP in the 2019–2021 biennium from the capital budget (Phase 2). The funding will cover site class assessments and detailed engineering analyses for many more schools across Washington.

The goal of the SSSP is two-fold: First, to provide the state legislature and each school district that participated in the study with the seismic safety information needed to make improvements to the earthquake safety of their school buildings. Secondly, the results will also be extrapolated to other school buildings in the State. This will help us to illustrate the scope of seismic risk and inform schools, districts, and public officials of the policy and funding needs for improving the seismic safety of our state's K–12 public school buildings.

SITE CLASS ASSESSMENTS

Site class is an approximation of how much the soils at a site will amplify ground motion relative to hard rock during an earthquake. Using the empirical observations of Borcherdt (1994), the Building Seismic Safety Council (BSSC, 1997; 2004) developed the site class parameter (Table 1) to categorize the potential for amplification of seismic waves by the local soils.

Site class is an integral parameter for determining the Seismic Design Category (SDC) of a structure. The SDC is a categorization scheme that dictates the seismic load that buildings must be designed to meet. Site class is also incorporated into all the major U.S. and international building codes, including the American Society of Civil Engineers 7-05 (ASCE, 2017b), the International Building Code (ICC, 2014a), and the International Residential Code (ICC, 2014b).

There are several ways to determine site class, including measuring Vs30, the method used in this project. The relationship between Vs30 and site class is defined by the National Earthquake Hazard Reduction Program (NEHRP) provisions (BSSC, 2004; 2015)(Table 1). Softer soils have a lower Vs30 (site classes E and D) and will amplify ground shaking more than harder soils or rock, which have a higher Vs30 (site classes A–C). A site class of A, B, or C is therefore expected to result in a more economical structural design requirement than a site class of D (BSSC, 2010). Without a measured site class, the NEHRP provisions require that a building be designed assuming a site class of D. An incorrect assumption of site class may affect estimated building costs or lead to inadequate design in seismically active areas.

Table 1. Correlation between site class, Vs30, and subsurface material, per NEHRP provisions. Generally, softer, lower-velocity soils amplify ground motions more than higher velocity, stiffer soils and rock (ASCE, 2017b).

NEHRP site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock/very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

Because measuring site class requires either a geophysical survey or boreholes, measuring site class can be prohibitively expensive. As a result, state and federal agencies and researchers have developed regional site class maps based on Vs30 proxies. These site class maps are based on topography (Wald and Allen, 2007; Allen and Wald, 2009), geology (Wills and Clahan, 2006; Palmer and others, 2004), or a combination of the two (Thompson and others, 2014). However, site class maps must assume lateral and vertical changes in geology. These assumptions can significantly over- or under-estimate site class in areas with complex geology. Site class maps therefore provide a good approximation for routine building design, but are not intended to replace site-specific testing needed for the design of essential facilities.

In Washington State, Palmer and others (2004) correlated Vs30 to 1:100,000-scale surficial geologic mapping. The predicted site classes for the 94 campuses and five fire stations range from B to E, but Palmer and others (2004) also assigned a site class range for units where the variance in Vs30 is high or falls at one end of the class range. These site class ranges are shown as C–D and D–E and convey that the site is one of the two values.

The SSSP site class assessments improve on the previous predictive mapping done by Palmer and others (2004) by conducting on-site geophysical assessments and using updated 1:24,000-scale geologic mapping where available. Appendix A describes the geophysical data collection and processing methods used to determine Vs30 for each school campus. Appendix B summarizes results for all the school campuses assessed as part of the 2017–2019 SSSP.

Appendix C presents reports for each of the site class assessments. Each report details the field deployment, geophysical data processing and analysis, interpretation of geophysical results, supplemental ground truth utilized, and a limited screening of the other geologic hazards present at each site.

The main text of this document evaluates the accuracy of the statewide site class map by comparing map values against measured Vs30 and provides additional information about the content of the site class assessment reports found in Appendix C.

USES OF SITE CLASS ASSESSMENTS

Site class results for each of the 94 school campuses were entered into the Earthquake Engineering Research Institute's (EERI) Earthquake Performance Assessment Tool (EPAT) worksheet (Goettel and others, 2017). The EPAT worksheet provides a rudimentary calculation of seismic risk using information about modeled earthquake hazards and site class, as well as several building-specific inputs, such as building irregularities and construction type. The EPAT worksheets can complement more detailed building-specific ASCE 41-17 Tier 1 seismic screenings. These tools can provide school districts a preliminary assessment of the level of seismic risk (low to very high) at school buildings and can help classify the level of life safety risk and priority for further evaluation. The accuracy of the risk calculations output by the EPAT worksheet depends partly on the assigned site class, among other parameters. Thus an incorrect site class can lead to an inaccurate risk assessment.

The Vs30 and EPAT results are inventoried into the OSPI Information and Condition of Schools (ICOS) database, which is integrated into the Pre-disaster Mitigation Program (PDM) module (Goettel and Dengel, 2014). This database and module provide detailed data that school district administrators can use to guide seismic upgrades of buildings and steer future funding strategies.

Additionally, the Vs30 measurements were added to the WGS shear wave database (Washington Geological Survey, 2019a). The published Vs30 measurements are identified as single points representing the midpoint of the geophone array.

SITE CLASS ASSESSMENT REPORTS

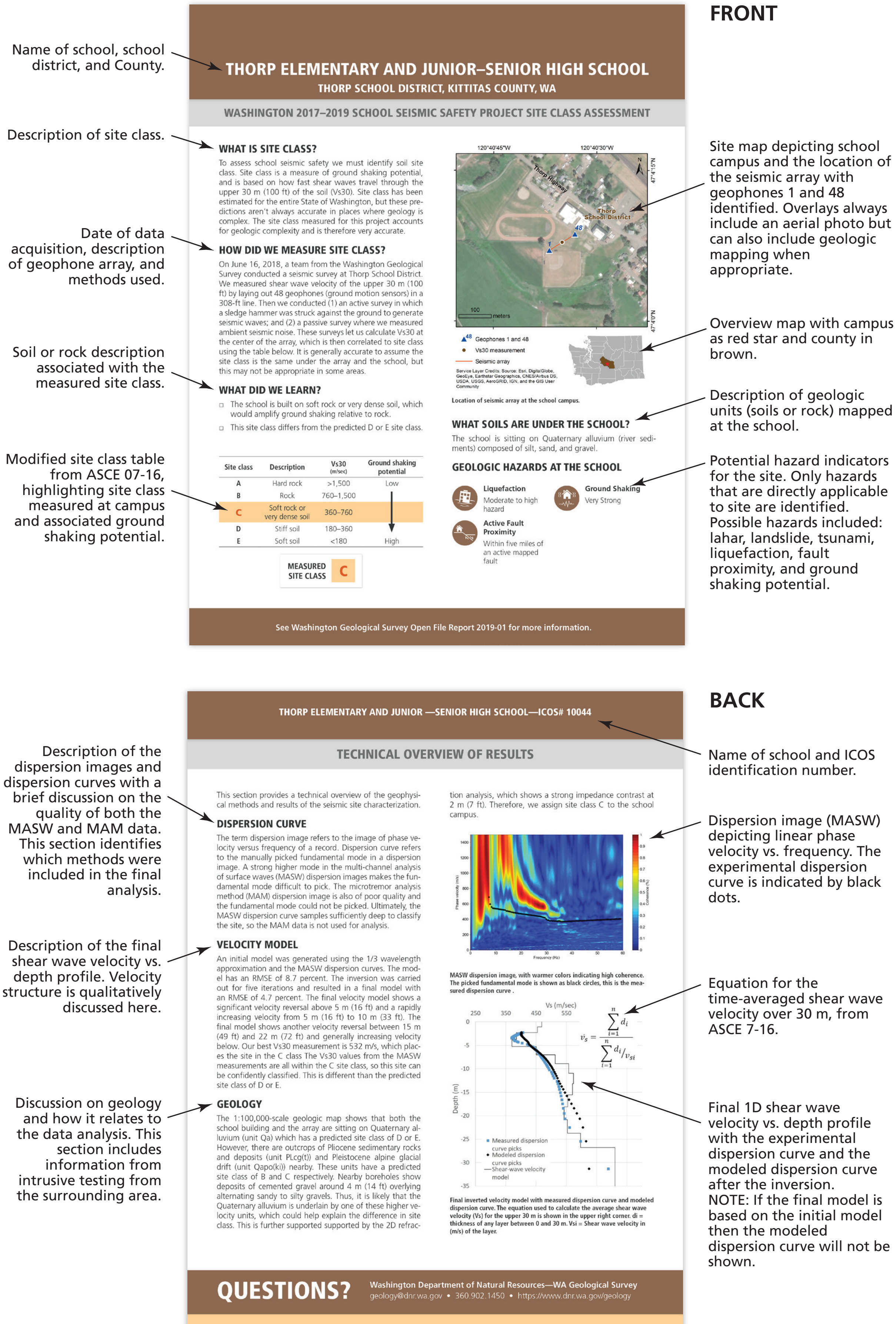
The site class assessment reports (Appendix C) summarize the key results and observations for each site. We break the results into two parts: a non-technical front page, intended for a more general audience, and a technical summary on the back page, intended for geotechnical practitioners (Fig. 2). The non-technical summary provides site information about the field deployment, methods used, the measured site class, an overview of the soils mapped at the school structures, and any other key findings. The non-technical summary also presents available information about other mapped geologic hazards that could affect the school, such as landslides, tsunamis, and active faults.

The technical overview expands on the basic results. The first section briefly discusses the quality of the dispersion images and dispersion curves used for determining Vs30. This section also details the methods and the Shear-Velocity Depth Profile (SVDP) used to determine Vs30. The technical overview may also contain dispersion images, a 2D Multi-channel Analysis of Surface Waves (MASW) velocity model, or a 2D P-wave velocity model. If there is significant lateral heterogeneity in the velocity structure it is usually discussed in this part of the report. The third section summarizes how the velocity model fits into the larger geological context and discusses relevant nearby boreholes.

Screening For Geologic Hazards

For each site class assessment, we review available maps and datasets in order to identify other geologic hazards that might affect each school campus. The screenings at each campus identify possible hazards without extensively characterizing them. These results provide important supplemental information, but do not factor into the calculation of site class.

Lahars are fast-moving destructive mud or debris flows that originate on the flanks of a volcano and usually travel along



FRONT

THORP ELEMENTARY AND JUNIOR–SENIOR HIGH SCHOOL

THORP SCHOOL DISTRICT, KITTITAS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

On June 16, 2018, a team from the Washington Geological Survey conducted a seismic survey at Thorp School District. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS C

Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium (river sediments) composed of silt, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction: Moderate to high hazard

Ground Shaking: Very Strong

Active Fault Proximity: Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

BACK

THORP ELEMENTARY AND JUNIOR —SENIOR HIGH SCHOOL—ICOS# 10044

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. A strong higher mode in the multi-channel analysis of surface waves (MASW) dispersion images makes the fundamental mode difficult to pick. The microtremor analysis method (MAM) dispersion image is also of poor quality and the fundamental mode could not be picked. Ultimately, the MASW dispersion curve samples sufficiently deep to classify the site, so the MAM data is not used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curves. The model has an RMSE of 8.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final velocity model shows a significant velocity reversal above 5 m (16 ft) and a rapidly increasing velocity from 5 m (16 ft) to 10 m (33 ft). The final model shows another velocity reversal between 15 m (49 ft) and 22 m (72 ft) and generally increasing velocity below. Our best Vs30 measurement is 532 m/s, which places the site in the C class The Vs30 values from the MASW measurements are all within the C site class, so this site can be confidently classified. This is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school building and the array are sitting on Quaternary alluvium (unit Qa) which has a predicted site class of D or E. However, there are outcrops of Pliocene sedimentary rocks and deposits (unit PLcg(t)) and Pleistocene alpine glacial drift (unit Qapo(ki)) nearby. These units have a predicted site class of B and C respectively. Nearby boreholes show deposits of cemented gravel around 4 m (14 ft) overlying alternating sandy to silty gravels. Thus, it is likely that the Quaternary alluvium is underlain by one of these higher velocity units, which could help explain the difference in site class. This is further supported supported by the 2D refraction analysis, which shows a strong impedance contrast at 2 m (7 ft). Therefore, we assign site class C to the school campus.

MASW dispersion image, with warmer colors indicating high coherence. The picked fundamental mode is shown as black circles, this is the measured dispersion curve .

$$v_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i/v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

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Figure 2. Site class assessment reports, with front of sheet shown on top and back of sheet shown on bottom.

river valleys. A school is identified as having a lahar hazard if the campus is in a mapped volcanic hazard area (Washington Division of Geology and Earth Resources, 2016).

Landslide hazard was identified by WGS landslide geologist Stephen Slaughter, based on high-resolution lidar, orthoimagery, and the landslide activity of an area. The site class assessment reports do not thoroughly assess landslide hazard. If a hazard is suspected, it should be reviewed by a licensed engineer or engineering geologist.

Tsunami hazards are identified using WGS tsunami inundation modeling (Washington Geological Survey, 2019b). Not all of Washington is mapped for tsunami hazards. If your school is not flagged as being in a mapped tsunami hazard zone it does not necessarily mean there is not a tsunami hazard present.

Liquefaction hazard is the susceptibility of soils to liquefying during an earthquake. This hazard is identified based on the statewide liquefaction maps of Palmer and others (2004) and expressed as very low, low, medium, high, very high, or extreme based on the statewide liquefaction mapping.

All mapped active faults within a roughly five-mile radius of a school campus are identified. This information is derived from the WGS database of Quaternary faults (Bowman and Czajkowski, 2019).

Ground shaking hazard is an estimate of the chances the school site will experience a particular ground acceleration within 50 years. It is measured by the Peak Ground Acceleration (PGA) that has a two percent chance of being exceeded in the next 50 years (referred to as 'PGA 2% in 50 years'). We use our measured site class results and the Dynamic Conterminous U.S. 2014 (v. 4.1.1) USGS Earthquake Hazards Program Unified Hazard Tool (U.S. Geological Survey, 2019) to more accurately estimate PGA 2% in 50 years. We then relate this PGA value to level of ground shaking based on the classification of Worden and Wald (2016).

RESULTS AND DISCUSSION

Figure 3 shows the distribution of predicted and measured site class assignments. Most (84%) of the measured site class assignments fall into the C or D category. Of the 99 sites assessed, 29 have measured site classes that differ from those predicted by the statewide site class map (Palmer and others, 2004). This means the statewide map was approximately 70 percent accurate in predicting site class.

An under or overestimation of site class may lead to inaccurate earthquake hazard characterization, which can potentially lead to inappropriate structural designs. For example, at two sites, the predicted site class was B and the measured site class was D. This inaccuracy, indicating that amplification of seismic waves would be greater than expected, could have led to an under-designed structure or foundation system. Nineteen sites had a measured site class that went from a predicted D or ranged D–E site class to a C or B site class, indicating less amplification of seismic waves than expected. Using the statewide classification could therefore have led to unnecessarily conservative foundation and building designs, possibly increasing building development costs.

For most of the sites where the measured site class was different from the predicted, site class went from a lower velocity predicted site class (increased amplification) to a higher velocity measured site class (decreased amplification). This is expected because the predicted site class map is based on surficial geology. Subsurface changes often affect site class in river valleys, where a thin layer of low velocity alluvium overlays high-velocity bedrock. In eastern Washington, the Palouse Formation thinly covers unweathered volcanic material, also leading to inaccurately predicted site classes.

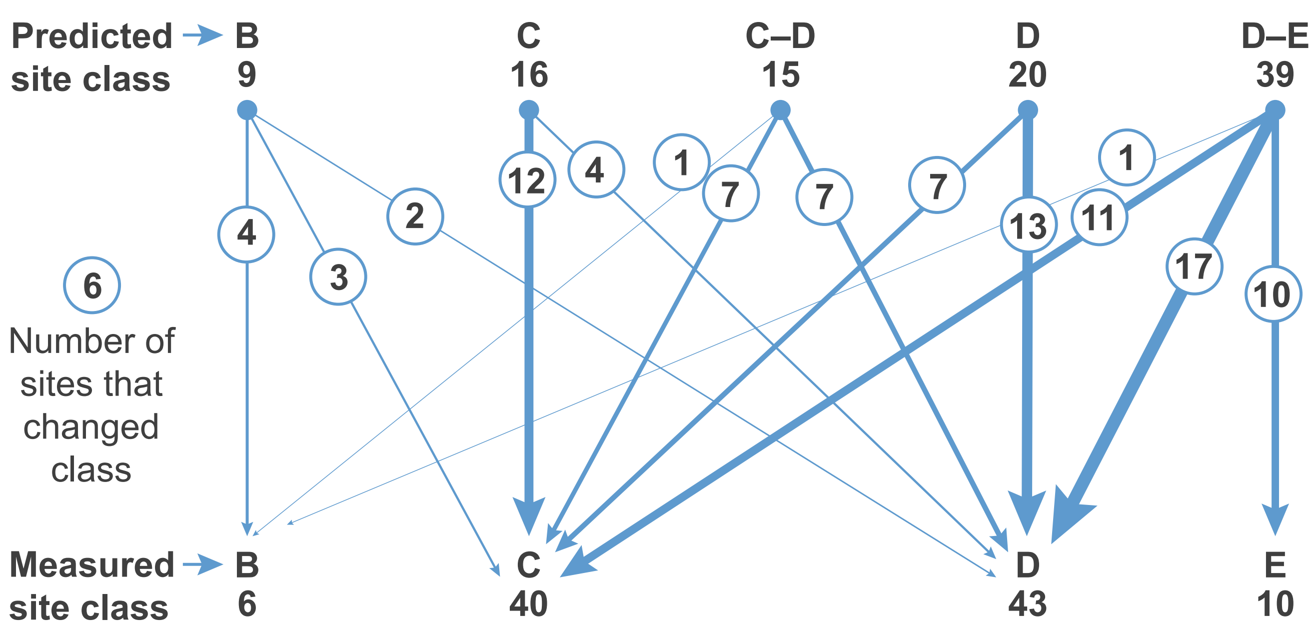

Figure 3. Changes between site class assignments predicted based on the statewide map of Palmer and others (2004)(top row) and site class assignments measured as part of this project (bottom row). Numbers indicate number of campuses assigned each site class. Arrows indicate a change in site class between predicted and measured. The thickness of the arrows and the circular labels on the arrows indicate the number of campuses for which site class changed.

CONCLUSIONS

The site class assessment results significantly expand the current OSPI ICOS database and statewide site class information. These data provide structural engineers with more accurate site class measurements compared to current seismic hazard mapping tools. This information is critical for determining seismic design parameters for the Washington school buildings assessed as part of the SSSP. Without these site-specific site class assessments, structural engineers would have to rely on values predicted from the statewide map, or default to a site class of D. These inaccuracies could lead to evaluations of foundation and building structural systems that are either too conservative or not conservative enough. The result would be inappropriate seismic designs, which could enhance damage, or potentially inflate seismic retrofit or upgrade costs.

Most of the inaccuracies of the statewide site class map have to do with 3D geological variations not accounted for in the smaller-scale mapping. Future iterations of the SSSP might therefore focus on sites with more complex geology, such as schools situated on alluvium in river valleys. In addition, schools in eastern Washington, where shallow high-velocity bedrock could vary in thickness, might require additional on-site geophysical testing.

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We would like to extend our sincere gratitude to all the school employees and facility managers who provided access to their school campuses and facilitated all our information requests. This project would not have been as successful without the participation of these dedicated and committed personnel. We would also like to thank the Washington State Legislature and the Governor for funding this project and supporting the seismic assessment of schools. Continued funding and prioritization of these efforts will help to keep Washington's children and teachers safe from earthquakes.

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Appendix A. Methods

This appendix details the methods used to determine Vs30 for each school campus assessed as part of the SSSP.

DATA ACQUISITION

At each of the 94 school campuses and five fire stations, WGS personnel deployed a linear geophone array and collected seismic data for active-sourced Multi-channel Analysis of Surface Waves (MASW)(Park and others, 1999; Xia and others, 1999) and passive-sourced Microtremor Array Measurements (MAM) (Geometrics, 2009a). These results were used to model the 1D Shear-Velocity Depth Profile (SVDP) at each school site. Vs30 is calculated directly from SVDP.

All data were collected using two Geometrics 24-channel Geode™ seismographs (GEODE). The geophone arrays usually consisted of 48 4.5 Hz single-channel vertical geophones. A small number of surveys used 24 geophones. Figures A1A and A1B show the typical geophone layout. Geophone spacing was typically 2 m (6.6 ft) for a total array length of 94 m (308 ft), but occasionally was reduced to 1.5 m (4.9 ft) to accommodate smaller sites, for a total array length of 70.5 m (231 ft). For the MASW surveys, seismic waves were generated by striking a 16 lb sledgehammer against a steel plate (Fig. A1A) at shot locations within and outside the array. At each shot location, multiple hammer strikes were stacked into a single shot-gather (Fig. A1C), thereby increasing the signal to noise ratio. The MAM surveys used the same array configuration as the MASW, but rather than using a hammer strike, we collected between 20 and 30, 32-second-long records of ambient seismic noise (Fig. A2A).

Most field deployments occurred on the playing fields of each campus. During each deployment we oriented the array in order to mitigate near- and far-field effects, such as heavy vehicle traffic, heavy machinery, air conditioning units, and transformers. Arrays were located as far from roadways as possible and were situated to avoid crossing culverts and septic tanks. Steeply sloping or undulating terrain was avoided.

Certain sites have enough lateral variation in the velocity structure to make a simple 1D SVDP model insufficient for a robust site characterization. At these sites, all of the MASW shot gathers are used to construct a pseudo 2D shear-wave velocity (Vs) model (Fig. A3B) from common mid-point (CMP) cross-correlation gathers using the method described by Hayashi and Suzuki (2004). We also processed single CMP gathers for 1D SVDP using the standard MASW method. The shot gathers are also processed to make compressional wave (P-wave) velocity models. This is done by picking the P-wave first arrivals and using a refraction tomography algorithm (Geometrics, 2009b) to generate a 2D P-wave velocity model (Fig. A3A). The 2D P-wave velocity model (Fig. A3A) and 2D S-wave velocity model (Fig. A3B) help quantify the lateral variation in seismic wave velocities.

At about half the sites, we collected ambient seismic noise (or microtremor) data using a broadband three-component (3C) digital seismograph Tromino® (zero version) to calculate the single-station Microtremor Horizontal-to-Vertical-Spectral Ratio (MHVSR)(Molnar and others, 2018). The predominant site period was determined from the MHVSR by plotting spectral amplification against frequency; the highest peak is the predominant site period. All data were processed using MOHO Science and Technologies' Grilla software version 6.2 (Micromed s.p.a., 2012) and generally followed the SESAME (2004) guidelines. We also used the MHVSR to characterize lateral changes in geology outside the geophone array. MHVSR results for predominant period are summarized in Appendix B.

MAM AND MASW PROCESSING AND ANALYSIS

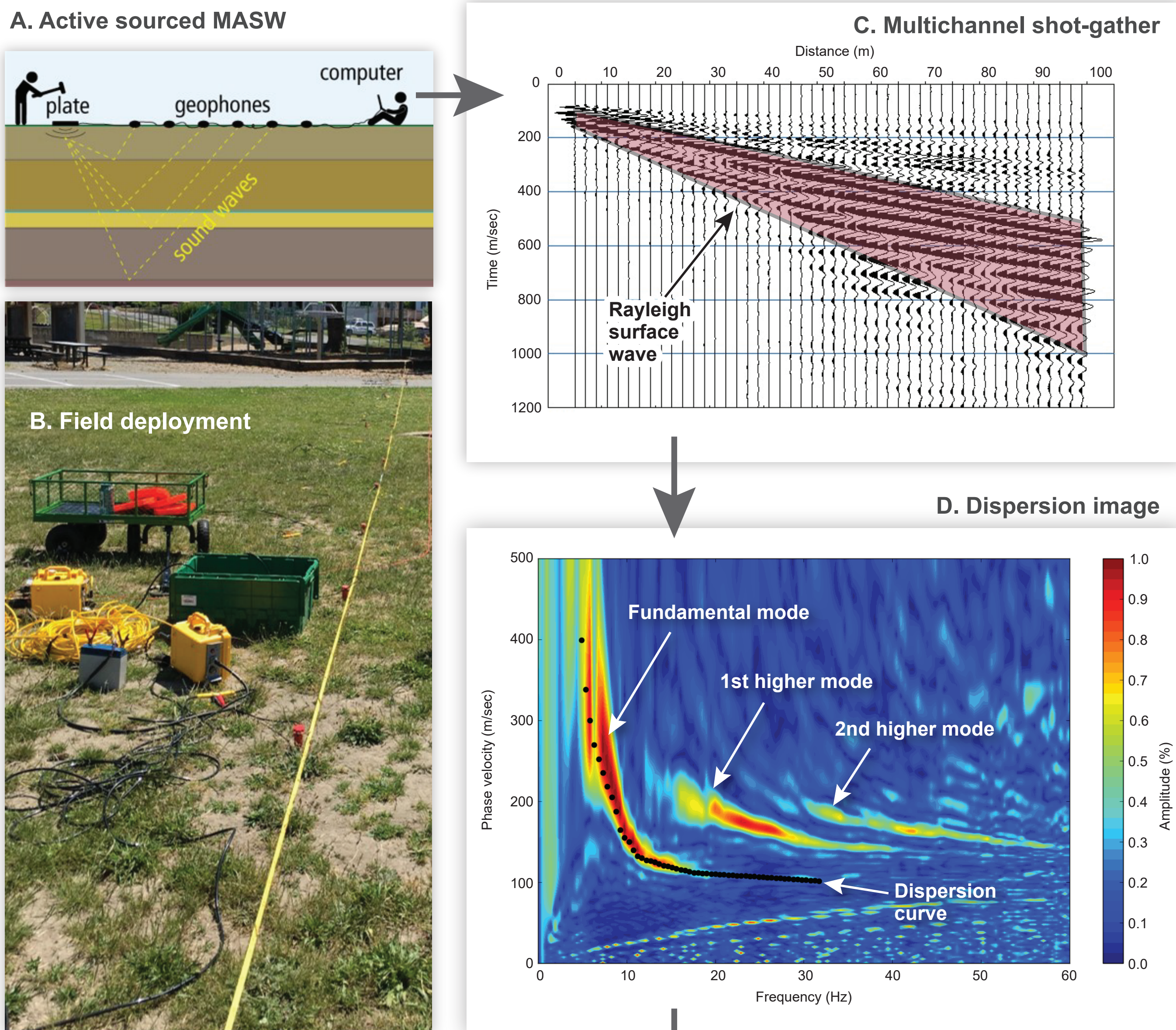
Both the MASW shot gathers and the MAM records were screened to remove bad data. The MASW shot-gathers (Fig. A1C) were screened for surface wave coherency and, if needed, were edited through filtering and (or) muting. MAM records (Fig. A2A) were inspected for quality, and noisy records were deleted. No filtering or muting was applied to the MAM records. All of the processing for the MASW and MAM was done using Geometrics's SeisImager/SW™ Pro.

MASW shot gathers are transformed from the time domain to the frequency-phase velocity domain via the phase shift transform (Park and others, 1999), resulting in a dispersion image (Fig. A1D). This process separates the fundamental mode of Rayleigh waves from coherent noise caused by body waves, higher modes, and non-planer surface waves. From the dispersion image, the trend of Rayleigh wave fundamental mode (Fig. A1D) is visually identified and its trend is picked manually. These picks constitute what is referred to as the experimental or measured dispersion curve. The experimental dispersion curve is a plot of the frequency vs. phase velocity of the fundamental mode.

The MAM method uses the spatial autocorrelation (SPAC) method, as first proposed in Aki (1957), to generate a dispersion image of the ambient seismic signals. Like the MASW dispersion image, the MAM dispersion image is in the frequency-phase velocity domain (Fig. A2B) and the fundamental mode is picked manually, resulting in a dispersion curve.

The measured dispersion curve is used to calculate an initial model using the one-third-wavelength approximation (Geometrics, 2009a). An inversion is carried out using the damped non-linear least squares method with single value decomposition (Xia and others, 1999). The ultimate goal of the inversion is to calculate the velocity model that best fits the measured dispersion curve (Fig. A2C). This is an iterative process that starts with an initial model, modifying it at each iteration to reduce the difference between the observed data and modeled data (Hayashi, 2003). For most models, a five percent Root-Mean-Square Error (RMSE) between the modeled and measured data is considered acceptable. The initial model is critical to the inversion process (Foti and others, 2018) so different initial models with different velocity structures are tested.

We verify our results using both MASW and MAM, making our measurements more robust. Since sampling depth is a function of wavelength, and lower frequency surface waves



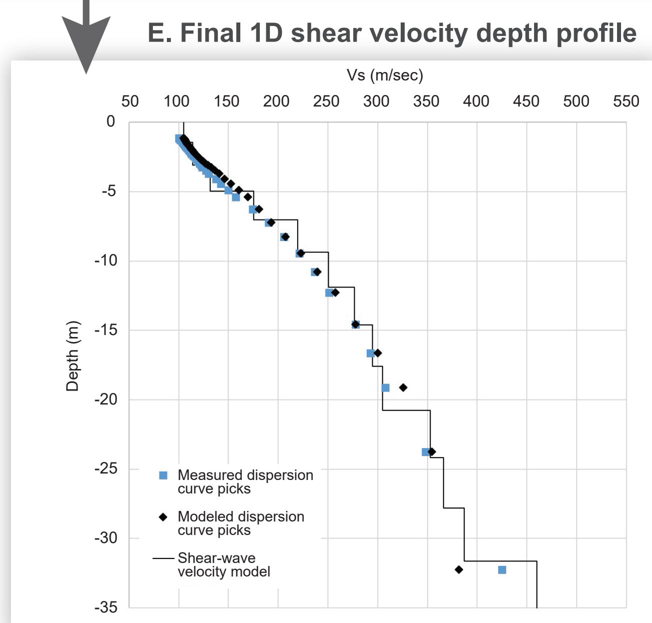


Figure A1. Processing and data acquisition flow for the active-sourced MASW method. **A.** Simplified schematic of an MASW geophone array. **B.** Photo of part of 48-channel geophone array deployment. **C.** Shot-gather of a shot in which the source is outside the array. The Rayleigh surface wave propagation is highlighted in red. **D.** Phase-velocity vs. frequency dispersion image with the trend of the fundamental mode of surface waves identified by black circles. The fundamental mode is identified as the high spectral amplitude (warmer colors) with the lowest phase velocity. For this dispersion image, the fundamental mode can still be identified despite higher modes. **E.** The final inverted 1D SVDP showing the measured dispersion curve (blue squares) and the modeled dispersion curve (black diamonds).

sample deeper than higher frequency surface waves, MAM and MASW typically sample lower and higher frequencies, respectively. Thus, we maximize the depth sampling of the final SVDP (Fig. A1E) by employing both methods. If neither the geophysical results nor mapped geology indicate lateral heterogeneity and the MASW samples down to 30 m depth, the final SVDP is the inverted model with the lowest RMSE and best quality dispersion image. If the MASW did not sample down to 30 m, and the MASW and MAM dispersion curves are in good agreement, the MASW and MAM dispersion curves are averaged and inverted for the final model.

EVALUATING LATERAL HETEROGENEITY

Some sites encompass contacts between geologic units. Abrupt changes in geology can significantly affect the final SVDP. Each site class assessment therefore included an evaluation for lateral heterogeneity. One way to evaluate lateral heterogeneity is to compare the dispersion curves from the MASW for hammer strikes at either end of the geophone array A lack of similarity between the two can indicate lateral heterogeneity. Mapped geology can also suggest that lateral heterogeneity may be present in the subsurface.

If lateral heterogeneity is observed in the MASW dispersion curves or is suspected based on mapped geology, the 2D velocity structure under the array is evaluated using 2D MASW and (or) 2D P-wave refraction tomography. A pseudo 2D-model was generated by stacking all the individual shots into center mid-point gathers and performing a laterally constrained 1D inversion (Fig. A3B). The more shot points in the interior of the array, the higher the resolution. This produces a 2D Vs cross section of the subsurface under the geophone array. A 2D refraction tomographic model (Fig. A3A) was generated from the P-wave first arrivals using a tomographic inversion (Geometrics, 2009b). The procedure produces a 2D P-wave velocity cross section of the subsurface beneath the geophone array. We analyzed each of these cross sections for abrupt changes in velocity structure. If lateral heterogeneity was present and the measured Vs30 values from either end of the geophone array were significantly different, we assigned the Vs30 associated with the end of the array that was situated closest to the school building.

Available borehole information from the surrounding area was also examined to help interpret the SVDP models. This information can be invaluable when the geophysics produces an unexpected result or if the scale of geologic mapping is not detailed enough. For the sites in which it was collected, MHVSR was used to evaluate possible lateral heterogeneity between the geophone array and building sites.

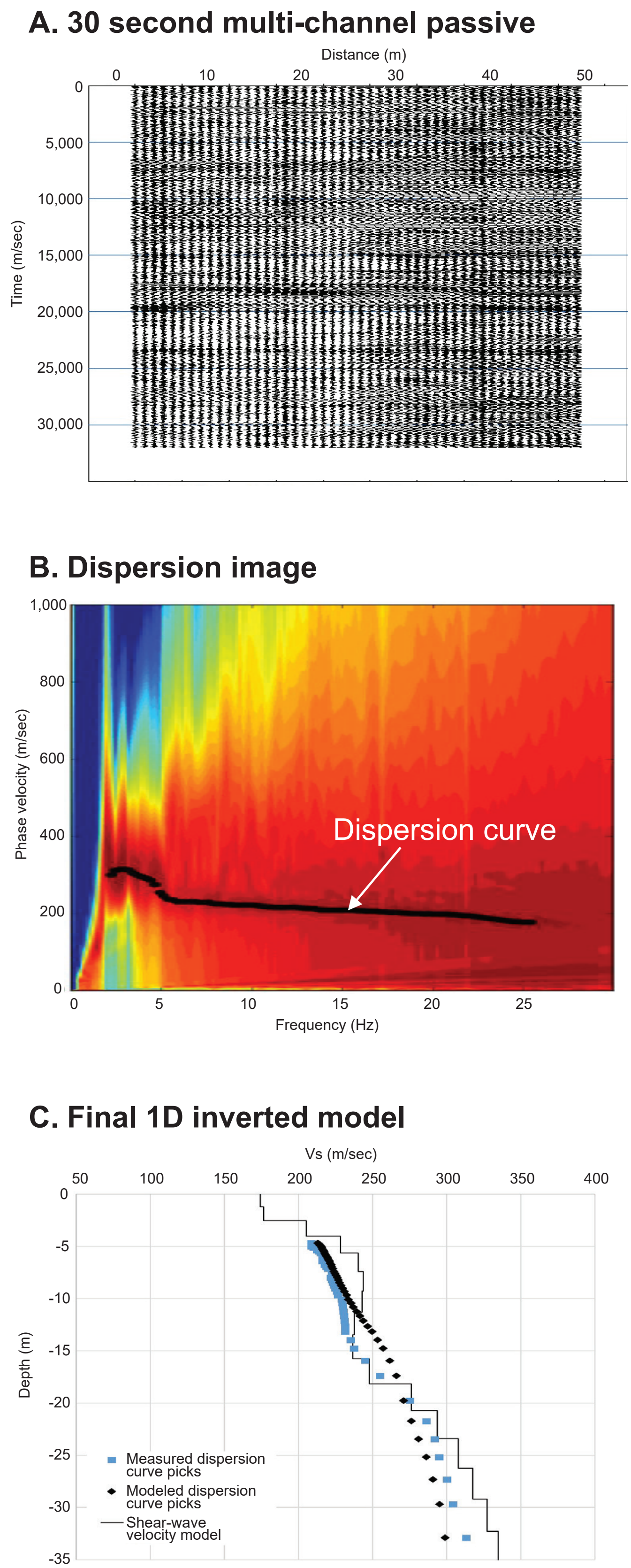


Figure A2. Processing flow for the passive array MAM method. **A.** Passive 30 sec multi-channel record. **B.** Phase-velocity vs. frequency dispersion image with the trend of the fundamental mode identified by the black dots. **C.** The final inverted 1D model with the measured dispersion curve (blue squares) and the modeled dispersion curve (black diamonds).

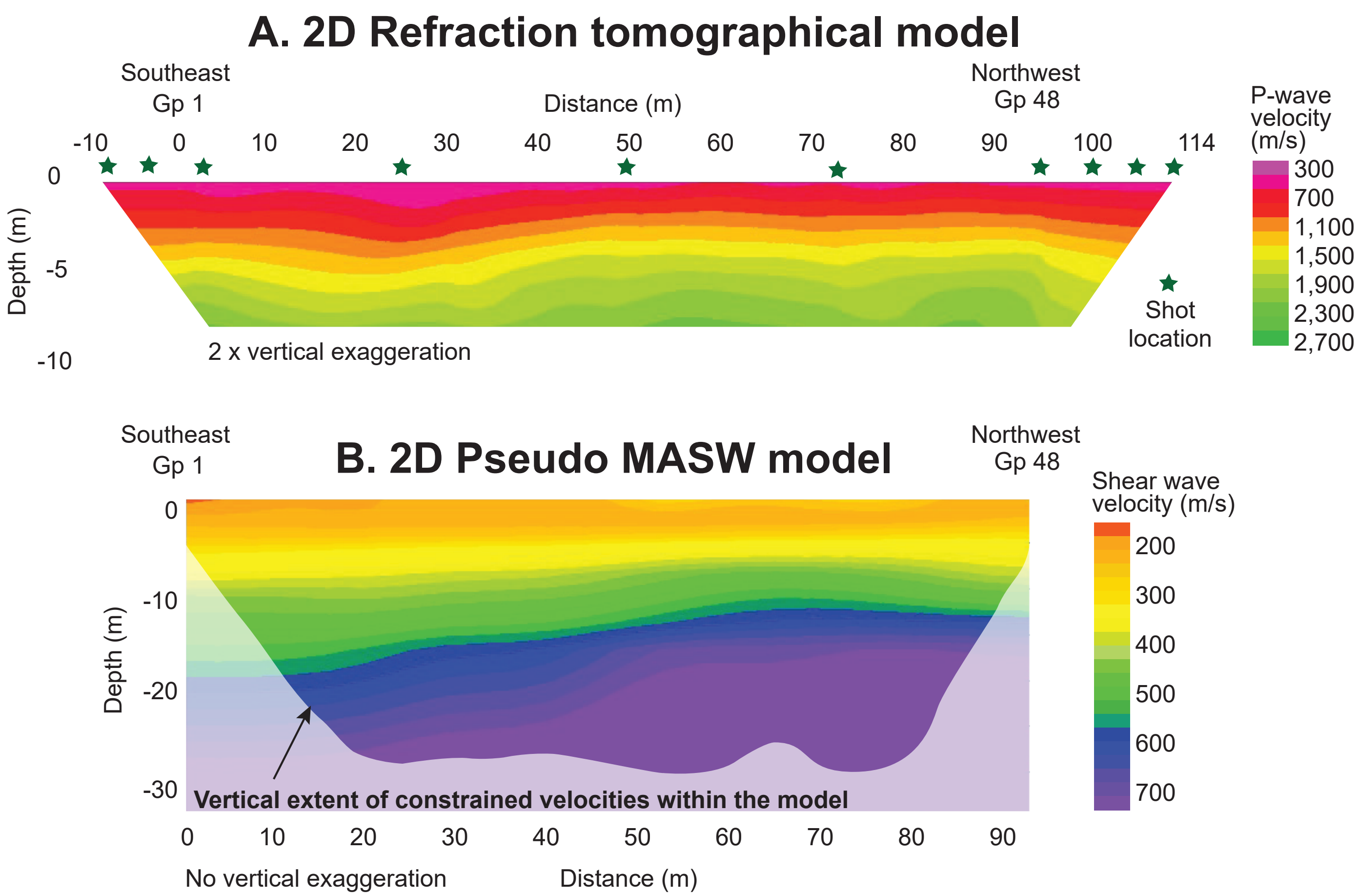


Figure A3. 2D P-wave and S-wave velocity models for Lincoln Elementary School (ICOS #12495). Geophone 1 (Gp 1) is located at the left for both images and geophone 48 (Gp 48) is located to the right (at 94 meters (308 ft)). Models represent velocity structure directly under the geophone array and both are derived using the active MASW shot gathers (green stars). **A.** 2D refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth across the geophone array. For this model, velocity is fairly consistent, with no observed heterogeneity. **B.** The 2D MASW pseudo model depicts shear wave velocity (Vs) varying across the site as a function of depth. The dotted line shows the approximate depth extent constrained by the data. For this model, Vs is generally laterally continuous with velocity increasing with depth and free of anomalous or discontinuous velocities that would indicate heterogeneity.

Appendix B. Site Class Findings

Key results for each school and fire station studied as part of the SSSP. The ICOS number is the unique OSPI identifier for each school. Predominant period is the site-dependent period at which earthquake ground motions are amplified the most by the subsurface materials. Measured Vs30 is the site-specific shear wave velocity measured in the upper 30 m (100 ft) of the subsurface. Measured site class is the site class that corresponds to the measured Vs30. Predicted site class is the mapped site class extracted from the statewide site class map of Palmer and others (2004), based on the center point of each building footprint. ES = Elementary School, MS = Middle School, JHS = Junior High School, HS = High School, JSHS = Junior Senior High School.

School	ICOS No.	Predominant period	Measured Vs30 (m/sec)	Measured site class	Predicted site class
Adams ES	10486	– – –	553	C	B
Audubon ES	12427	– – –	422	C	C
Beach ES	10288	– – –	699	C	D
Bickleton ES and HS	10522	– – –	1031	B	B
Black Lake ES	10611	1.5	394	C	D
Boistfort ES	10441	3.5	320	D	D–E
Carbonado Historical School 19	11248	– – –	411	C	C–D
Carrolls ES	10689	– – –	1038	B	B
Centerville ES	10167	– – –	412	C	C–D
Chattaroy ES	10900	– – –	291	D	D
Clallam Bay K–12	11636	2	295	D	D–E
Columbia JHS	11714	0.6	168	E	D–E
Concrete HS; Concrete K–6 School	10972, 12307	0.5	470	C	D–E
Cosmopolis ES	10975	– – –	230	D	D–E
Coupeville ES	11903	6.4	412	C	C
Coupeville HS; Coupeville MS	11136, 10967	2	279	D	D
Creston ES, JHS, HS	10372	– – –	302	D	D
Darrington ES; Darrington SHS	10754, 11118	2.06	343	D	D–E
Dayton HS; Dayton K–8 School	12210, 11321	– – –	1013	B	D–E
Dixie ES	11381	– – –	359	D	D–E
East Valley Central MS	10494	– – –	487	C	D
East Valley ES	12530	– – –	582	C	D
Edison ES (Burlington–Edison)	10031	– – –	173	E	D–E
Edison ES (Centralia)	12216	– – –	424	C	D–E
Edwin Markham ES	11669	– – –	332	D	D
Evaline ES	12324	– – –	326	D	C–D
Everett Fire Station No. 2	– – –	– – –	475	C	C
Fern Hill ES	10169	– – –	535	C	C
Fife HS	11822	– – –	171	E	D–E
Glenwood ES	10419	– – –	659	C	D–E
Green Mountain School	12007	4.63	341	D	B
Harrington ES & HS	12885	– – –	601	C	B
Hathaway ES	10296	1.47	525	C	D–E
Highline Woodside School (Choice Academy)	12812	– – –	355	D	C–D
Hoquiam HS	12309	2.98	242	D	D–E
Hulan L. Whitson ES	11511	1.5	464	C	B

School	ICOS No.	Predominant period	Measured Vs30 (m/sec)	Measured site class	Predicted site class
Ilwaco HS; Ilwaco (Hilltop) MS	11997, 11737	2.06	184	D	B
Index ES	10385	– – –	419	C	D–E
La Conner HSI; La Conner MSI (form. ES)	10683, 11153	1.22	184	D	D–E
Lacamas Heights ES	11833	6.25	415	C	C–D
Lake Roosevelt K–12	12823	– – –	304	D	D
Libby Center	11231	– – –	385	C	C
Liberty ES; Marysville MS	11698, 10616	– – –	245	D	D–E
Liberty MS	11220	– – –	667	C	C–D
Lincoln ES (Hoquiam)	12193	1.56	111	E	D–E
Lincoln ES (Mount Vernon)	12495	– – –	463	C	D
Long Beach ES	12330	– – –	212	D	D
Mabton JSHS	12772	– – –	327	D	D
Mansfield ES and HS	11647	– – –	864	B	C–D
Maple Grove K–8; River Homelink	11856, 12402	– – –	320	D	C
Maplewood ES	10055	0.69	165	E	D–E
Methow Valley ES; Liberty Bell JSHS	10620, 11419	– – –	333	D	D
Morton ES	10190	– – –	455	C	D–E
Morton JSHS	11868	0.91	175	E	D–E
Mount Baker JHS; Mount Baker Senior HS	10867, 11955	8.5	248	D	D–E
Naches Valley HS	10868	– – –	343	D	D
Naches Valley MS	10533	– – –	587	C	D–E
Neah Bay JSHS; Neah Bay ES	12040, 11547	– – –	232	D	D–E
Newport HS	10923	– – –	427	C	C
Oakland HS	11394	– – –	458	C	C–D
Ocean Park ES	10155	0.5	250	D	D
Ocosta ES; Ocosta JSHS	12476, 11919	– – –	220	D	D
Oroville ES	10516	– – –	258	D	C–D
Outlook ES	11495	1.72	279	D	D
Pacific Beach ES	11715	6.2	272	D	C–D
Palisades ES	11629	– – –	263	D	D–E
Pateros K–12 School	11925	– – –	327	D	D–E
Paterson ES	12001	– – –	980	B	B
Port Townsend HS	12006	4	355	D	C
Prairie HS	10719	2.59	297	D	C
Puyallup HS	10624	0.69	165	E	D–E
Quilcene HS and ES	12092	2.3	514	C	C–D
R. A. Long HS	11569	– – –	166	E	D–E
Raymond ES; Raymond JSHS	10382, 10926	3.5	305	D	D–E
Raymond Fire Station	– – –	– – –	174	E	D–E
Red Rock ES; Royal MS; Royal HS	12362, 10671, 11889	– – –	391	C	C
Ridgetop JHS; Silver Ridge ES	11699, 11745	– – –	521	C	C
Roosevelt ES	11703	– – –	431	C	C–D
Shaw Island School	10186	– – –	1674	B	B
Skykomish HS	11195	– – –	347	D	D–E
Skyridge MS	10049	2.5	312	D	C–D

School	ICOS No.	Predominant period	Measured Vs30 (m/sec)	Measured site class	Predicted site class
South Bend JSHS	10373	1.2	109	E	D–E
South Whidbey ES	10199	– – –	456	C	C
Spinning ES	12100	0.59	200	D	D–E
Taholah School	10818	1.88	278	D	D–E
Thorp ES and JSHS	10044	– – –	532	C	D–E
Tonasket ES; Tonasket HS	12342, 12540	– – –	313	D	C–D
Totem MS	11618	– – –	246	D	D–E
Touchet ES and HS	10625	– – –	427	C	D–E
Tumwater Fire Department Headquarters	– – –	– – –	318	D	D
Union Ridge ES	11175	3.28	268	D	C
Vancouver Fire Station No. 9	– – –	– – –	455	C	D
Vashon Island HS	10465	0.28	375	C	C
Walla Walla County Fire District No. 4	– – –	– – –	450	C	D–E
Warden K–12	10921	– – –	503	C	D
Washtucna ES and HS	11966	– – –	511	C	D–E
Wayne M. Henkle MS; Columbia HS	12450, 10734	– – –	380	C	C
White Pass ES; White Pass JSHS	11994, 10854	1.3	304	D	C–D
Wilson Creek ES–HS	10279	3.44	374	C	C

Appendix C. Site Class Assessment Reports

Reports of the results of the SSSP site class assessments, arranged in alphabetical order, with one report for each of the 94 school campuses and five fire stations. Some campuses encompass multiple school buildings, in which case the name of the first school building in the list defines the alphabetical order.

ADAMS ELEMENTARY SCHOOL

SPOKANE SCHOOL DISTRICT, SPOKANE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

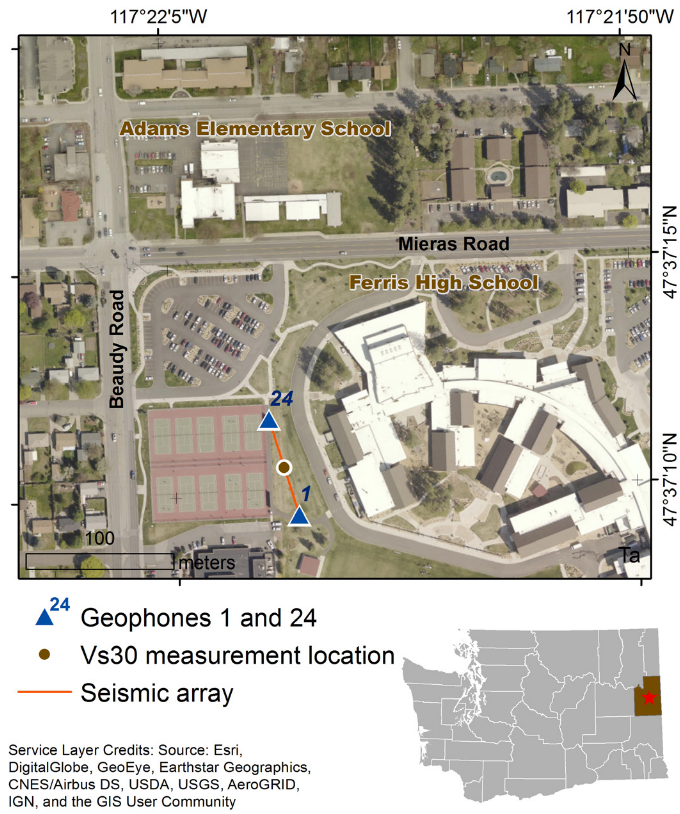
On November 25, 2009, a team from the Washington Geological Survey conducted a seismic survey near Adams Elementary School at the Ferris High School for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 230-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted B site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school building is sitting on bedrock—specifically basalt.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Strong

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

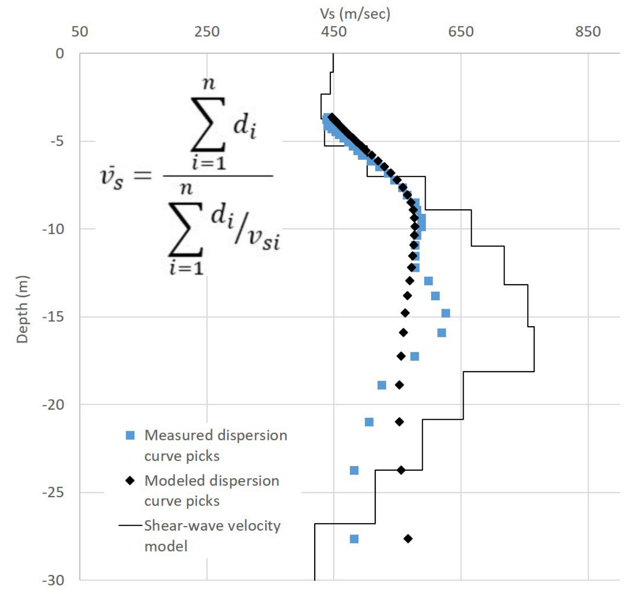
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is of reasonable quality and the fundamental mode can be picked. However, MASW dispersion curves sample just short of 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is not good quality and was not used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1). The initial model has an RMSE of 8.9 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 4.7 percent. The upper 4 m (13 ft) of the final velocity model shows constant velocity, but is unconstrained. Below 3 m (10 ft) the final velocity model shows a generally steady increase in velocity with depth from 4 m (13 ft) to 17 m (56 ft), then a velocity inversion. Our best Vs30 measurement is 553 m/s, which places the site in the middle of the C class. This is different than the predicted site class of B. Although the MASW does not sample past 30 m (100 ft), it is unlikely that the velocity structure between 27 m (89 ft) and 30 m (98 ft) could change the Vs30 significantly enough to alter the site class, so this site can be confidently classified as C.

GEOLOGY

The 1:24,000-scale geologic map shows that both Adams Elementary School and the geophone array are sitting on the Priest Rapids Member of the Wanapum Basalt, Columbia River Basalt Group (unit Mv(wp)). A nearby borehole confirms shallow bedrock, showing basalt from 3 m (10 ft) to the maximum depth of 16 m (52 ft). The low velocity inversion below 17 m (56 ft) most likely related to a lower velocity unit below the basalt. In fact, nearby geologic cross sections interpret the Wanapum Basalt as laying on top of the Latah Formation, a layer of siltstone, claystone, and minor sandstone measured by Palmer and others (2004) to be within site class C. Although we do not have ground truth to establish this, it is possible that the lower velocity Latah formation is underlying the higher velocity Wanapum Basalt at the site, which is contributing to the change between the predicted and measured site classes. Furthermore, although the Vs30 measurement was made at nearby Ferris High School, a lack of evidence for a significant change in stratigraphy between the Vs30 measurement and Adams Elementary School, indictes the site class should be the same at both schools.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

AUDUBON ELEMENTARY SCHOOL

SPOKANE SCHOOL DISTRICT, SPOKANE COUNTY

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

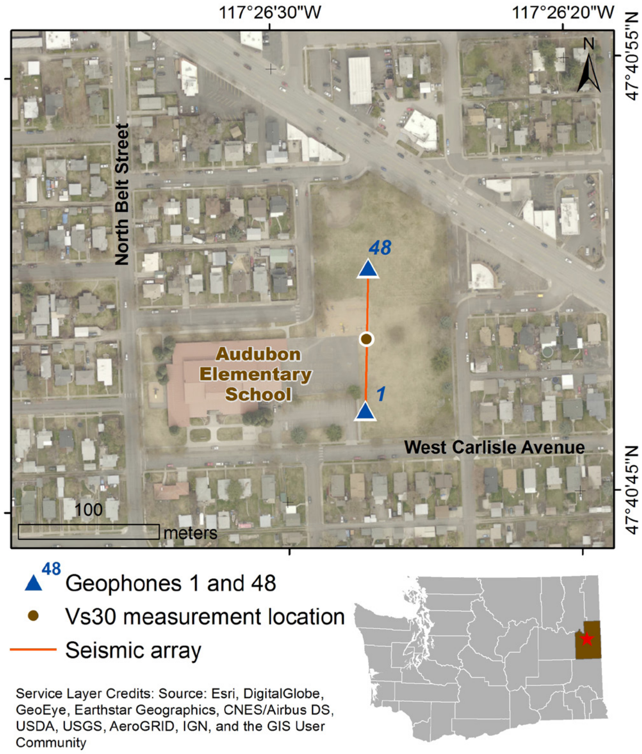
On July 18, 2018, a team from the Washington Geological Survey conducted a seismic survey at Audubon Elementary school. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock and very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial flood-channel deposits, consisting predominantly of gravel, with sand and cobbles.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

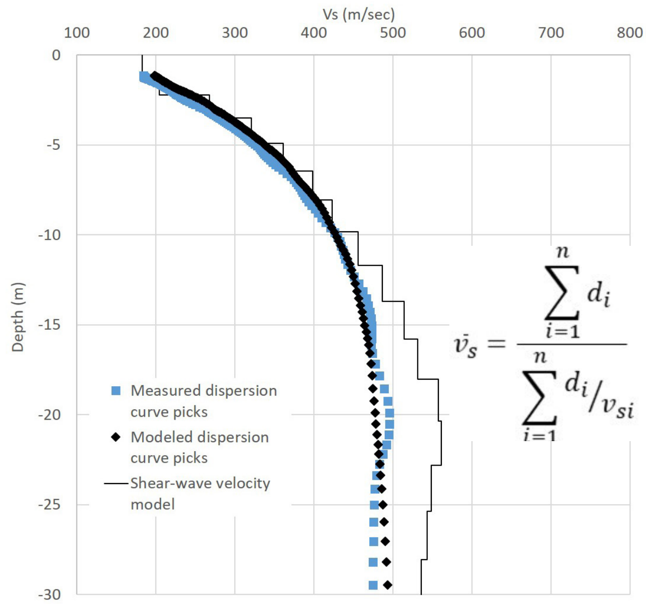
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse direction) and MAM dispersion curves are averaged and smoothed together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 8.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final velocity model shows steadily increasing velocity to a depth of approximately 22 m (72 ft) and slightly decreasing velocity below. Our best Vs30 measurement is 422 m/s which places the site in the middle of the site class C. The Vs30 values derived from the combined MASW and MAM measurements are all within the C class, so we can confidently classify the site as a C. This Vs30 measurement and site class is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

BEACH ELEMENTARY SCHOOL

FERNDALE SCHOOL DISTRICT, ISLAND COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

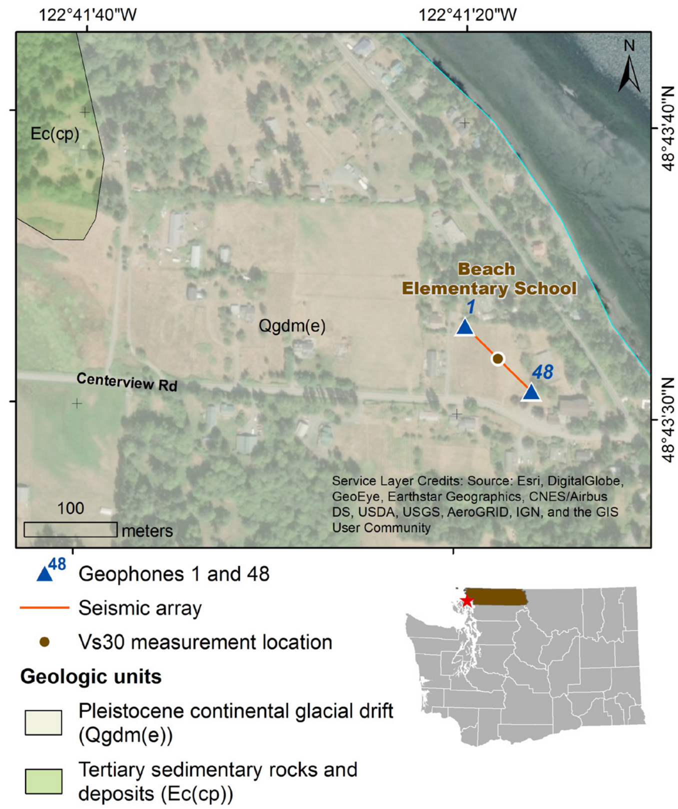
On July 31, 2018, a team from the Washington Geological Survey conducted a seismic survey at Beach Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on poorly sorted sediments of clay to boulders, in a matrix of mud or sand (unit Qgdm(e)). Exposures of conglomerate (unit Ec(cp)) are mapped nearby to the northwest of the site.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

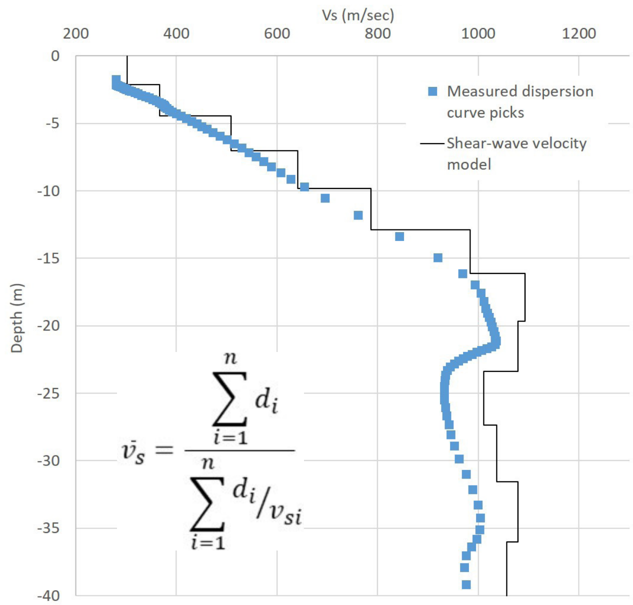
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are decent quality but the fundamental mode can be picked only down to 22 Hz. As a result, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality but the fundamental mode cannot be picked at higher frequencies. However, the dispersion curves correlate between 14 Hz to 18 Hz, below 14 Hz the MASW and MAM diverge. The dispersion curves were averaged together above 18 Hz. Below 18 Hz, the MAM curve was used as it is more coherent in the dispersion image.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The combined analysis did converge to a high RMSE, which suggests the model converged to a local minima. The resulting best estimate for Vs30 is 699 m/s and is based on the initial model, which places the site in the C class. The final velocity model shows a generally steady increase in velocity with depth to 20 m (66 ft) and constant velocity below down to 30 m (100 ft). Despite the lack of convergence, all initial models resulted in a Vs30 in the middle of the C class, so we are confident in the measured site class of C. Furthermore, the inversion would have to change the Vs30 by 60 m/s or 340 m/s to change site class so we are confident in the measured site class of C. The measured Vs30 and site class is different than the predicted site class of D.

GEOLOGY

The 1:100,000-scale geologic map shows the school building and the geophone array are sitting on Pleistocene continental glacial drift composed of diamicton and poorly stratified gravelly silt with dropstones (unit Qgdm(e)) which has a predicted site class of D. Mapped nearby are outcrops of the Padden Member of the Chuckanut formation which is primarily massive arkose and conglomerate (unit Ec(cp)) and has a predicted site class of B. A nearby borehole confirms sandstone at a depth 5 m (16 ft). The velocity model does shows high velocities at around 10 m (33 ft), which suggest that there is a contact, and that the difference between the measured and predicted site class is likely due to a change in the subsurface geology.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

BICKLETON ELEMENTARY AND HIGH SCHOOL

BICKLETON SCHOOL DISTRICT, KLICKITAT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

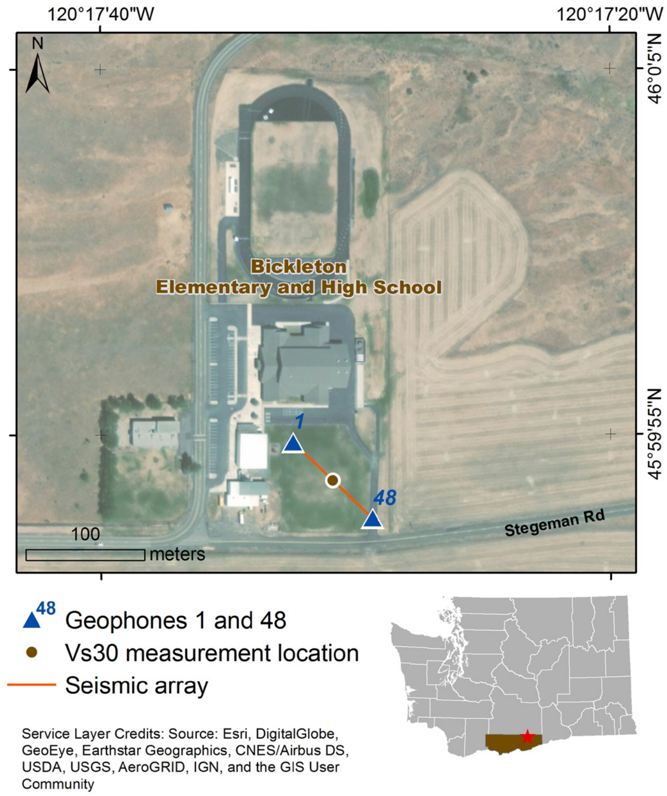
On July 11, 2018, a team from the Washington Geological Survey conducted a seismic survey at Bickleton Elementary and High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **B**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on basalt.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Strong

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

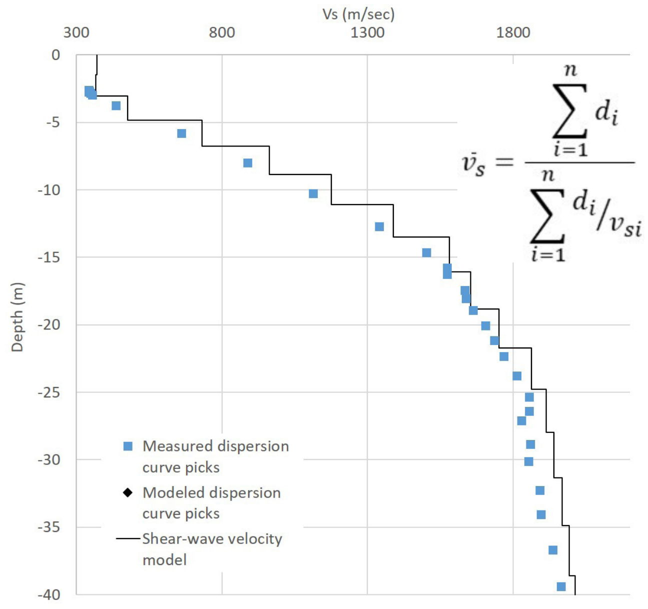
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is of decent quality and the fundamental mode can be picked. The MASW dispersion curves from the forward and reverse directions do indicate some variability but adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of poor quality, so the MAM is not used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1). The inversion was unable to converge. The resulting best estimate for Vs30 is 1031m/s and is based on the initial model, which places the site in the B class. The velocity model shows velocity steadily increasing with depth down to 25 m (82 ft), then gradually increasing velocity below. Although the MASW dispersion curves indicate some variability across the array, the initial models from both ends of the geophone array resulted in a Vs30 in the middle of the B site class. Therefore, despite the lack of the MASW models to converge, this site can be confidently classified. This estimate correlates with the predicted site class of B.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

BLACK LAKE ELEMENTARY SCHOOL

TUMWATER SCHOOL DISTRICT, THURSTON COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

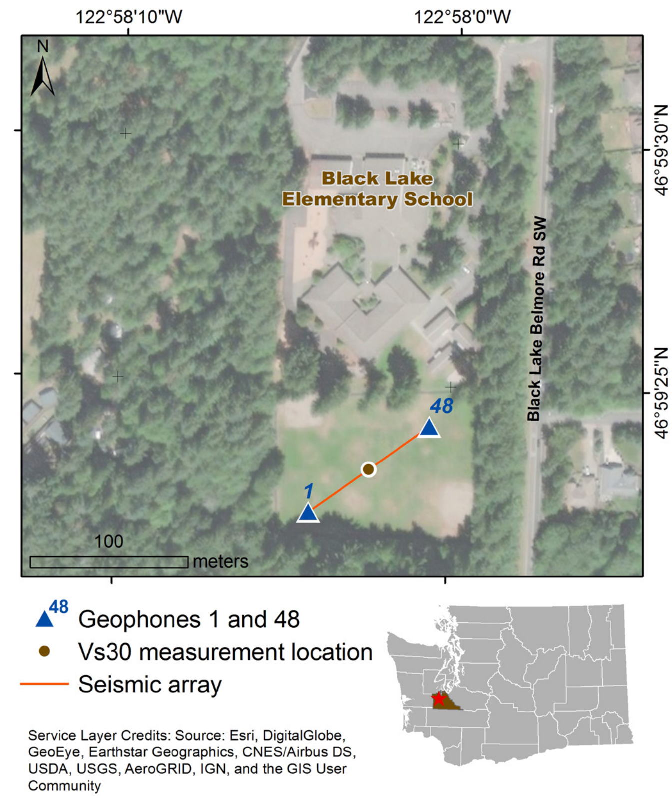
On June 21, 2018, a team from the Washington Geological Survey conducted a seismic survey at Black Lake Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on sand and silt with minor gravel interbeds deposited by a glacier.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

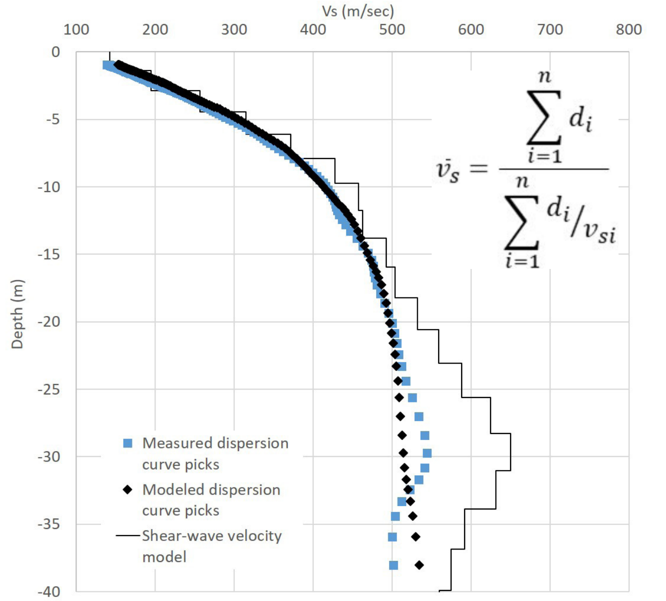
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 22.3 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 5.4 percent. The final velocity model shows a general increase in velocity down to 30 m (100 ft) and varying velocity below that. Our best Vs30 measurement is 394 m/s, which places the site in the C class. This is different than the predicted site class of D.

GEOLOGY

The 1:24,000-scale geologic map shows the school building and the geophone array are sitting on Pleistocene continental glacial drift (unit Qgos) which have a predicted site class of D. Unit Qgos is descrbed as consisting of sand and silt with minor gravel interbeds. The discrepancy between the measured and predicted could be due to a local lateral lithology change within the unit within the unit Qgos.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

BOISTFORT ELEMENTARY SCHOOL

BOISTFORT SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

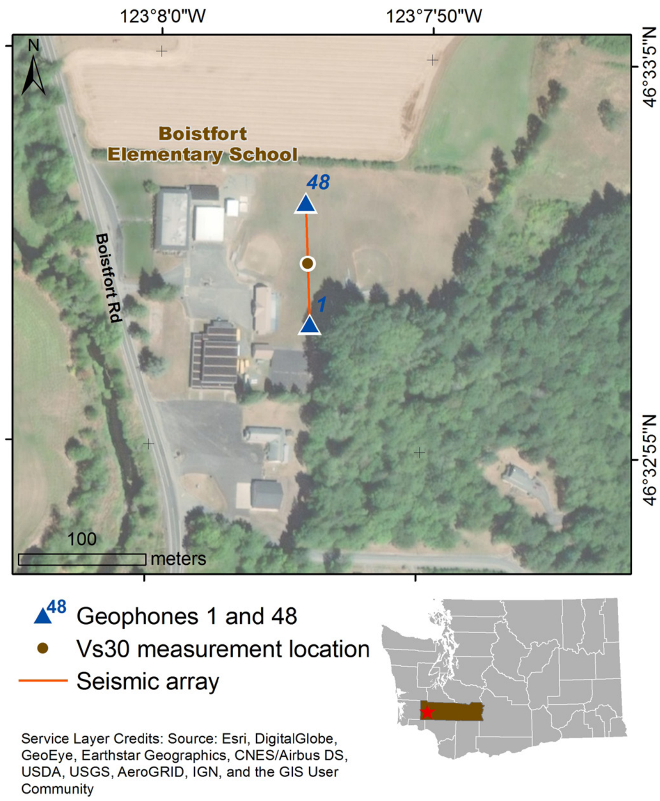
On July 25, 2018, a team from the Washington Geological Survey conducted a seismic survey at Boistfort Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on stream sediments composed of silt, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

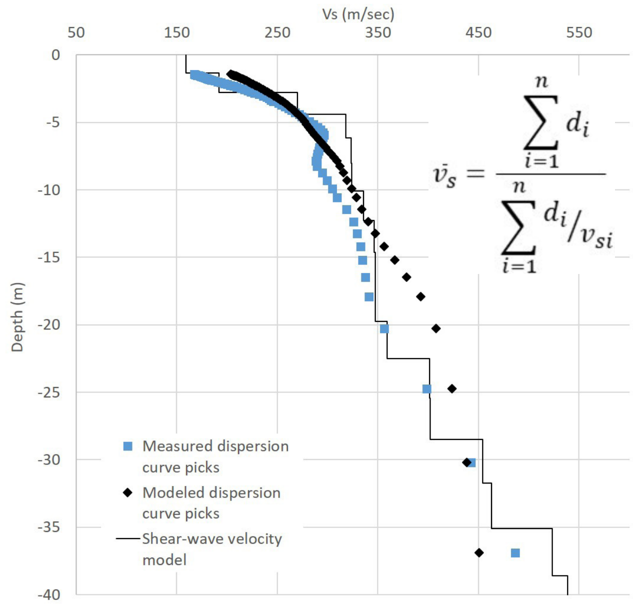
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is generally of good quality and it samples down to 30 m (100 ft), but is difficult to interpret between 12 Hz and 26 Hz. The microtremor analysis method (MAM) dispersion image is of poor quailty, so the only MASW dispersion curves are used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1). The inital model has an RMSE of 8.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.8 percent. The final velocity model shows a rapid velocity increase down to 5 m (16 ft), a generally constant velocity from 5 m (16 ft) to 22 m (72 ft) and velocity increasing below that. Our best Vs30 measurement is 320 m/s, which places the site in the D class. The predicted site class is D or E, which is correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

CARBONADO HISTORICAL SCHOOL

CARBONADO SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

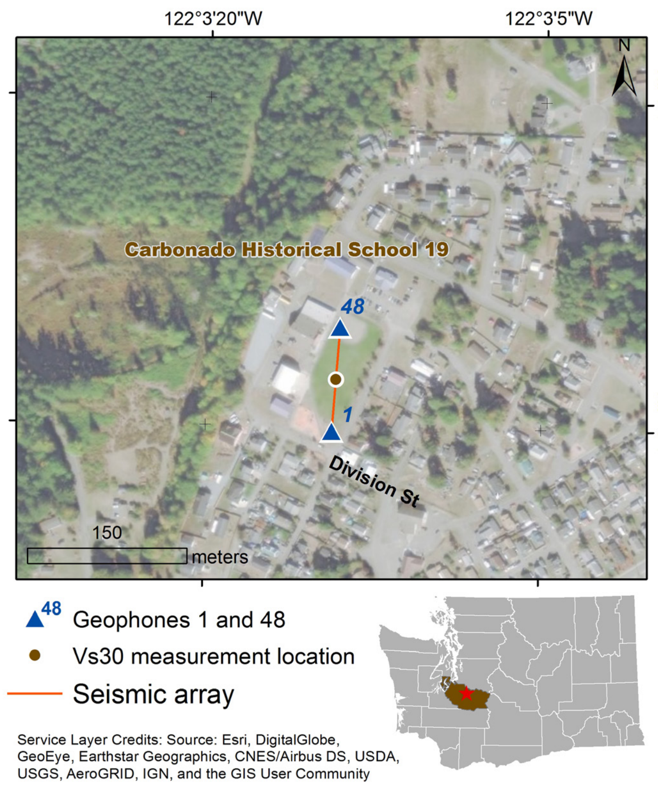
On June 18, 2018, a team from the Washington Geological Survey conducted a seismic survey at Carbonado Historical School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mostly deposits of sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low hazard

Ground Shaking
Severe

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

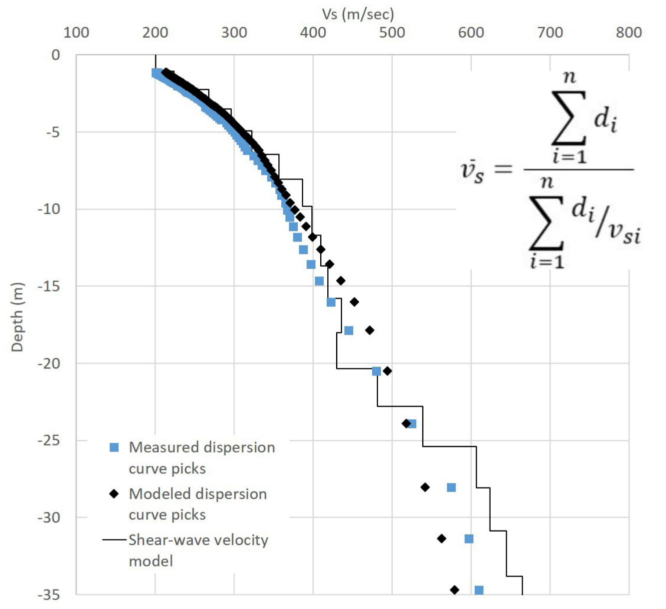
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can also be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse and forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 9.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.8 percent. The final velocity model shows generally increasing velocity with depth from 1 m (3 ft) to 30 m (100 ft) depth. Our best Vs30 measurement is 411 m/s, which places the site in the C class. The Vs30 measurment and the site class is the same as the predicted site class C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity ($\bar{v}_s$) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. v_{si} = shear wave velocity of the layer in (m/s).

CARROLLS ELEMENTARY SCHOOL

KELSO SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

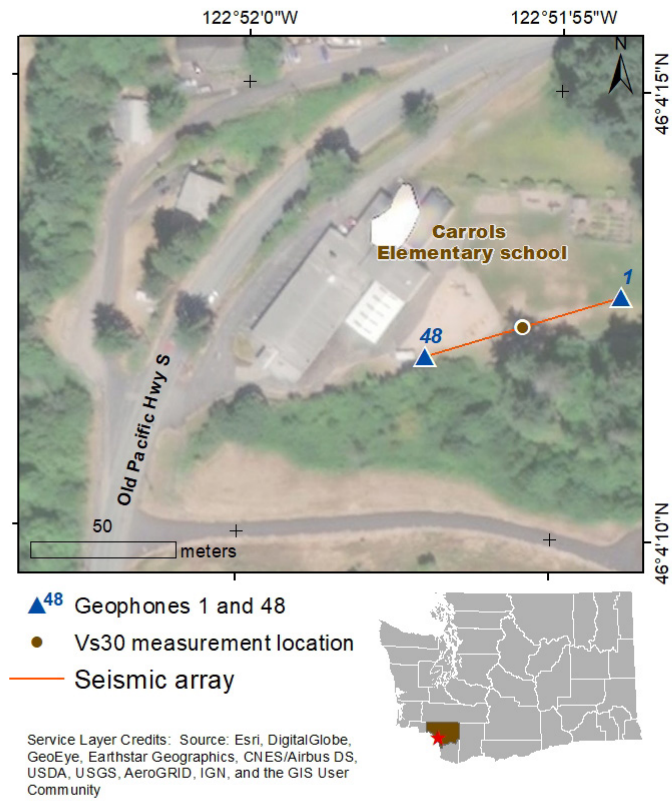
On August 8, 2018, a team from the Washington Geological Survey conducted a seismic survey at the Carrolls Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 231-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **B**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school building is sitting on bedrock, specifically, andesite flows (unit OEva(g)).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Very strong

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

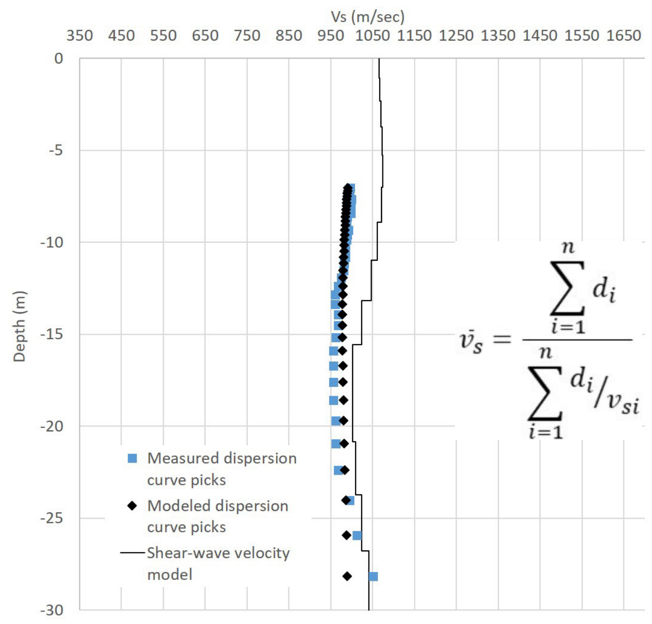
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW forward direction (located off end geophone 48). The initial model has an RMSE of 1.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 1.1 percent. The final velocity model shows constant velocity with depth from 0 m to 30 m (100 ft), with the upper 6 m (20 ft) of the model being unconstrained by the picked dispersion curve. Our best Vs30 measurement is 1038 m/s, which places the site in the middle of the B class and is the same as the predicted site class.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school building and the array are sitting on the Oligocene-Eocene andesite flows (unit OEva(g)). Unfortunately, the MASW does not sample the upper 6 m (20 ft) and we do not have ground truth to varify the shallow velocities of the final model. Therefore, it is possible that the upper 6 m (20 ft) consists of much lower velocity material that could significantly affect the final Vs30 measurements. However, the P-wave 2D tomographic model suggests that there is a hard contact less than 1 m (3 ft) from the surface at the location of the geophone array. Thus, we the assign site class B to the school campus and buildings, but we recommend further geotechnical investigation to verify the depth to unit OEva(g) at the site.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

CENTERVILLE ELEMENTARY SCHOOL

CENTERVILLE SCHOOL DISTRICT, KLICKITAT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

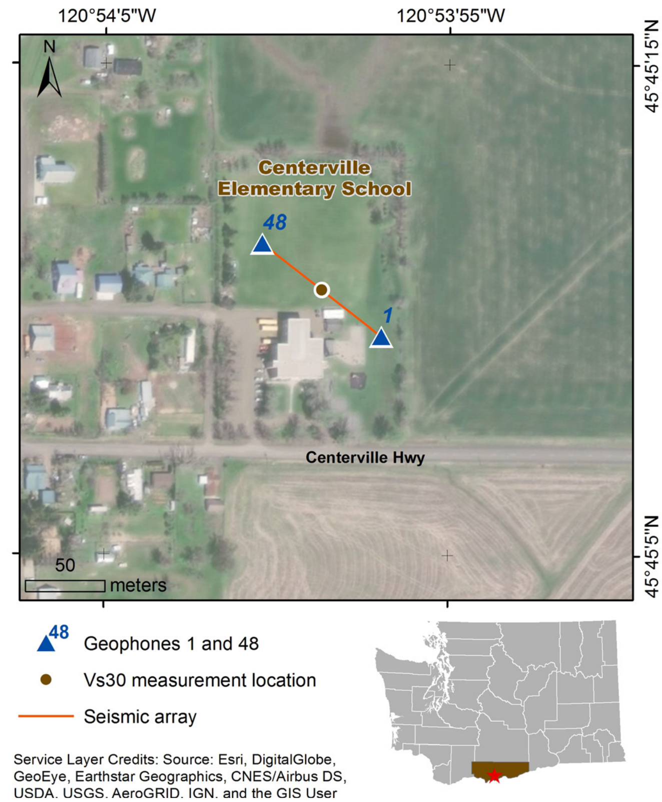
On August 2, 2018, a team from the Washington Geological Survey conducted a seismic survey at Centerville Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on gravel, sand, silt, and clay that are deposits of the ancestral Columbia River.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Very strong

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

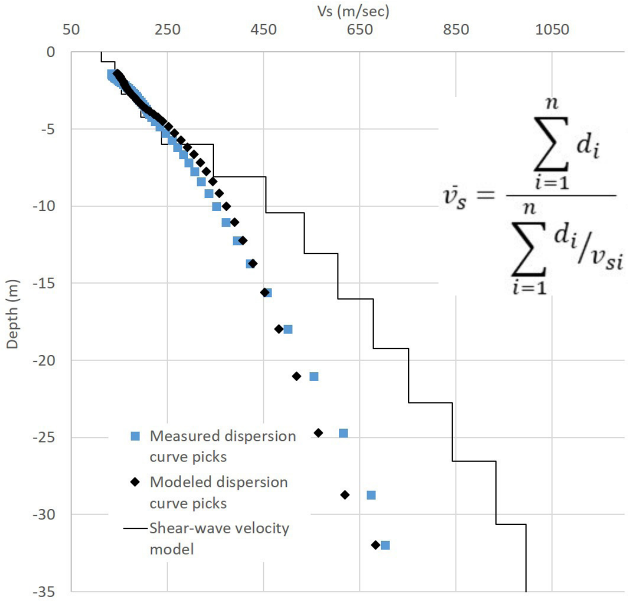
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image contains higher modes but the fundamental mode can easily be picked. The microtremor analysis method (MAM) dispersion image is not of good quality and was not used for analysis. The MASW adequately samples down to 30 m (100 ft) depth.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined MASW dispersion curves. The model has an RMSE of 13.3 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 5.7 percent. The final velocity model shows a generally steady increase in velocity with depth. Our best Vs30 measurement is 412 m/s, which places the site in the C class. The predicted site class is C or D, which correlates with the measured C site class.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i/v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

CHATTAROY ELEMENTARY SCHOOL

RIVERSIDE SCHOOL DISTRICT, SPOKANE COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

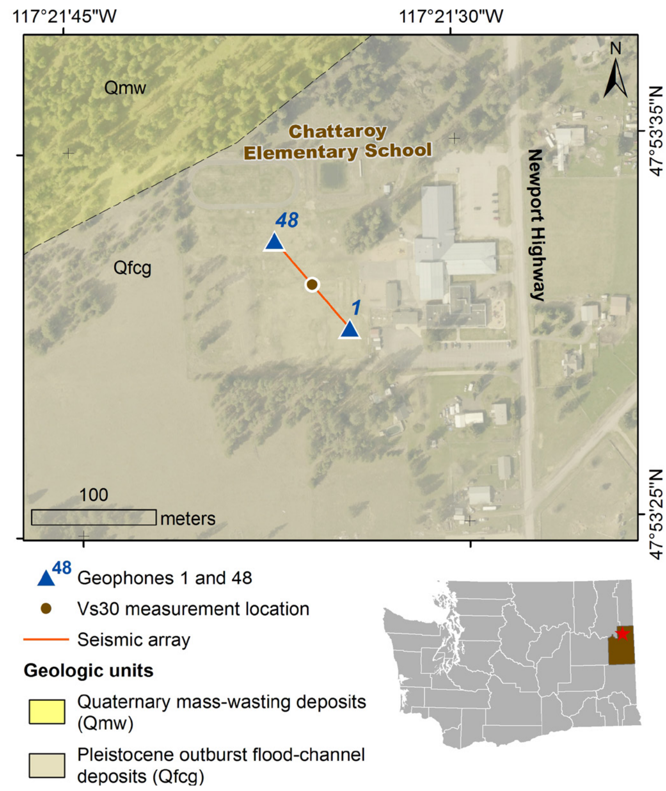
On July 18, 2018, a team from the Washington Geological Survey conducted a seismic survey at Chattaroy Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same than what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene outburst flood deposits (unit Qfcg). Mass wasting deposits (unit Qmw) are mapped just the northwest of the school.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Moderate hazard

Landslide
Low hazard, based on topography

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

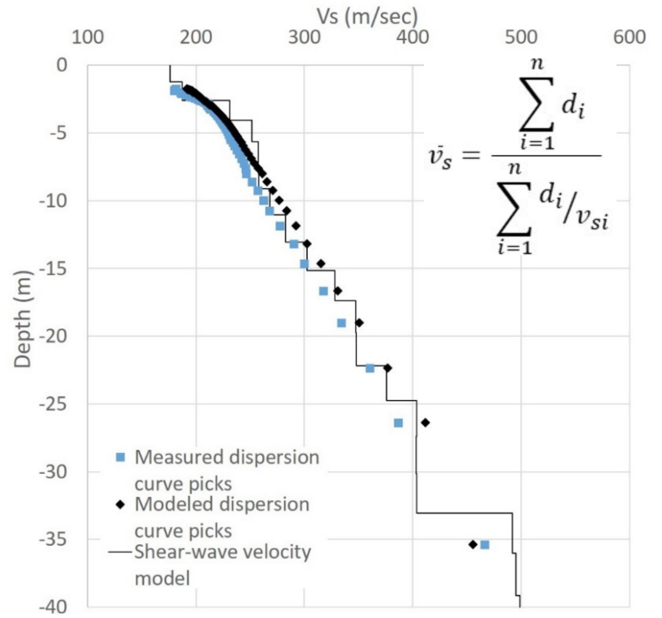
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do indicate some variability and neither adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of also of excellent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

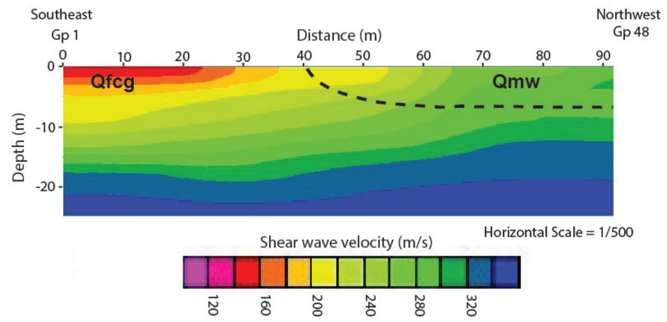
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 10.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.6 percent. The velocity profile shows a generally steady increase in velocity with depth. Our best Vs30 estimate is 291 m/s, which places the site in the D site class. The velocity models from both ends of the array are within the middle of the D class, so this site can be confidently classified. This is the same as the predicted site class of D.

GEOLOGY

The 1:24,000-scale geologic map shows the school and geophone array are sitting on Pleistocene outburst flood deposits (unit Qfcg) while Quaternary mass-wasting deposits (unit Qmw) are mapped just to the northwest. Laterally heterogeneous velocity structure is confirmed in the upper 3 m (10 ft), putting lower velocities close to geophone 1 in the 2D MASW model. However, below this depth, the 2D model is laterally homogeneous. Although the mapped contact between units Qmw and Qfcg is approximately 88 m (289 ft) to the north, the observed low velocities along the 2D array suggest that the debris flow extends into the school grounds. However, if the contact between unit Qfcg and unit Qmw is indeed being picked up along the array, the contact likely parallels the hill slope that produced unit Qmw. Thus the school is more likely on unit Qfcg, and the Vs30 measurement taken with the source on the south side of the array (291 m/s) is the most representative of the soil the school is built on.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.



Pseudo 2D MASW shear-wave velocity model with locations for geophones 1 and 48. Interpreted geologic units are annotated with a dashed line showing the approximate contact.

CLALLAM BAY K–12 SCHOOL

CAPE FLATTERY SCHOOL DISTRICT, CALLAM COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

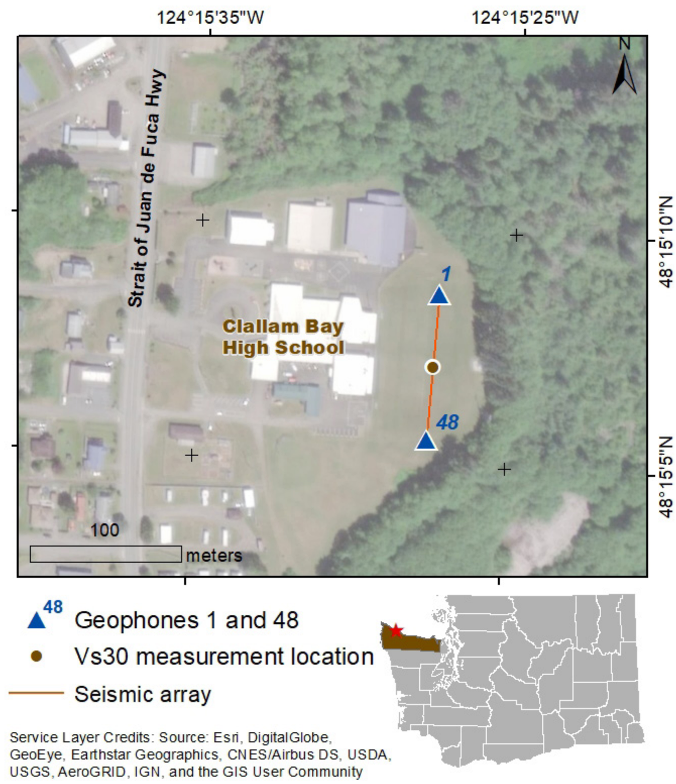
On July 31, 2018, a team from the Washington Geological Survey conducted a seismic survey at Clallam Bay K–12 School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARD AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Active Fault Proximity
Within five miles of an active mapped fault

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

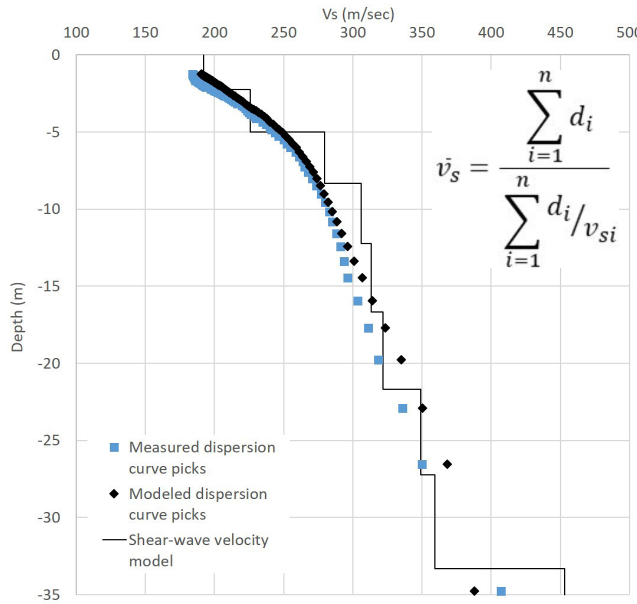
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curve. The inital model has an RMSE of 8.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.3 percent. The final velocity model shows generally increasing velocity with depth from 1 m (3 ft) to 30 m (100 ft). Our best Vs30 measurement is 295 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

COLUMBIA JUNIOR HIGH SCHOOL

FIFE SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

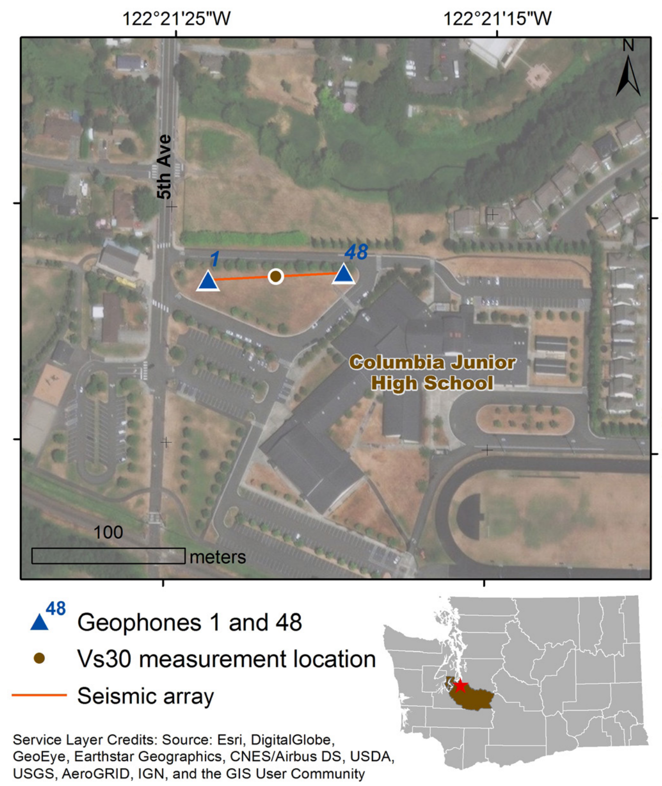
On August 8, 2018, a team from the Washington Geological Survey conducted a seismic survey at Columbia Junior High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mostly sand deposited by the river system.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
High hazard

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

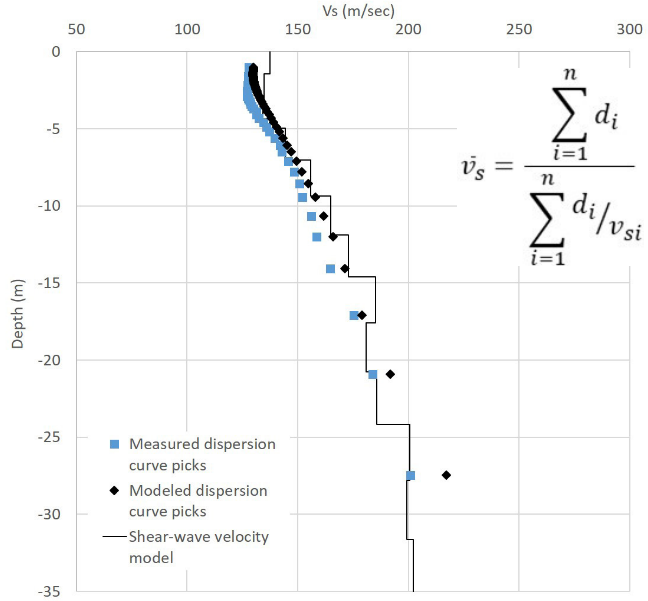
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked from 2 to 31 Hz. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 5.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 6.1 percent. The final velocity model shows velocity generally increasing with depth from 1 m (3 ft) to 30 m (100 ft). Our best Vs30 measurement is 168 m/s, which places the site in the E class. The predicted site class is D or E, which correlates with the measured E site class.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

CONCRETE HIGH SCHOOL AND CONCRETE ELEMENTARY SCHOOL

CONCRETE SCHOOL DISTRICT, SKAGIT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

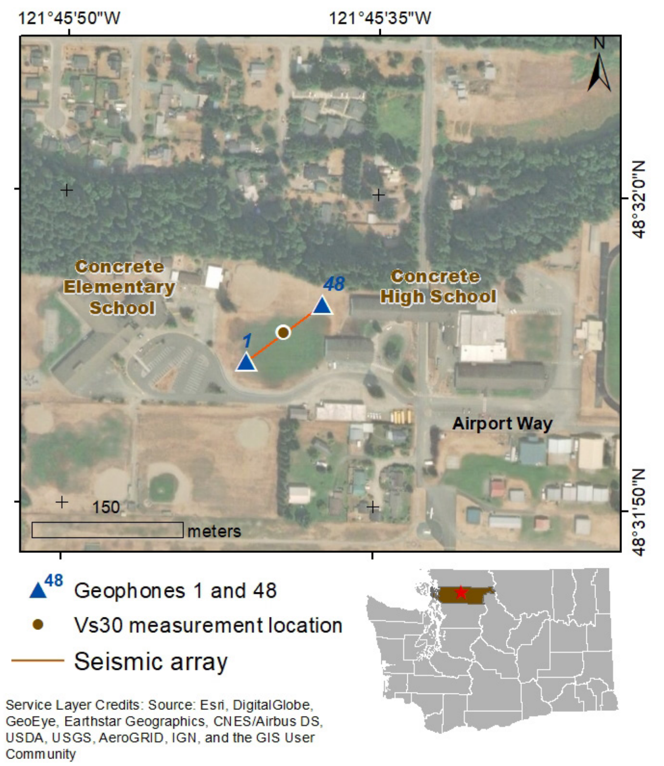
On July 2, 2018, a team from the Washington Geological Survey conducted a seismic survey at Concrete Elementary school and Concrete High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting primarily on Quaternary Alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to low hazard

Ground Shaking
Severe

Lahar
In a mapped lahar hazard zone

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

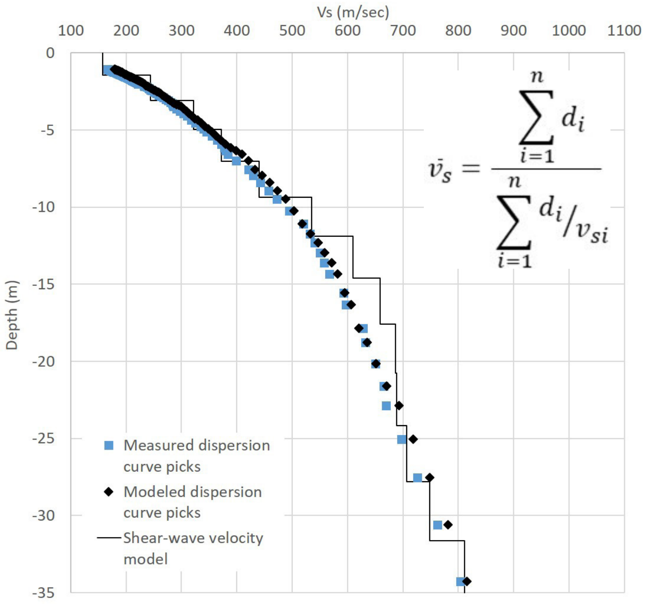
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves contain higher modes but the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is of decent quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the reverse direction (off-end geophone 48). The model has an RMSE of 12.9 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 4.1 percent. The velocity profile shows generally steadily increasing velocity from 2 m (7 ft) down to 30 m (100 ft) depth. Our best Vs30 measurement is 470 m/s, which places the site in the middle of the C class. The measured site class is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school site and the geophone array are sitting on Quaternary Alluvium (unit Qa), which has a predicted site class of D to E in this area. However, Pleistocene continental glacial drift (unit Qga) is mapped to the north and south on either side of the valley, which has a prediced site class of C to D. Although, the final model does not show velocity structure that would indicate a contact between units Qa and Qga, it is likely that unit Qa is lying on top of unit Qga, which is shallow enough to effect the Vs30. However, due to the proximity of the array to the building and a lack of evidence for significant heterogeneous velocity structure along the array, we assign site class C to the school campus and buildings.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

COSMOPOLIS ELEMENTARY SCHOOL

COSMOPOLIS SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

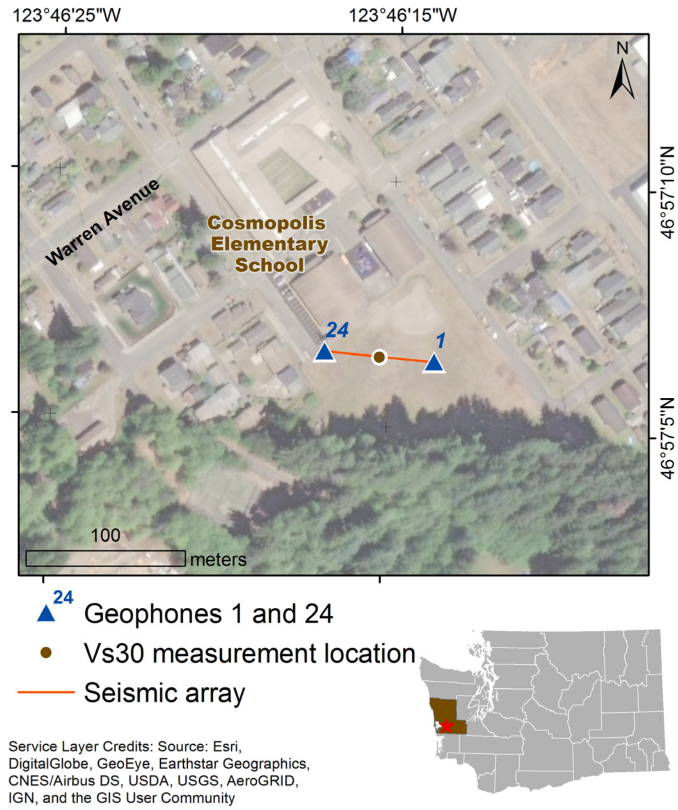
On February 26, 2007, a team from the Washington Geological Survey conducted a seismic survey at Cosmopolis Elementary School for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 226-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was previously thought.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

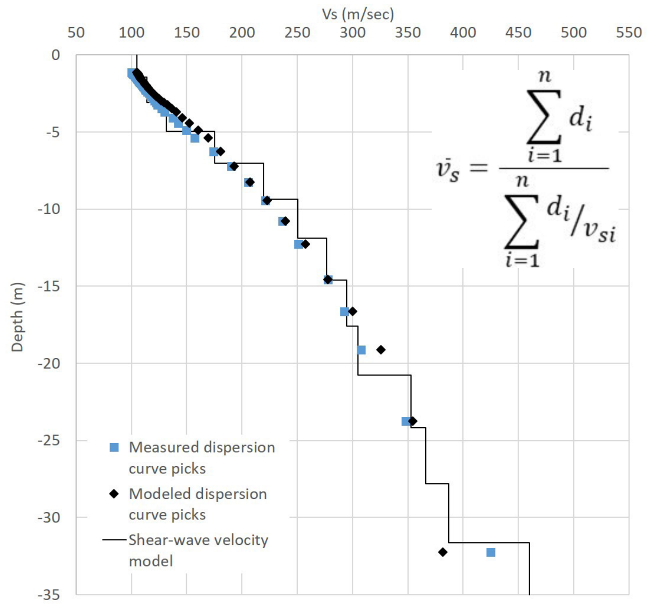
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curve contains higher modes but the fundamental mode can be picked from 4 Hz to 30 Hz frequency. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as a check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the reverse MASW (offend geophone 24). The inital model has an RMSE of 11.0 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.2 percent. The final velocity model shows a generally steady increase in velocity from 1 m (3 ft) down to 30 m (100 ft) depth. Our best Vs30 measurement is 230 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

COUPEVILLE ELEMENTARY SCHOOL

COUPEVILLE SCHOOL DISTRICT, ISLAND COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

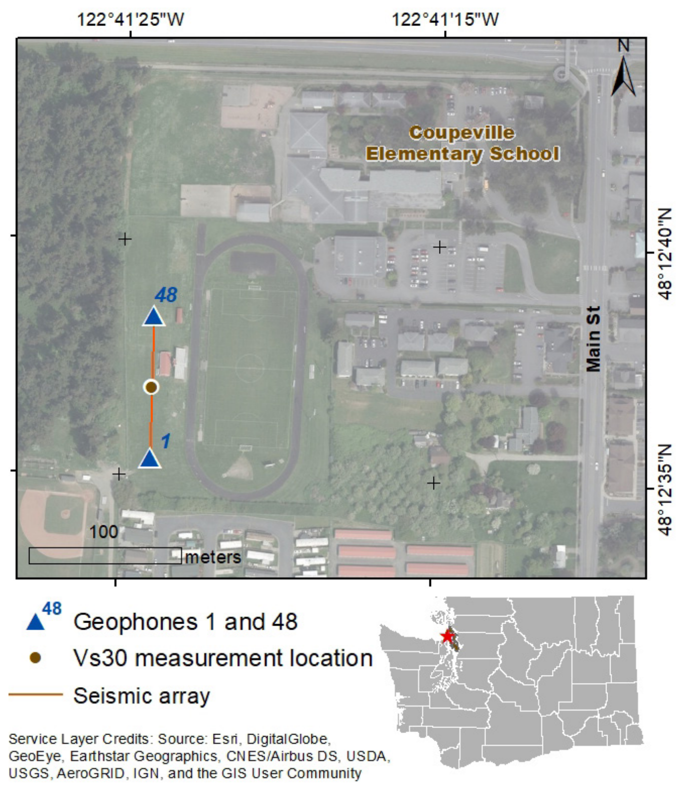
On July 11, 2018, a team from the Washington Geological Survey conducted a seismic survey at Coupeville Elementary school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- ☐ The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- ☐ Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift deposits containing silt, clay, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

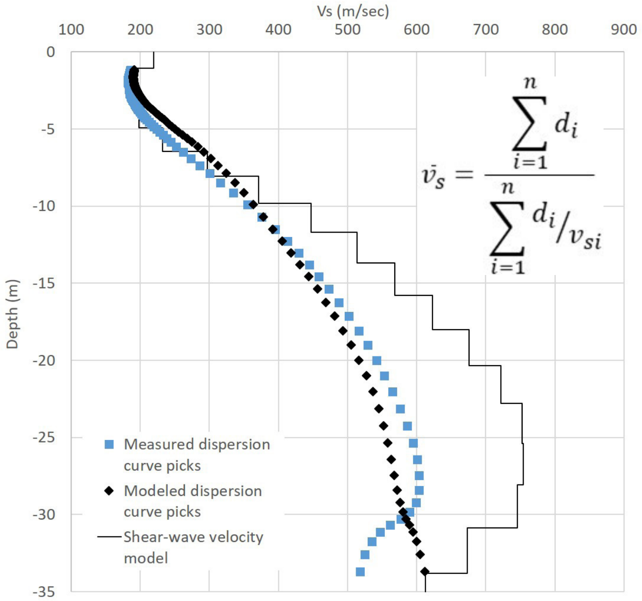
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of excellent quality and the fundamental mode can be picked down to 2 Hz frequency. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 11.0 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 5.3 percent. The velocity profile shows a slight inversion in the top layer and steadily increasing velocity from 2 m (7 ft) down to 26 m (85 ft) depth. Then a velocity reversal is below. Our best Vs30 measurement is 412 m/s, which places the site in the C class. The measured site class is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

COUPEVILLE HIGH SCHOOL AND COUPEVILLE MIDDLE SCHOOL

COUPEVILLE SCHOOL DISTRICT, ISLAND COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

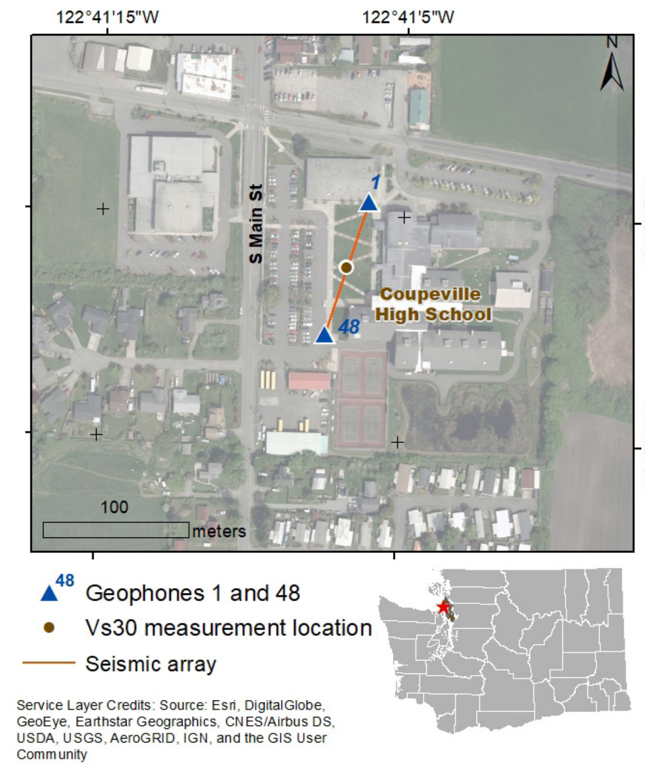
On July 12, 2018, a team from the Washington Geological Survey conducted a seismic survey at Coupeville High and Middle school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was previously thought.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift deposits containing silt, clay, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

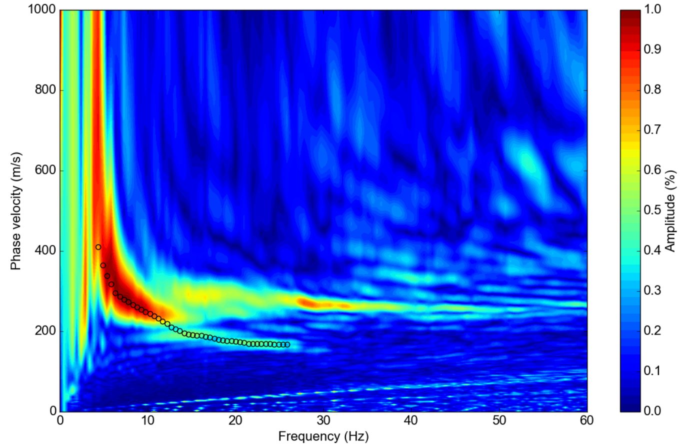
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

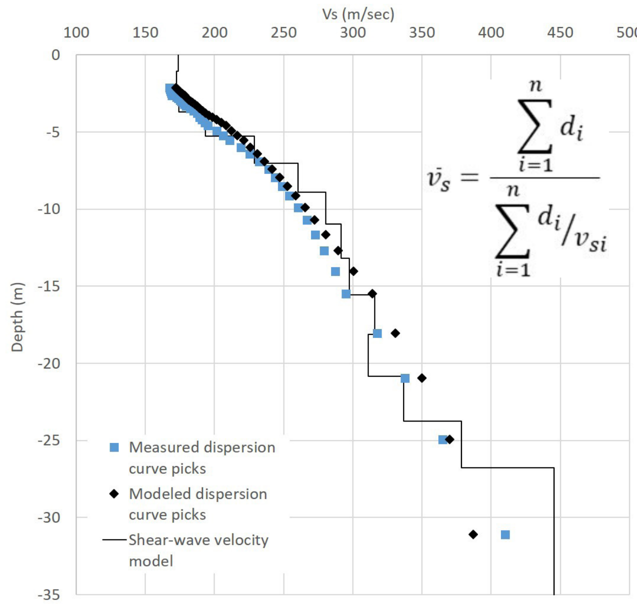
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes but the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is not of good quality and is not used for analysis. The MASW adequately samples down to 30 m (100 ft) depth.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the reverse direction (located off end geophone 48). The model has an RMSE of 11.3 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.4 percent. The velocity profile shows steadily increasing velocity from 1 m (3 ft) down to 30 m (100 ft) depth. Our best Vs30 measurement is 279 m/s, which places the site in the D class. The measured site class is the same as the predicted site class of D.



MASW dispersion image, with warmer colors indicating high coherence. The picked fundamental mode is shown as black circles, this is the measured dispersion curve .



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i/v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

CRESTON ELEMENTARY, JUNIOR & SENIOR HIGH SCHOOL

CRESTON SCHOOL DISTRICT, LINCOLN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

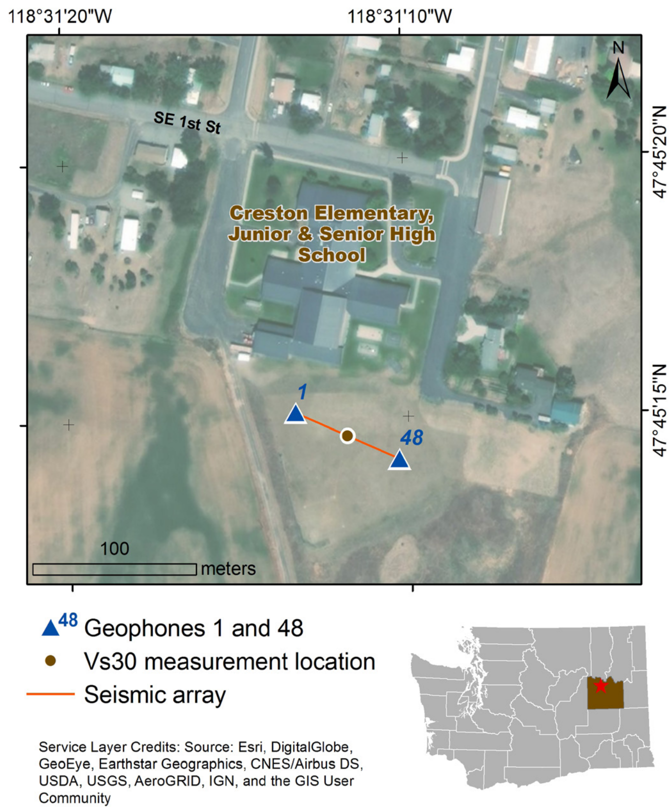
On July 16, 2018, a team from the Washington Geological Survey conducted a seismic survey at Creston Schools. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on wind deposited silt and sand that contains layers of caliche and/or volcanic ash.

GEOLOGIC HAZARD AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

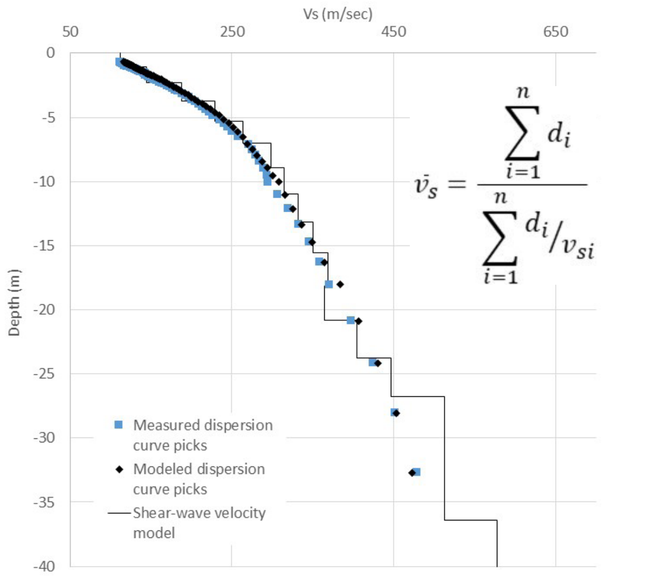
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image contains higher modes but the fundamental mode can easily be picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only to check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW forward direction (located off end geophone 1). The model has an RMSE of 11.5 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 3.5 percent. The velocity models shows a generally, but not uniformily, increase in velocity with depth. The best estimate for Vs30 is 302 m/s, which places the site in the middle of site class D. This site class is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

DARRINGTON ELEMENTARY AND HIGH SCHOOL

DARRINGTON SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

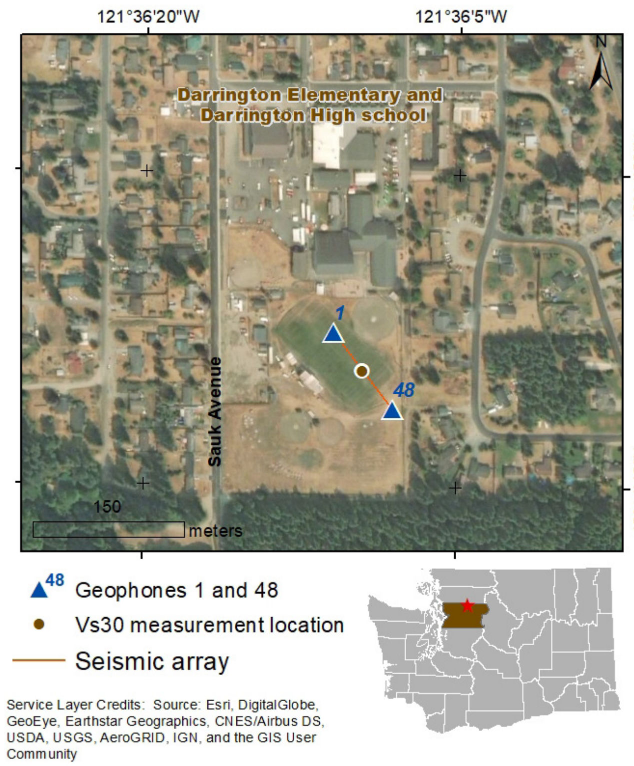
On July 2, 2018, a team from the Washington Geological Survey conducted a seismic survey at Darringotn Elementary and High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting primarily on lahar deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

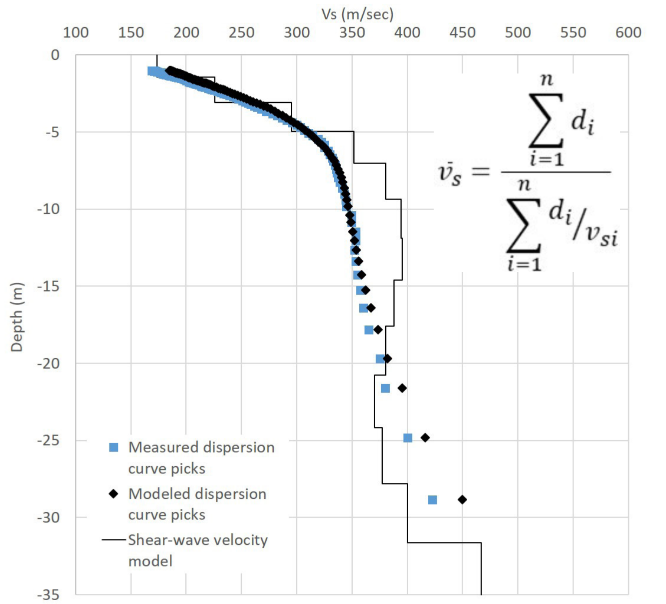
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 13.9 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 4.5 percent. The velocity profile shows rapidly increasing velocity from 2 m (7 ft) to 12 m (39 ft) depth, then generally constant velocity from 12 m (39 ft) to 25 m (82 ft), and increasing velocity below 20 m (65 ft). Our best Vs30 measurement is 343 m/s, which places the site near the high end of the D class. The predicted site class is D or E, which correlates with the measured D site class.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

DAYTON ELEMENTARY, MIDDLE, AND HIGH SCHOOL

DAYTON SCHOOL DISTRICT, COLUMBIA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

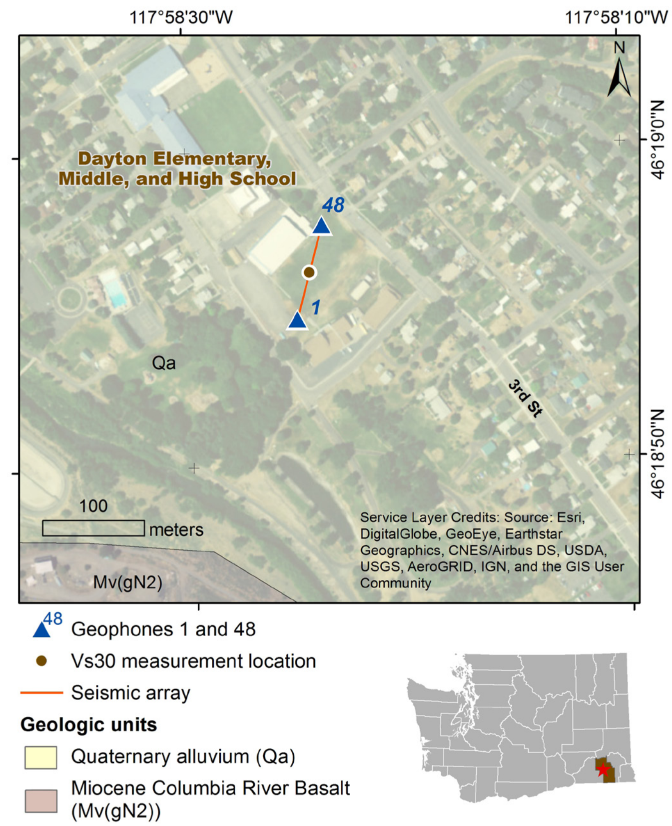
On July 3, 2018, a team from the Washington Geological Survey conducted a seismic survey at Dayton Elementary, Middle, and High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS B



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on alluvium (river sediments), unit Qa. Outcrops of Miocene Columbia River Basalt Group, Wanapum Basalt, unit Mv(gN2), are mapped just to the south.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Strong

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

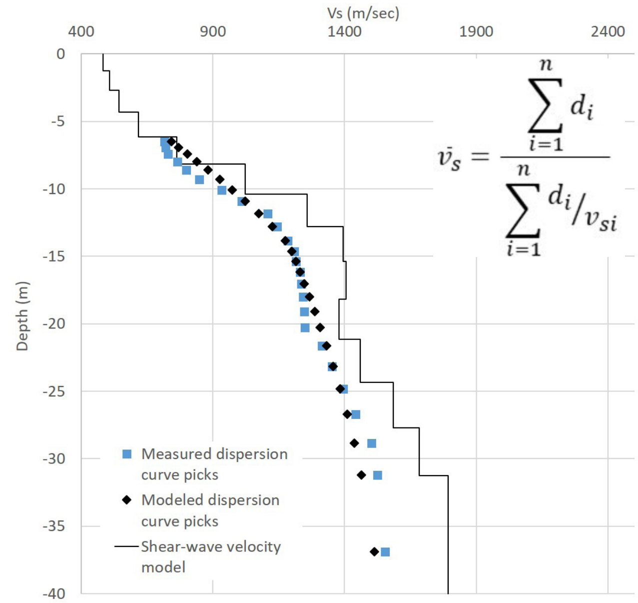
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves are slightly different, which indicates some variability across the geophone array. The microtremor analysis method (MAM) dispersion image is also of decent quality but is used only as a check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW reverse direction (located off end geophone 48). The initial model has an RMSE of 10.7 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 3.5 percent. The upper 6 m (20 ft) of the final velocity model is unconstrained but the model shows generally increasing velocity from 1 m (3 ft) to 12 m (39 ft). Below 12 m (39 ft), the velocity model shows constant velocity down to 20 m (66 ft) and steadily increasing velocity below that, down to 30 m (100 ft). Our best Vs30 measurement is 1013 m/s, which places the site in the middle of the B site class. Although, the MASW dispersion curves from the reverse and forward directions do show some variability, the inverted models from each are in the middle of the B class, so the site can be confidently classified. The predicted site-class is a D-E class, which is significantly different than what we measured.

GEOLOGY

The 1:100,000-scale geologic map shows the school building is sitting on a Quaternary Alluvium (unit Qa) which has a predicted site class of D to E. Mapped just south of the site is an outcrop of Miocene Columbia River Basalt Group, Grande Ronde Basalt (unit Mv(gN2)) which has a predicted site class of B. P-wave refraction produced a slow velocity top layer that is 6 m (20 ft) thick and has a P-wave velocity of ~300 m/s and a bottom layer of ~3600 m/s. This would be consistent with a Quaternary alluvium layer overlaying an unweathered basalt flow. It is also consistent with the final velocity model and nearby boreholes that show shallow basalt deposits as shallow as 1 m (3 ft). All of this suggests that the difference between the measured and predicted site class is due to change in subsurface materials. Due to the proximity of the array to the building and a lack of evidence for significant heterogeneous velocity structure along the array in the 2D P-wave refraction, we assignment site class B to the campus. However, we recommend further geotechnical investigation to verify the thickness of unit Qa at the site.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

DIXIE ELEMENTARY SCHOOL

DIXIE SCHOOL DISTRICT, WALLA WALLA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

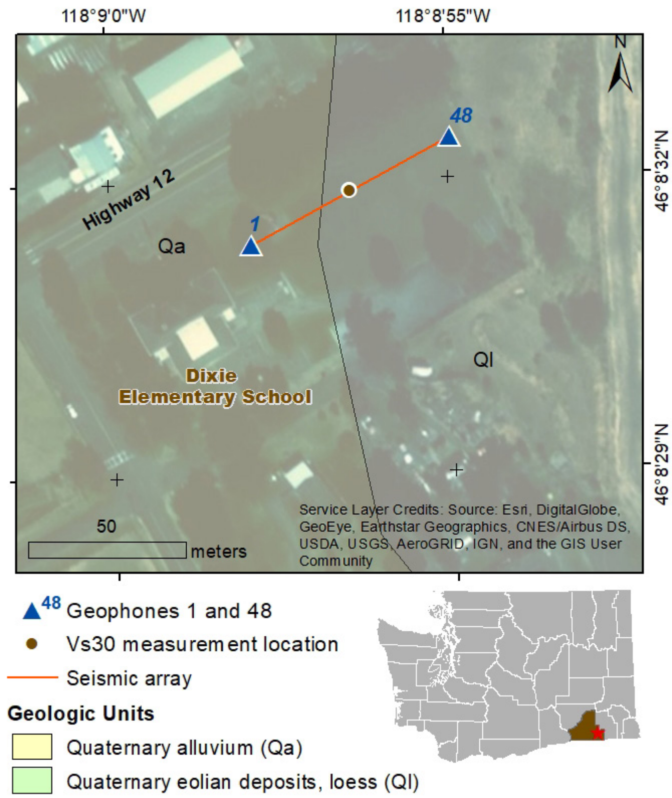
On July 3, 2018, a team from the Washington Geological Survey conducted a seismic survey at Dixie Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on siff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Very strong

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

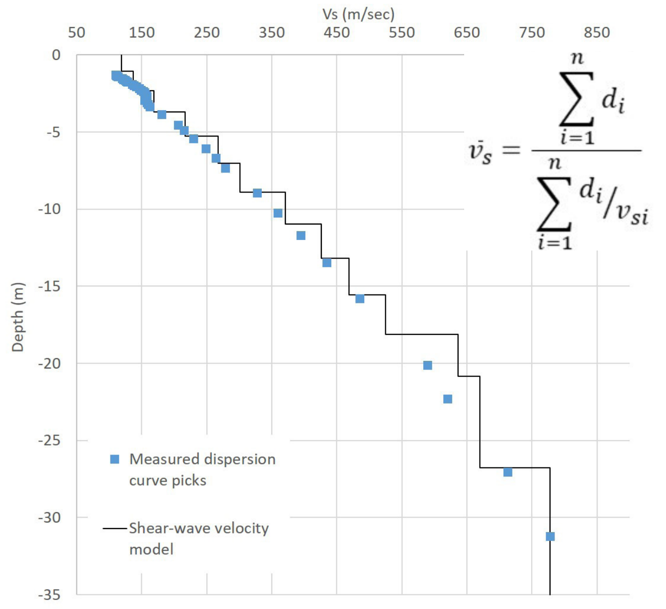
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are dominated by higher modes but the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is not of good quality and is not used for analysis. The MASW dispersion curve (reverse direction) samples down to 30 m (100 ft), so it is sufficient for determining site class.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve. The analysis did not converge to below 5 percent RMSE. The resulting best estimate for Vs30 is 359 m/s and is based on the initial model, which places the site on the D to C boundary. The inital model shows steadily increasing velocity with depth from 1 m (3 ft) to 30 m (100 ft). The predicted site class is D or E, which correlates with the measured D site class.

GEOLOGY

The 1:100,000 scale geologic map show that the school buildings are sitting on Quaternary alluvium (unit Qa) and the geophone array is sitting partially on unit Qa and partially on Palouse loess (unit Ql). The site class for unit Qa in this area is D to E, while the site class for unit Ql is D. Although the aperture of the array crosses mapped geologic units, the measured site class of D at the location of the array falls within the predicted site class of both units. Furthermore, the final shear wave velocity profile does not indicate a contact between the two mapped units. Although the measured site class is on the D to C boundary, under these circumstances, we take the conservative approach and assign site class D.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

EAST VALLEY ELEMENTARY SCHOOL

EAST VALLEY (YAKIMA) SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

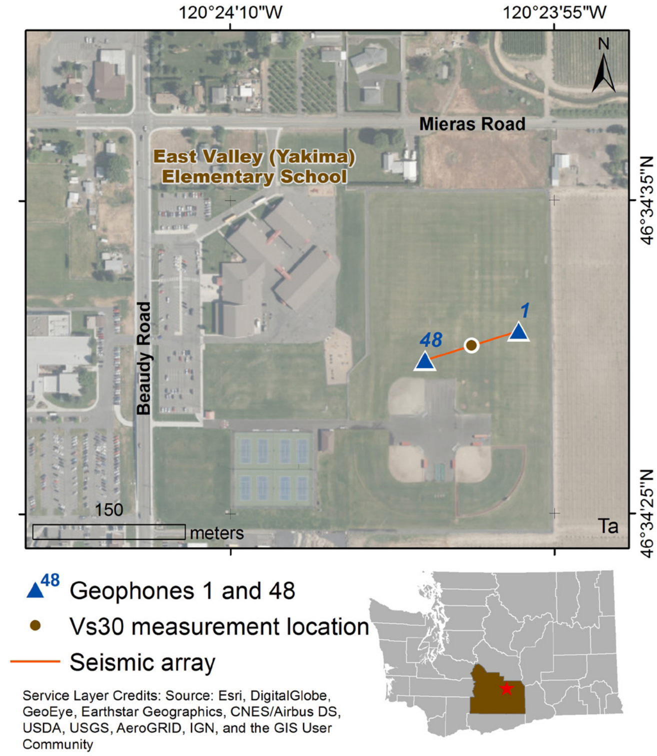
On June 26, 2018, a team from the Washington Geological Survey conducted a seismic survey at East Valley Elementary school. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on very dense soil and soft rock, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on eolian silt and fine sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Very Strong

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

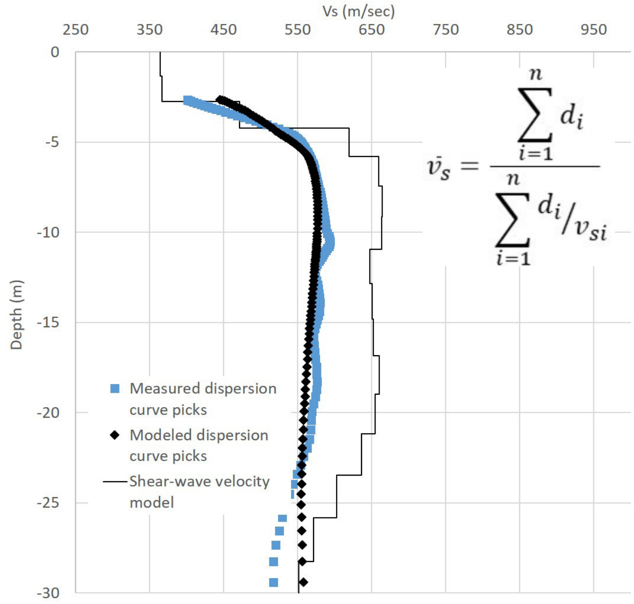
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality below 23 Hz. The MASW and MAM dispersion curves correlate well between 17 Hz and 23 Hz, but begin to diverge below 17 Hz. Despite this lack of correlation, the dispersion curves depict a similar trend and the MASW (forward and reverse direction) and MAM dispersion curves are combined and averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 4.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.1 percent. The upper 3 m (10 ft) of the final velocity model is unconstrained, but below 3 m (10 ft) the model shows rapidly increasing velocity to a depth of 8 m (26 ft). Below 8 m (26 ft) the model shows constant velocity down to 20 m (66 ft), then decreasing velocity below 20 m (66 ft). The Vs30 values derived from the combined MASW and MAM measurements are all within the middle of the C class, so this site can be confidently classified. This is different from the predicted site class of D.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school and geophone array are sitting on the Palouse formation (unit Ql) which is described as Quaternary eolian loess deposit consisting of silt and fine sand, including multiple local layers of caliche and tephra beds. Although located too far away to be directly correlated with the seismic data, borehole logs in the surrounding area show thick, cemented gravel deposits below 3 m (10 ft) depth, which are underlain by uncemented deposits. Cemented deposits can vary significantly in thickness over relatively short distances, increasing shear wave velocities locally. Deposits of cemented gravels underlain by uncemented gravels could contribute to the relatively high velocity at shallow depths. Velocity becomes more variable below 8 m (26 ft). This ultimately could explain the discrepancy between the predicted and measured site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

EAST VALLEY CENTRAL MIDDLE SCHOOL

EAST VALLEY (YAKIMA) SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

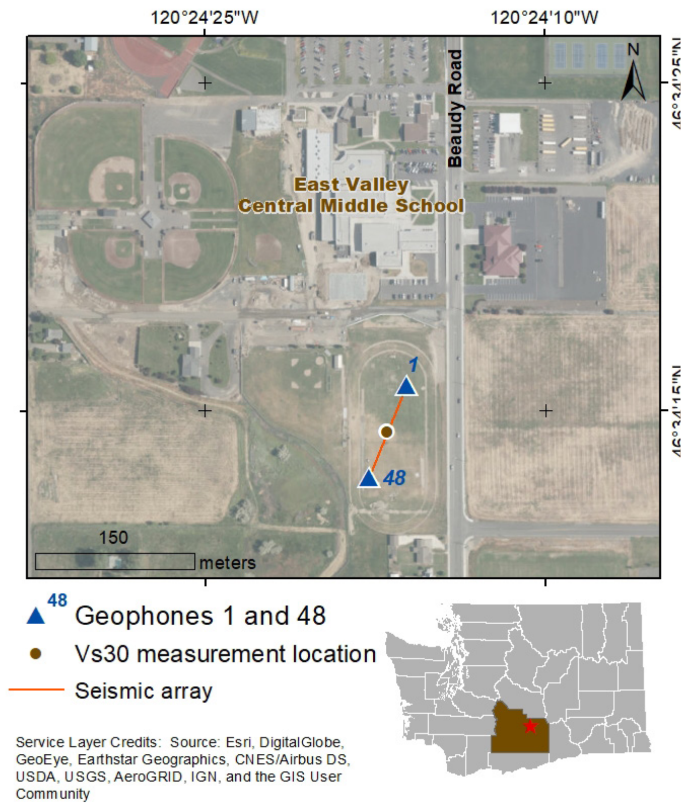
On June 26, 2018, a team from the Washington Geological Survey conducted a seismic survey at East Valley Central Middle school. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock and very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on eolian silt and fine sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Very strong

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

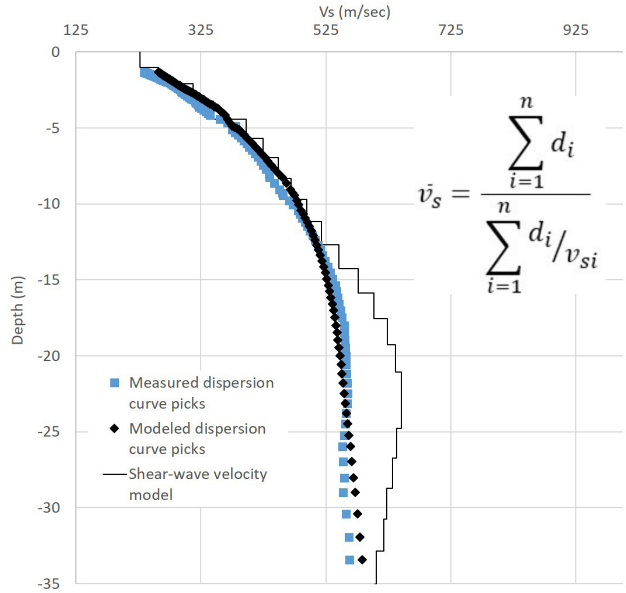
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality and the fundamental can picked. The microtremor analysis method (MAM) dispersion image is of good quality below 15 Hz but not above. This makes the MAM fundamental dispersion curve difficult to identify above 15 Hz. The MASW dispersion curves from the forward and reverse directions do indicate some variability and neither adequately sample down to 30 m (100 ft). However, the combined MASW and MAM dispersion curves correlate well with similar overall trends.

VELOCITY MODEL

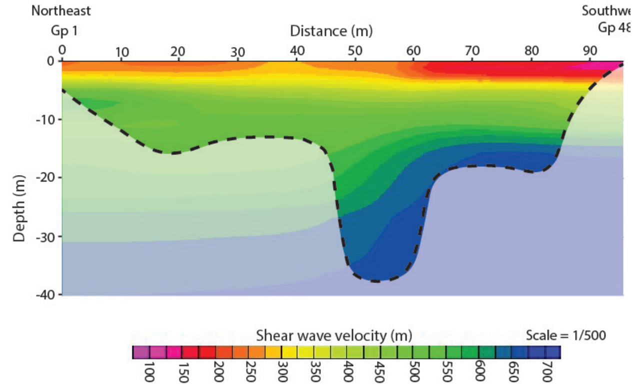
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves from the forward MASW (geophone 1) and the MAM. The combined dispersion curves were averaged and then smoothed before the initial model was constructed with an RMSE of 7.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.1 percent. The final velocity model shows a steady increase in velocity with depth down to approximately 20 m (66 ft) and steady velocity below. Lateral heterogeneous velocity structure is confirmed in the 2D Vs model, which shows a lateral change at a depth of 15 m (49 ft) beginning at a distance along the array around 55 m (180 ft). This puts higher velocity materials at around 15 m (49 ft) to the southwest and at a deeper depth to the northeast. The Vs30 values derived from the MASW and MAM combined measurements are all within the middle of the C class, so this site can be confidently classified. This is different from the predicted site class of D.

GEOLOGY

The 1:24,000-scale geologic map shows the school and geophone array are sitting on alluvium, flood plain deposits (unit Qal). Nearby borehole logs from the surrounding area show thick layers of hard conglomerates at varying depths below 4 m (13 ft). These deposits of conglomerate would likely result in a bulk velocity effect that increases velocity locally and could be contributing to the observed lateral heterogeneous velocity structure along the array. They could also explain the discrepancy between the predicted and measured site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.



Pseudo 2D MASW shear-wave velocity model with locations for Geophones 1 and 48. Dashed line approximately delineates the model's reliability in the vertical extent. Portions of the model at depths below the dashed line (shaded area) are not constrained.

EDISON ELEMENTARY SCHOOL

BURLINGTON-EDISON SCHOOL DISTRICT, SKAGIT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

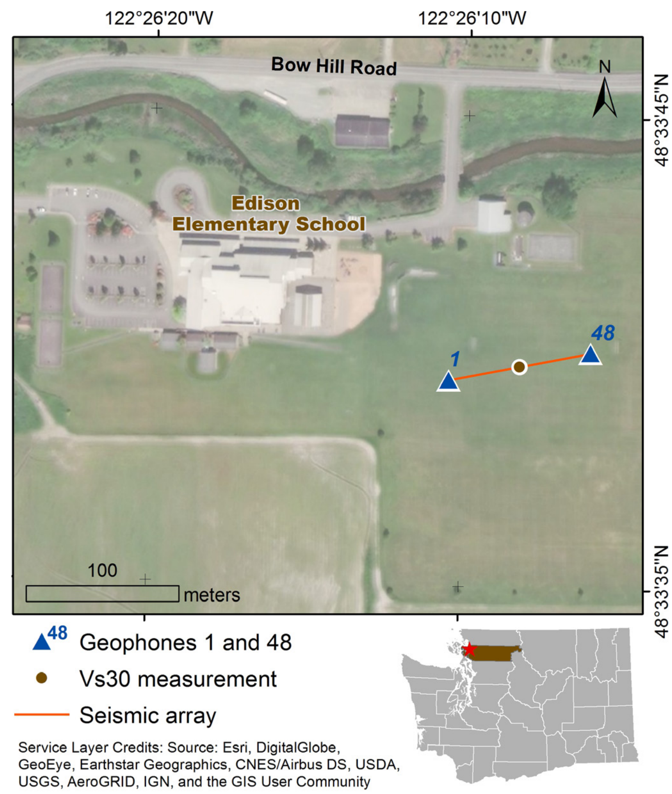
On July 30, 2018, a team from the Washington Geological Survey conducted a seismic survey at Edison Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on alluvium (river sediments) of layered and well-sorted deposits of cobbly gravel, gravel, and sand with flood-generated silt, clay, and locally peat.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

Lahar
In a mapped lahar hazard zone

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

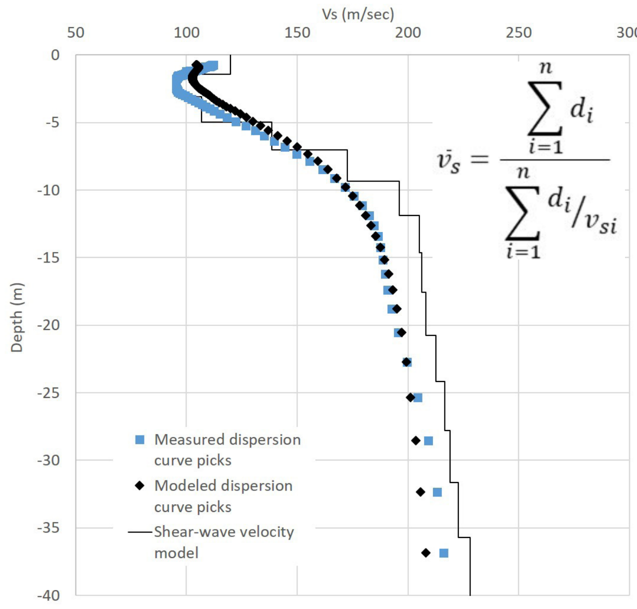
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 8.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.4 percent. The final velocity model shows a slight velocity reversal in the upper 2 m (6 ft), then rapidly increasing velocity down to 10 m (33 ft). The final model then shows a generally steady increase in velocity with depth to 30 m (100 ft). Our best Vs30 measurement is 173 m/s, which places the site in the E class. The predicted site class is either D or E, which correlates with the measured E site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

EDISON ELEMENTARY SCHOOL (CENTRALIA)

CENTRALIA SCHOOL DISTRICT, LEWIS COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

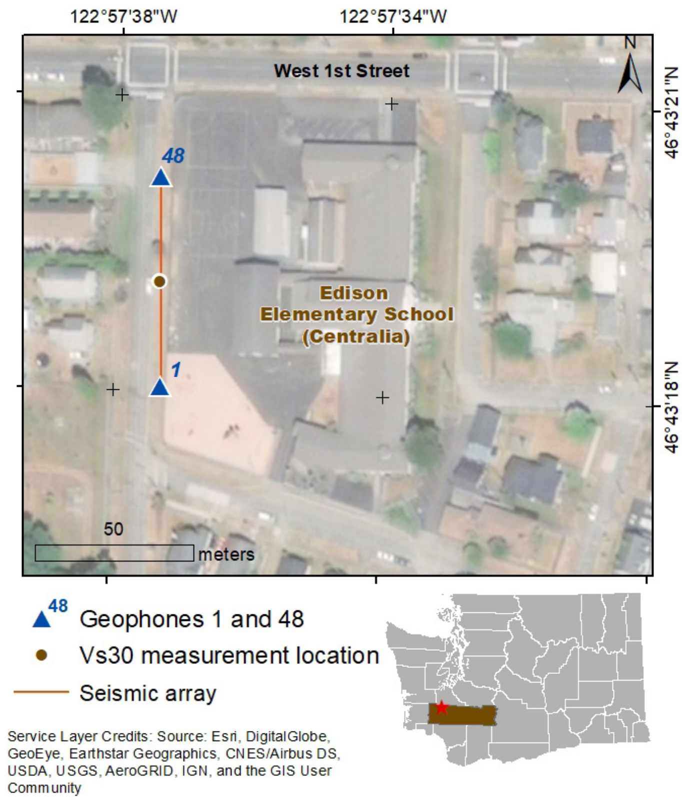
On July 25, 2018, a team from the Washington Geological Survey conducted a seismic survey at Edison Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on stream sediments composed of silt, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

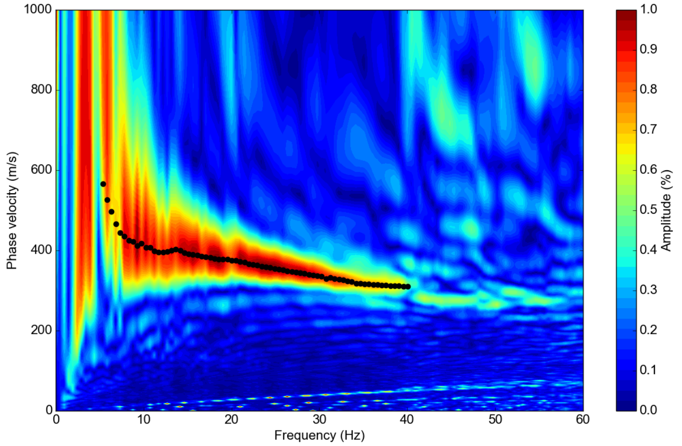
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality. However, it is used only as check for consistency in the analysis because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

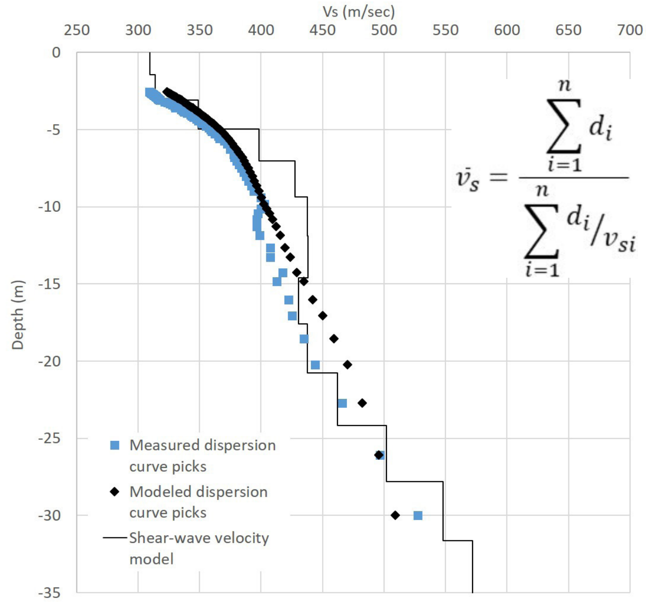
An initial model was generated using the 1/3 wavelength approximation and the forward MASW (off end geophone 1). The initial model has an RMSE of 6.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.7 percent. The final velocity model shows a steady increase in velocity down to 10 m (33 ft), constant velocity from 10 to 20 m (33 to 66 ft), and a steadily increasing velocity below that. Our best Vs30 measurement is 424 m/s, which places the site in the C class. The predicted site class is D to E, which is different than what we measured.

GEOLOGY

The 1:100,000-scale geologic maps show that the school building and geophone array are sitting on Quaternary alluvium (unit Qa). However, there is an outcrop of Pleistocene continental glacial drift (unit Qgog) mapped just to the north of the school campus. In this area unit Qgog has a predicted site class of C. The discrepancy between the measured and predicted site class could be due to a change in the subsurface geology.



MASW dispersion image, with warmer colors indicating high coherence. The picked fundamental mode is shown as black circles. This is the measured dispersion curve .



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

EDWIN MARKHAM ELEMENTARY SCHOOL

PASCO SCHOOL DISTRICT, FRANKLIN COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

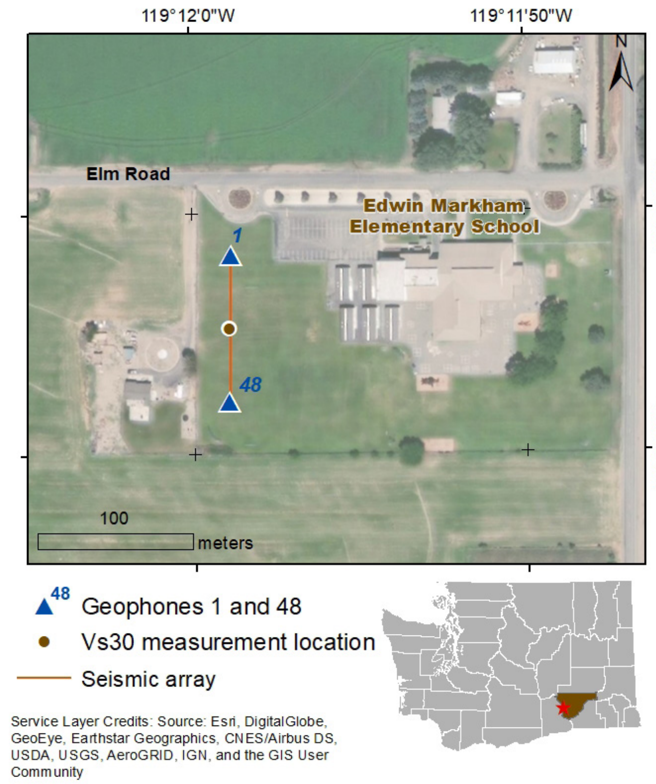
On August 8, 2018, a team from the Washington Geological Survey conducted a seismic survey at Edwin Markham Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on stabilized dune sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Very strong

TECHNICAL OVERVIEW OF RESULTS

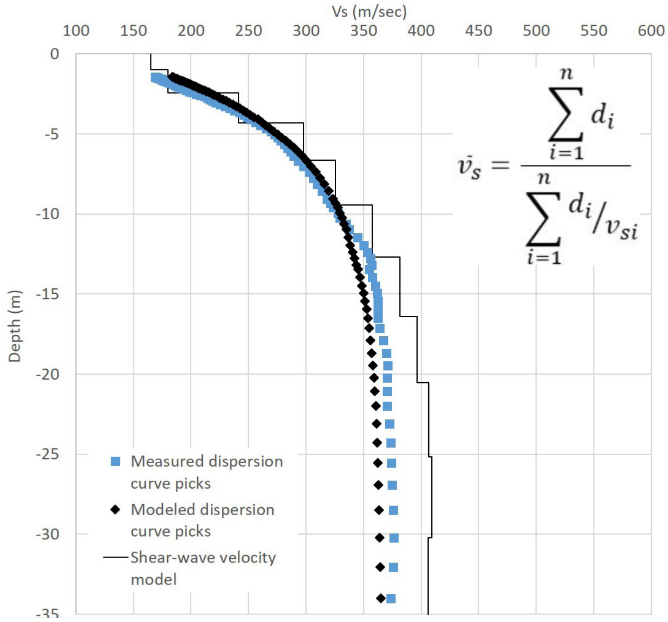
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality, with a fundamental mode that can be picked up to 12 Hz. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 9.2 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 3.3 percent. The final velocity model shows a generally steady increase in velocity from 1 m (3 ft) down to 15 m (49 ft) depth and constant velocity from 15 m (49 ft) to 30 m (100 ft). Our best Vs30 measurement is 332 m/s, which places the site in the D class. This Vs30 measurement and site class is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

EVALINE ELEMENTARY SCHOOL

EVALINE SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

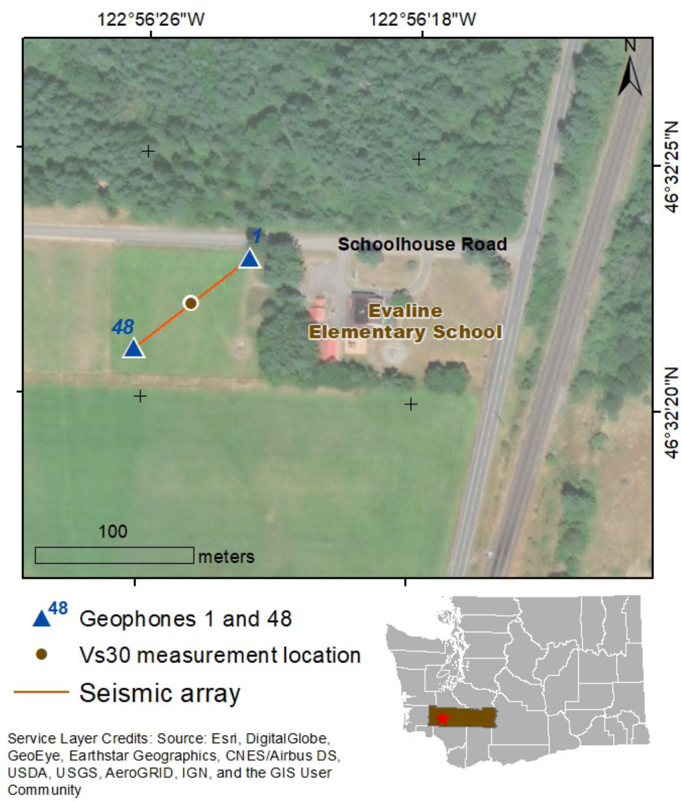
On August 13, 2018, a team from the Washington Geological Survey conducted a seismic survey at Evaline Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on alpine glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

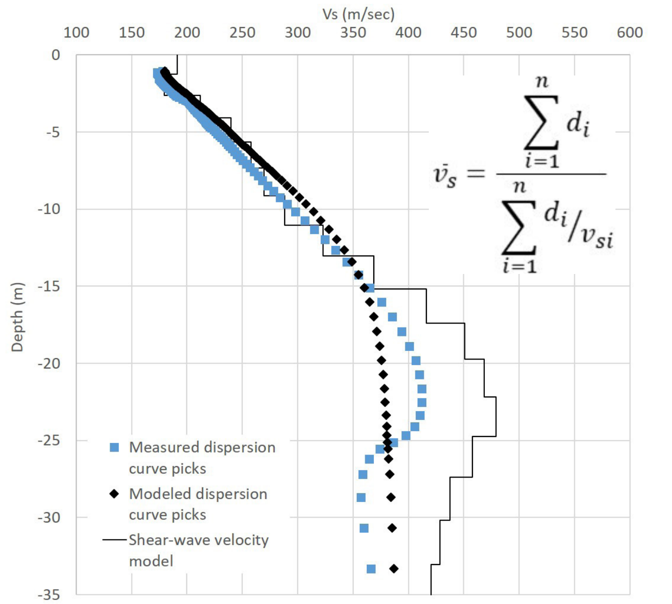
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality, with a fundamental mode that can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). Overall, the MASW and MAM dispersion curves generally agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 9.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.0 percent. The final velocity model shows a steady increase in velocity down to 25 m (82 ft), then a velocity reversal from 25 m (82 ft) depth. Our best Vs30 measurement is 326 m/s, which places the site in the D class. The predicted site-class is either C or D, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

EVERETT FIRE STATION NO. 2

2201 16TH STREET, EVERETT, SNOHOMISH COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

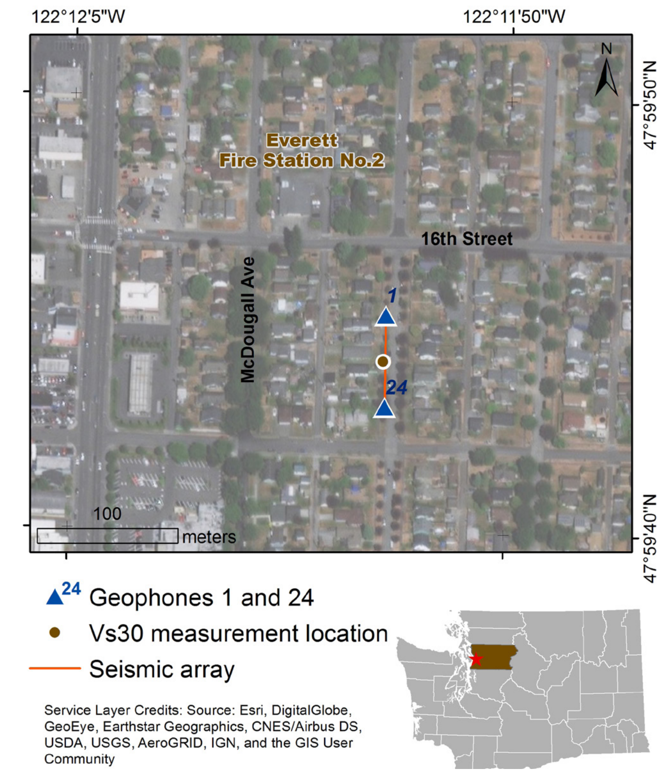
On July 22, 2010, a team from the Washington Geological Survey conducted a seismic survey near Everett Fire Department for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 230-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. t is generally accurate to assume the site class is the same under the array and the fire station, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The fire station is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the fire station.

WHAT SOILS ARE UNDER THE FIRE STATION?

The fire station is sitting on unsorted, unstratified, highly compacted mixture of clay, silt, sand, gravel, and boulders.

GEOLOGIC HAZARDS AT THE FIRE STATION

Liquefaction
Very low

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

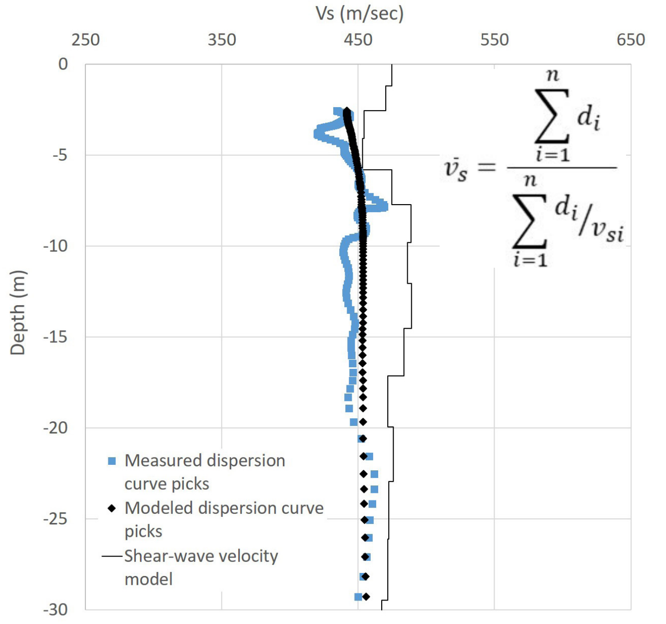
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is of good quality and the fundamental mode can be easily picked. However, it does not sample below 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality. The combined MASW and MAM dispersion curves correlate well with a similar overall trend.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves from the forward MASW (located off end of geophone 1) and MAM. The initial model has an RMSE of 3.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 1.9 percent. The upper 2 m (6 ft) of the final velocity model is unconstrained, but shows a generally constant velocity down to 30 m (98 ft). Our best Vs30 measurement is 475 m/s, which places the site in the middle of the C class. The Vs30 values derived from the combined MASW and MAM measurements are all within the middle of the C class, so this site can be confidently classified. This site class is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

FERN HILL ELEMENTARY SCHOOL

TACOMA PUBLIC SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

On September 5, 2018, a team from the Washington Geological Survey conducted a seismic survey at Fern Hill Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**

Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on unsorted, unstratified, highly compacted mixture of clay, silt, sand, gravel, and boulders deposited directly by glacial ice.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

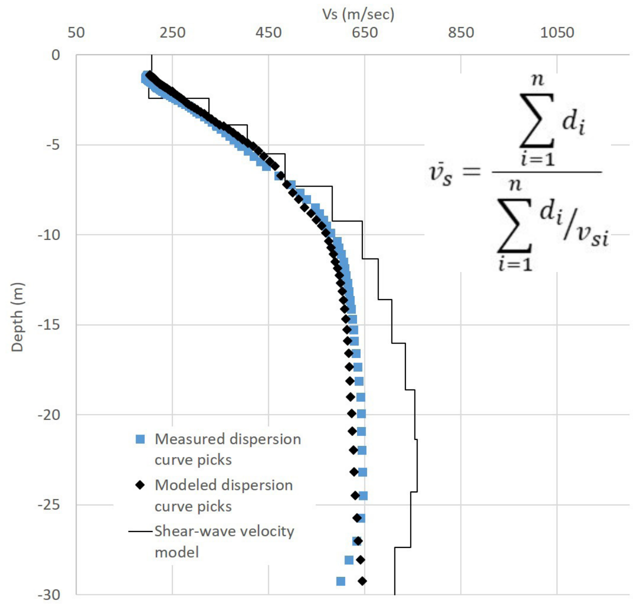
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image contains higher modes but the fundamental mode can easily be picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW forward direction (located off end geophone 1). The model has an RMSE of 13.6 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 5.5 percent. The final velocity model shows a general steady increase in velocity with depth. Our best Vs30 measurement is 535 m/s, which places the site in the C class. This site class is the same as the predicted site class of C.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

FIFE HIGH SCHOOL

FIFE SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

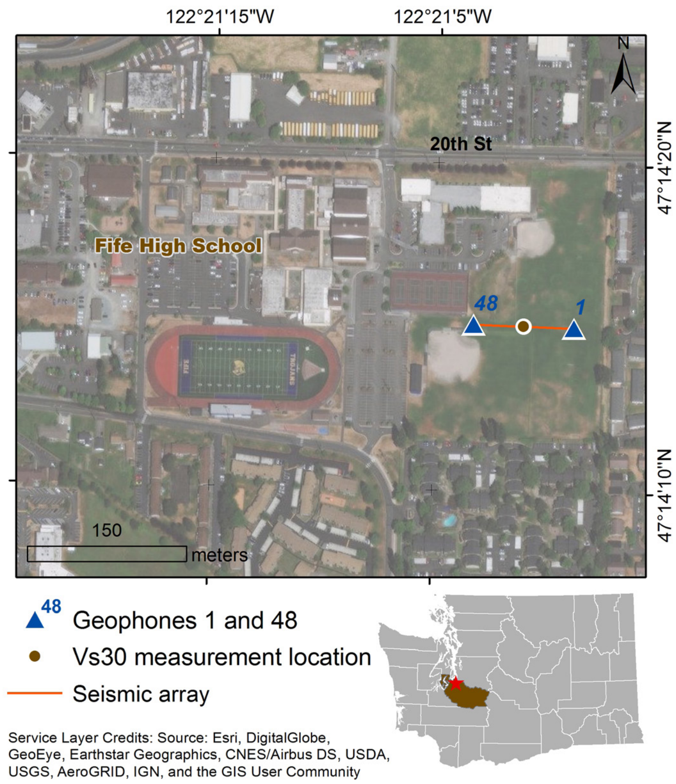
On August 9, 2018, a team from the Washington Geological Survey conducted a seismic survey at Fife High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mostly sand deposited by the river system.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
High hazard

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

TECHNICAL OVERVIEW OF RESULTS

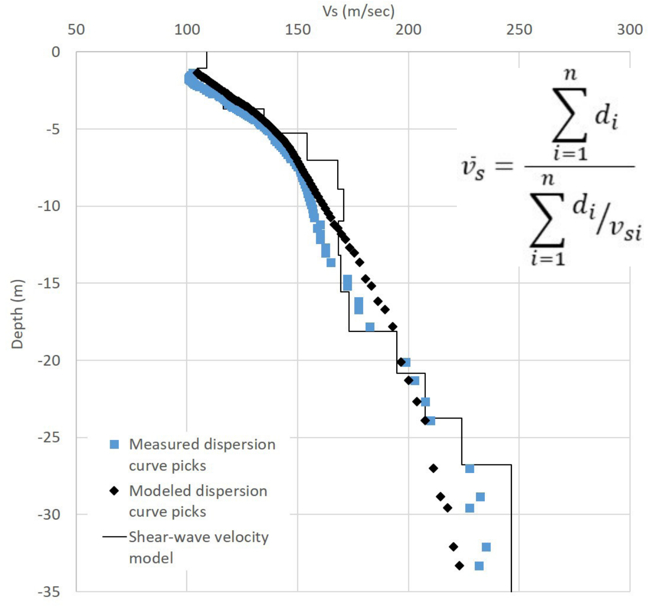
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality and the fundamental mode can be easily picked from 7 Hz to 25 Hz. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked from 2 to 13 Hz. Overall, the MASW and MAM dispersion curves agree well from 7 to 13 Hz so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 8.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.6 percent. The final velocity model shows a small velocity reversal in the top layer of the model, then generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft). Our best Vs30 measurement is 171 m/s, which places the site in the E class. The predicted site class is D or E, which correlates with the measured E site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

GLENWOOD ELEMENTARY

GLENWOOD SCHOOL DISTRICT, KLICKITAT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

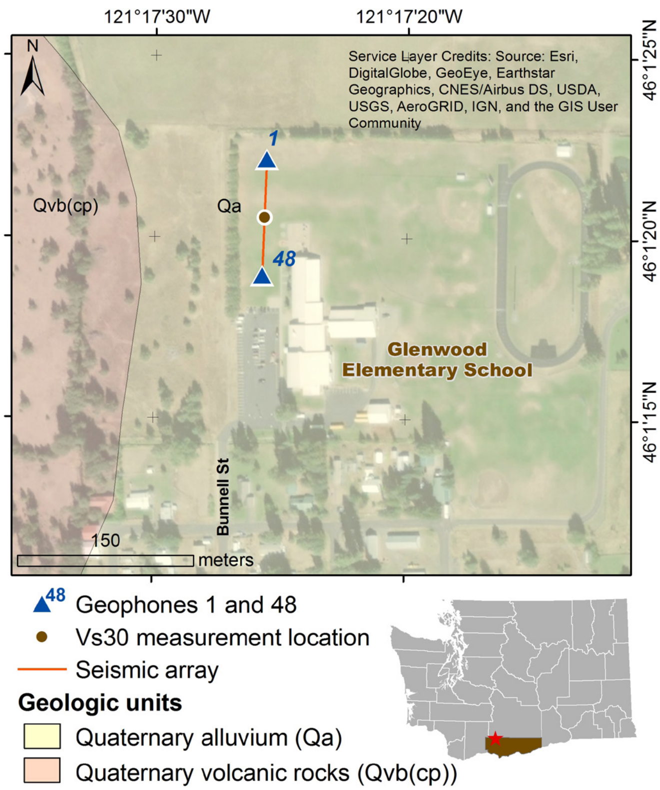
On July 10, 2018, a team from the Washington Geological Survey conducted a seismic survey at Glenwood Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on stream sediments composed of gravel, sand, silt, and mud, shown as unit Qa. A nearby exposure of relatively young basalt (unit Qvb(cp)) is mapped just to west.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate

Ground Shaking
Very strong

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

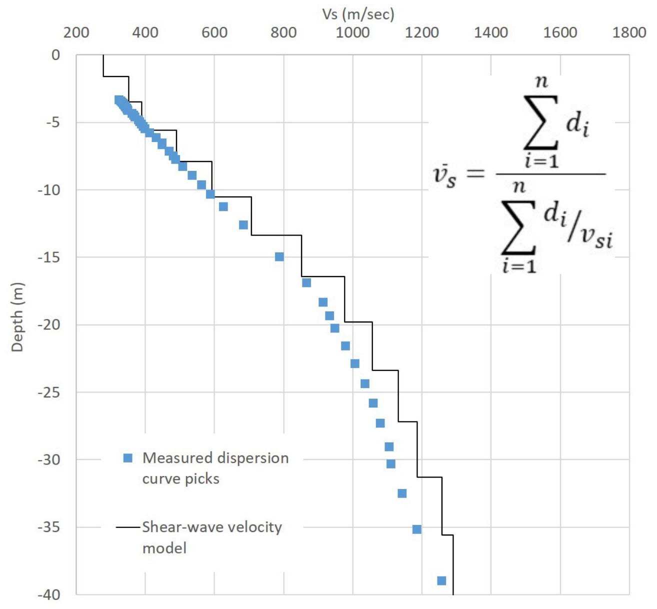
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is generally of good quality and samples down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of poor quality, so the MASW curves are used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the reverse direction (located off end geophone 48). The analysis did not converge to below 5 percent RMSE. The resulting best estimate for Vs30 is 659 m/s and is based on the initial model, which places the site in the C class. The final velocity model shows a generally steady increase in velocity with depth to 30 m (100 ft). Despite the lack of convergence, all initial models resulted in a Vs30 in the middle of the middle of the C class, so we are confident in the measured site class of C. This is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000 scale geologic map shows the school building and the geophone array are sitting on Quaternary alluvial river sediments (unit Qa) which have a predicted site class of D-E. Mapped to the west of the school are outcrops of Quaternary basalt (unit Qvb(cp)) which have a predicted site class of B. Nearby boreholes do confirm shallow basalt at depths 2 m (7 ft) and 4 m (13 ft). In addition, the velocity model shows high velocities at around 10 m (33 ft) that could mark the contact between units Qa and Qvb(cp). This suggests that the difference between the measured and predicted site class is likely due to a change in the subsurface geology.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

GREEN MOUNTAIN ELEMENTARY SCHOOL

GREEN MOUNTAIN SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

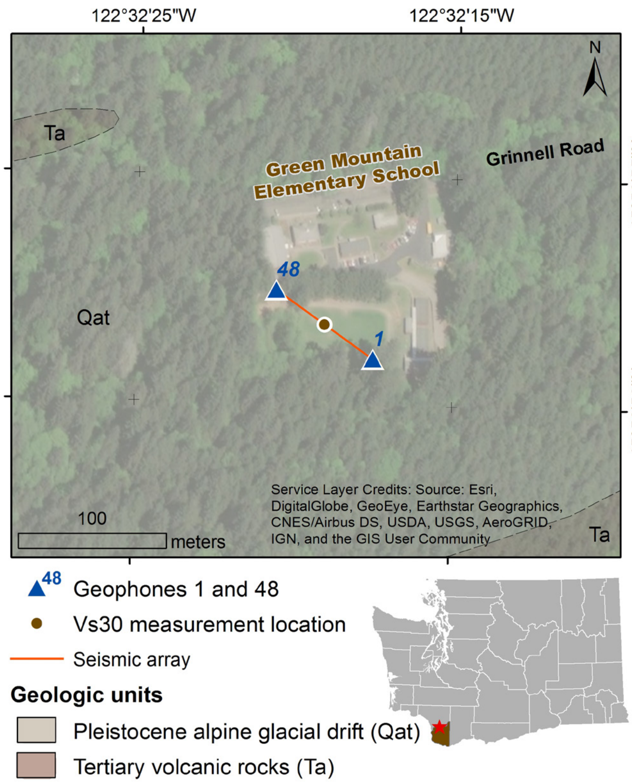
On June 28, 2018, a team from the Washington Geological Survey conducted a seismic survey at Green Mountain Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted B site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on alpine glacial drift. Exposures of Tertiary volcanics (Ta) are mapped to the southeast and northwest.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Severe

Landslide
Hazard present

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

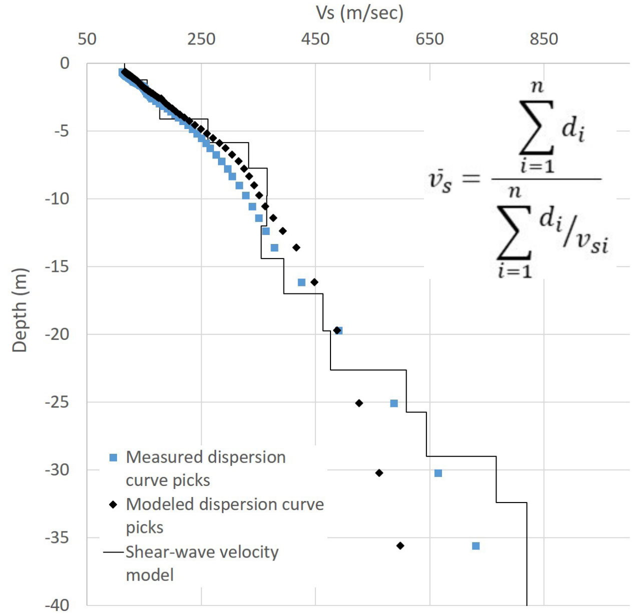
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface waves (MASW) dispersion images are of varying quality, but dispersion curves on both ends of the array can be picked. The microtremor analysis method (MAM) dispersion image is of poor quailty, so the only MASW dispersion curves are used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the reverse direction (located off end geophone 48). The model has an RMSE of 13.0 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 5.7 percent. The final velocity model shows a rapid increase in velocity from 0 m (0 ft) to 8 m (26 ft), steady velocity from 8 m (26 ft) to 15 m (49 ft) and generally increasing velocity below 15 m (49 ft). The resulting Vs30's are all within the D site class with the best estimate for Vs30 being 341 m/s. The measured site class is different than the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school site and the geophone array are sitting on Tertiary volcanics, which are mapped as a site class B in this area. However, the more detailed 1:24,000-scale maps show that the site and geophone array are sitting on Pleistocene alpine glacial drift (unit Qat). Exposoures of Tertiary volcanics are mapped to the northwest and to the south of the school, which in this area, has a predicted site class of C or D. However, velocities below 22 m (72 ft) are high enough to suggest a contact between sediment and hard rock, and nearby boreholes confirm rock at around 21 m (71 ft). Therefore, a mis-mapping in surficial geology between unit Qat and higher velocity volcanics helps explain the discrepancy between the predicted and measured site classes at the school campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

HARRINGTON ELEMENTARY AND HIGH SCHOOL

HARRINGTON SCHOOL DISTRICT, LINCOLN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

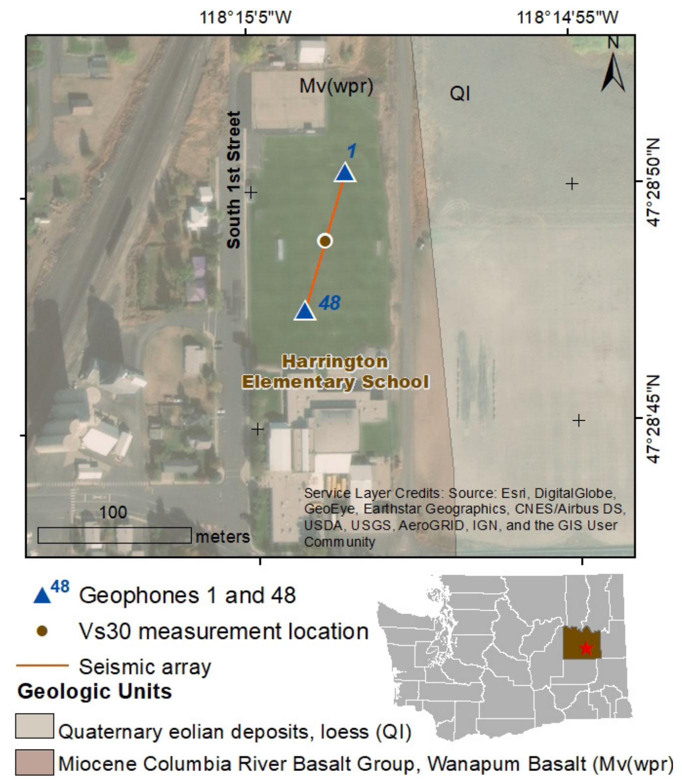
On July 17th, 2018, a team from the Washington Geological Survey conducted a seismic survey at the Harrington Elementary and High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted B site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school building is sitting on basalt.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

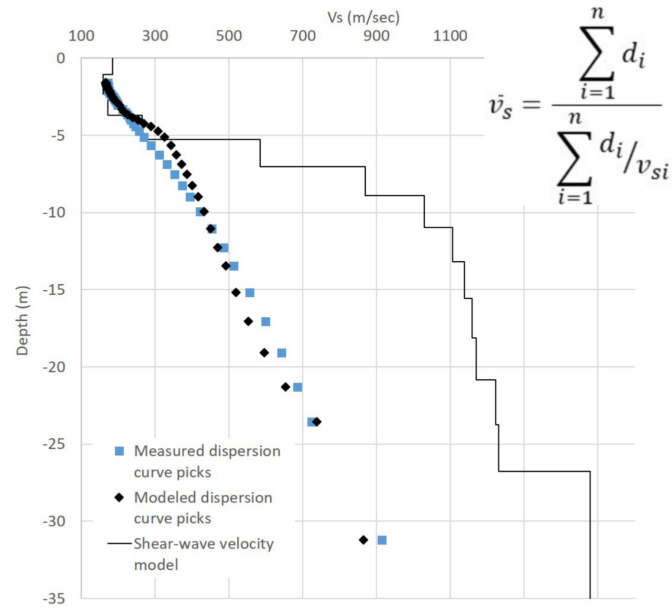
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are dominated by higher modes but the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is not good quality and is not used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1). The initial model has an RMSE of 17.2 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 4.7 percent. The final velocity model shows mostly constant low velocity in the upper 4m (13 ft)then a sharp increase in velocity down to 8 m (26 ft). From 5 m (16 ft) to 30 m (100 ft), the velocity is generally increasing. Our best Vs30 measurement is 601 m/s, which places the site in the middle of the C class. Although the initial model results in a Vs30 that is 125 m/s lower than the inverted model, both models are in the middle of the C class, so this site can be confidently classified. The measured site class is different than the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school building and the array are sitting on the Priest Rapids Member of the Wanapum Basalt, Columbia River Basalt Group (unit Mv(wpr)) and near the boundary of the Palouse formation (unit Ql). The final shear wave velcoity profile shows a layer of very low velocity material near the surface and sharp increase to high velocities at around 5 m (16 ft) depth. Nearby boreholes confirm shallow bedrock at around 4.5 m (15 ft) depth with silty gravel above. The velocity profile and boreholes indicate that there is a layer of the low velocity Palouse formation overlying the higher velocity Wanapum basalt at this site, which implies that the surficial geology is mis-mapped and the likely reason in the discrepancy between the predicted and measured site-classes.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i **= thickness of any layer between 0 and 30 m.** V_{si} **= Shear wave velocity in (m/s) of the layer.**

HATHAWAY ELEMENTARY SCHOOL

WASHOUGAL SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

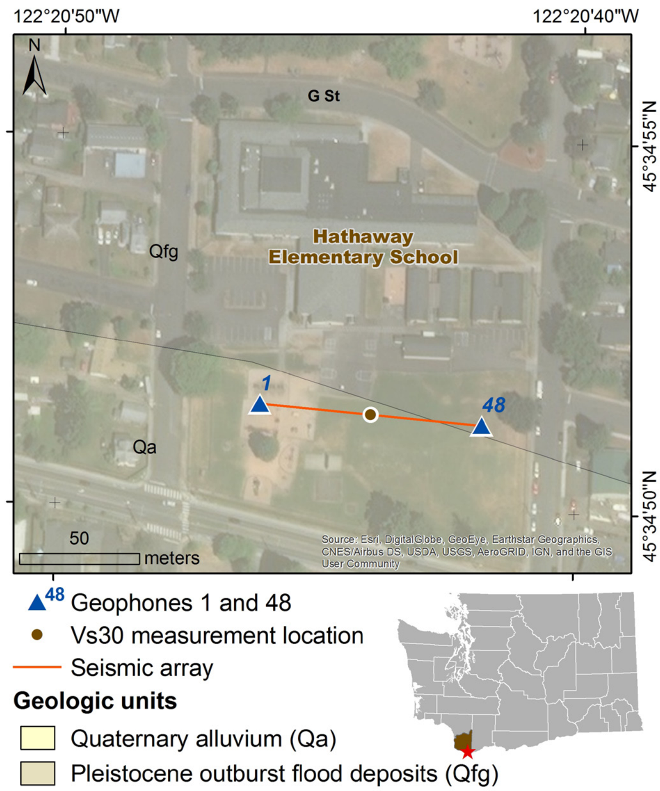
On August 23, 2018, a team from the Washington Geological Survey conducted a seismic survey at Hathaway Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school building is sitting on a boulder to cobble gravel in a sandy matrix, deposited by the Missoula floods unit (unit Qfg). Quaternary alluvium (unit Qa) is just south of the school building.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

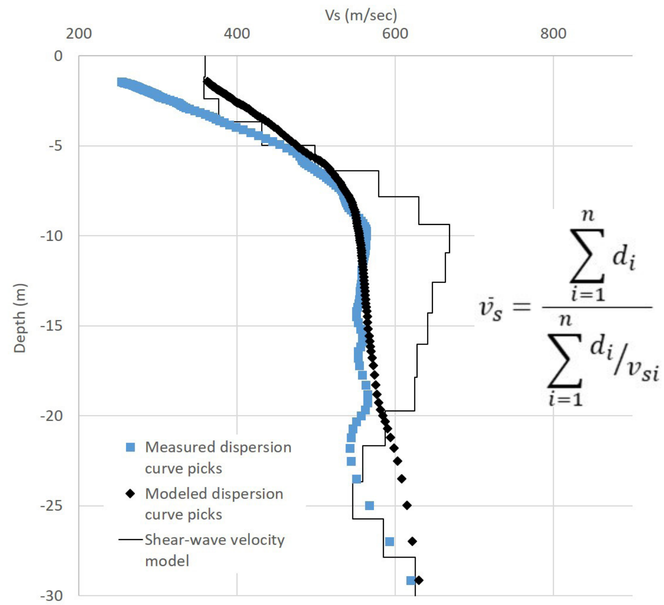
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do indicate some variability and neither adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. The combined dispersion curves correlate well with a similar overall trend, so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL AND GEOLOGY

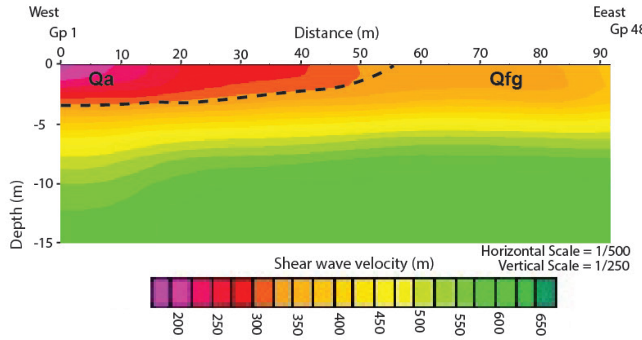
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model was constructed with an RMSE of 9.3 percent. The dispersion curves were inverted, resulting in a model with an RMSE of 5.1 percent. The final velocity model shows a steady increase in velocity with depth down to approximately 12 m (39 ft), then a slight velocity reversal down to 26 m (82 ft), and steady increasing velocity below. Our best estimate for Vs30 is 525 m/s, which places the site in the middle of site class C. The velocity models from both ends of the array show a similar velocity structure and both are within the middle of the C class, so this site can be confidently classified. This is different from the predicted site class of D.

GEOLOGY

The 1:100,000-scale geologic map shows that the school building is sitting on Pleistocene flood deposits (unit Qfg) which have a predicted site class of D. The geophone array is partially sitting on unit Qfg and partially on Quaternary alluvium (unit Qa) which is mapped as a site class D-E. Laterally heterogeneous velocity is confirmed in the upper 3 m (10 ft) in the 2D MASW and P-wave refraction results, with lower velocities close to geophone 1. Nearby boreholes show that the unit Qa varies in thickness from <1 m (3 ft) to 33 m (110 ft) and is underlain by unit Qfg. The observed lateral variation could be due to a contact between unit Qa and unit Qfg, which could explain the difference between the measured and predicted site class. We therefore based the final velocity model from the shots near geophone 48, which are the most representative of the school.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.



Pseudo 2D MASW shear-wave velocity model with locations for geophones 1 and 48. Interpreted geologic units are annotated with a dashed line showing the approximate contact.

QUESTIONS? Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

HIGHLINE WOODSIDE SCHOOL (CHOICE ACADEMY)

HIGHLINE SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

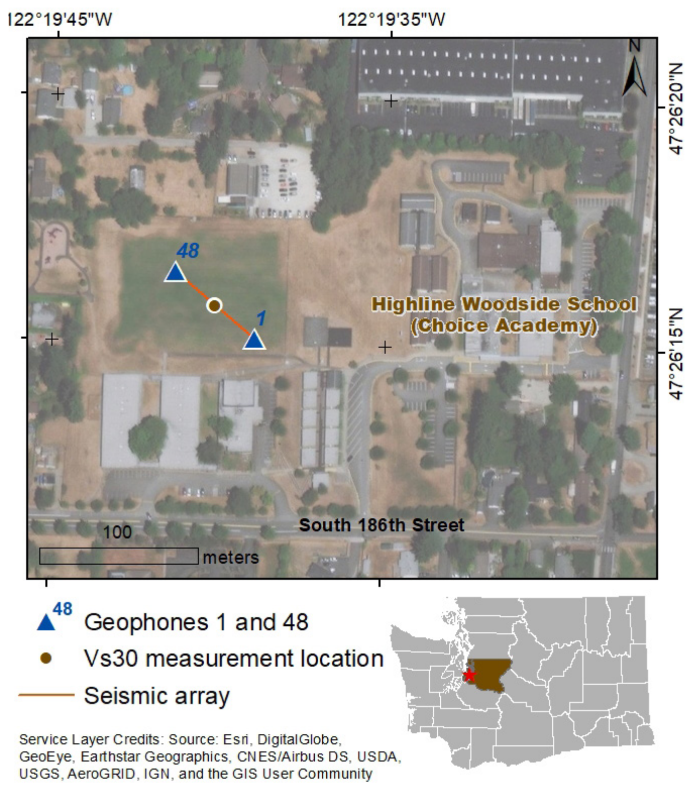
On December 4, 2018, a team from the Washington Geological Survey conducted a seismic survey at Highline Woodside School (Choice Academy). We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 231-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Violent

TECHNICAL OVERVIEW OF RESULTS

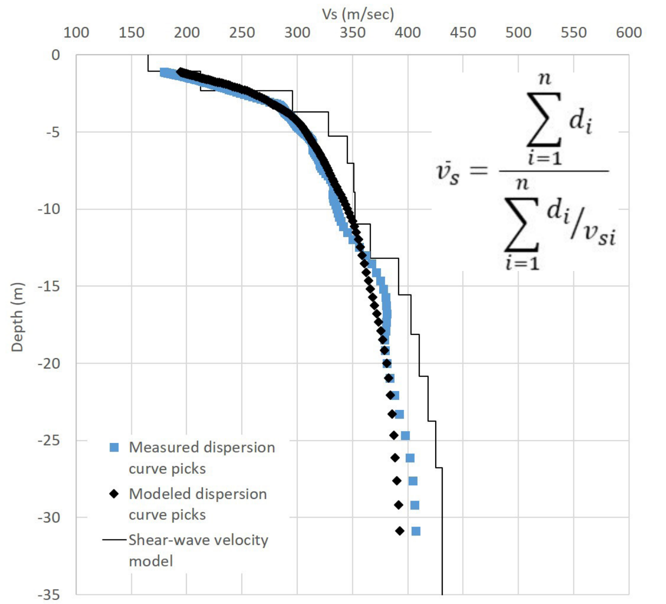
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 6.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.5 percent. The final velocity model shows generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft). Our best Vs30 measurement is 355 m/s, which places the site near the C-D boundary, closer to the very high end of the D class. The predicted site class is C or D, which correlates with the measured D site class.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

HOQUIAM HIGH SCHOOL

HOQUIAM SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

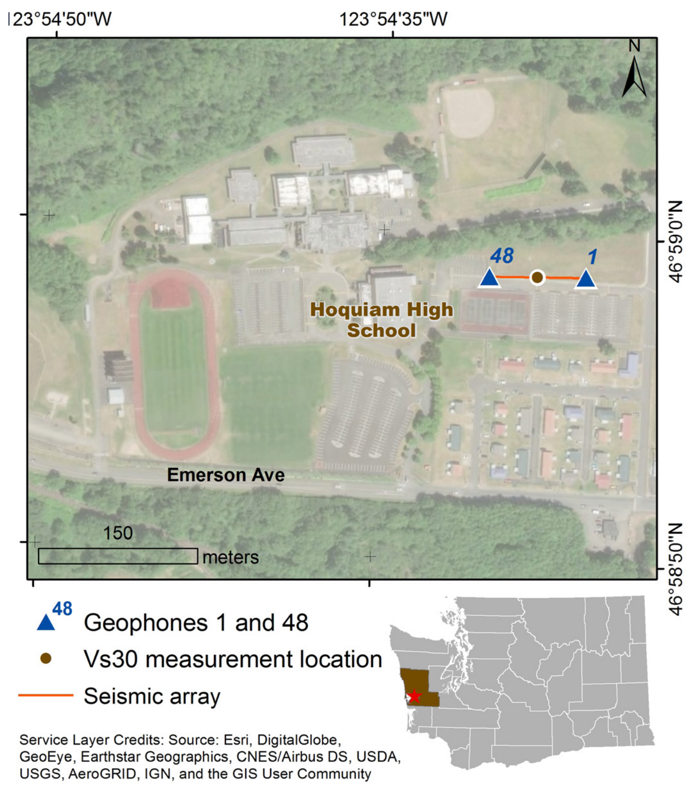
On July 24, 2018, a team from the Washington Geological Survey conducted a seismic survey at Hoquiam High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Landslide
Hazard present

TECHNICAL OVERVIEW OF RESULTS

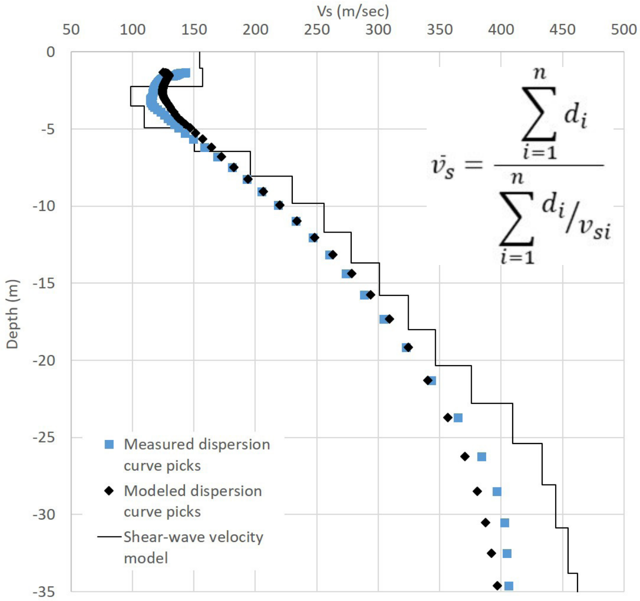
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse and forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 12.3 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 5.2 percent. The final velocity model shows a small velocity reversal in the top layers of the model, then steadily increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft). Our best Vs30 measurement is 242 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

HULAN L. WHITSON ELEMENTARY SCHOOL

WHITE SALMON SCHOOL DISTRICT, KLICKITAT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

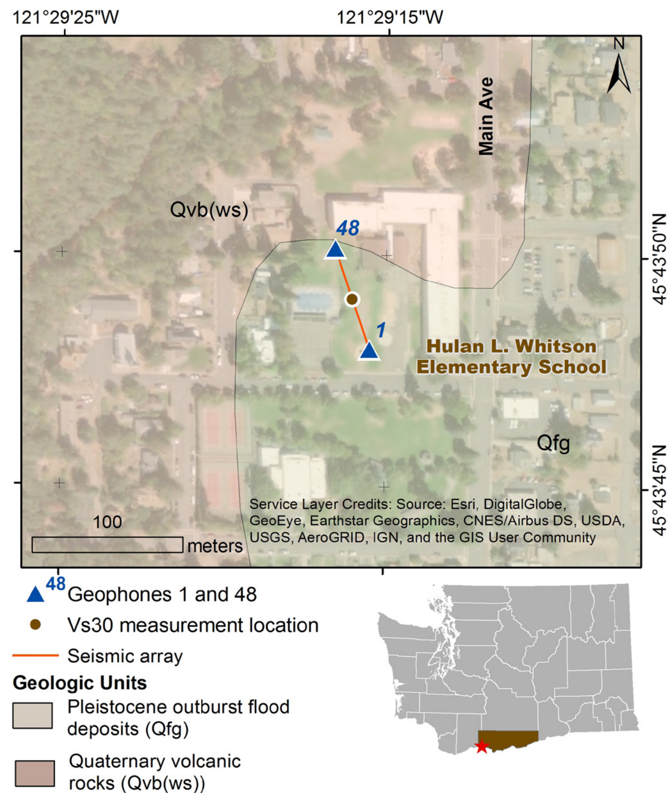
On August 23, 2018, a team from the Washington Geological Survey conducted a seismic survey at Hulan L. Whitson Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 231-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted B site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting partially on outburst flood deposits (unit Qfg) consisting of gravel and partially on basalt flows (unit Qvb(ws)).

Liquefaction
Very low/bedrock

Ground Shaking
Very strong

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

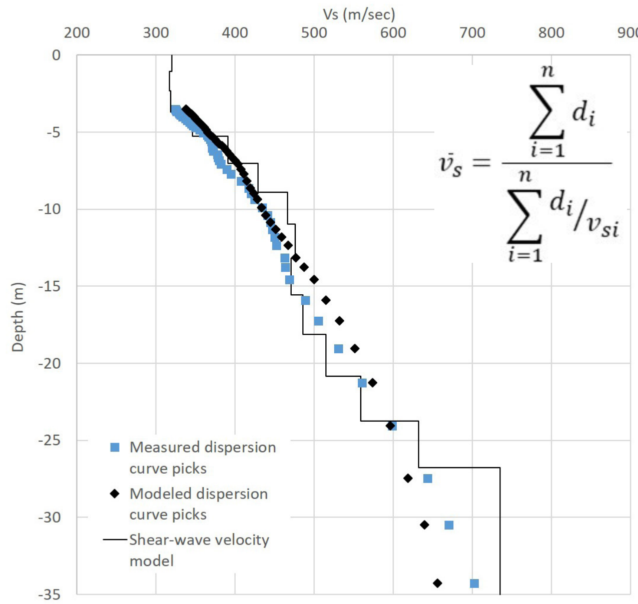
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is of decent quality. However, it is used only as check for consistency in the analysis because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the forward MASW (offend geophone 1). The initial model has an RMSE of 9.6 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 3.8 percent. The upper 4 m (13 ft) of the final model is unconstrained but shows constant velocity. Below 4 m (13 ft) depth the velocity model shows a steady increase in velocity down to 30 m (100 ft). Our best Vs30 measurement is 464 m/s, which places the site in the C class.

GEOLOGY

The 1:100,000-scale geologic map shows the school building is sitting partially on outburst flood gravel deposits (unit Qfg) and partially on Quaternary White Salmon basalt (unit Qvb(ws)). The predicted site class for unit Qfg is C, while the predicted site class for unit Qvb(ws) is B. Our array was placed entirely within unit Qfg, so our measured site class should be considered best representative of unit Qfg. Although the model shows velocity structure that could indicate rock at a depth around 30 m (100 ft), neither the existence or thickness of such units across the campus can be verified through ground truth. Therefore, taking a conservative approach to assigning the site class, we apply the measured site class of C across the school campus and the school buildings.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

ILWACO HIGH SCHOOL AND ILWACO HILLTOP MIDDLE SCHOOL

OCEAN BEACH SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

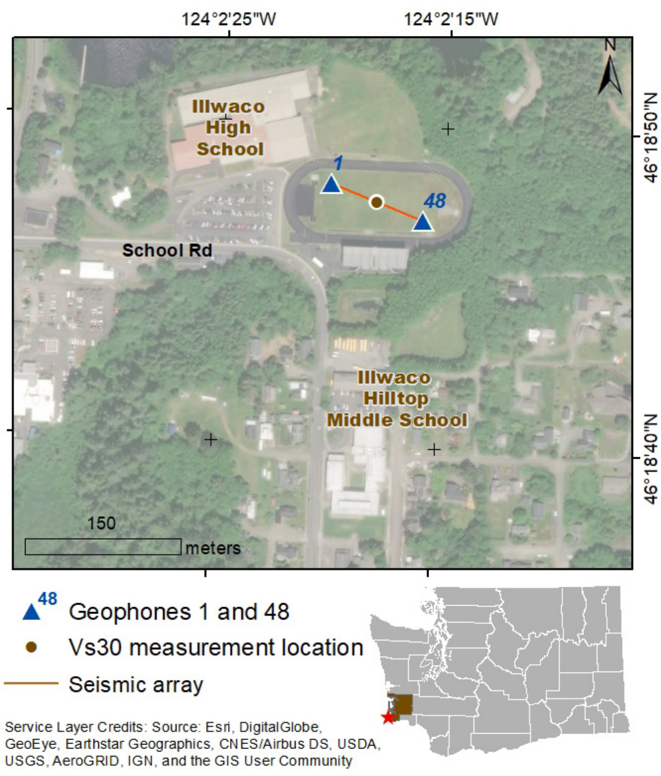
On June 18, 2018, a team from the Washington Geological Survey conducted a seismic survey at Ilwaco High and Hilltop Middle schools. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted B site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on marine sedimentary rocks.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

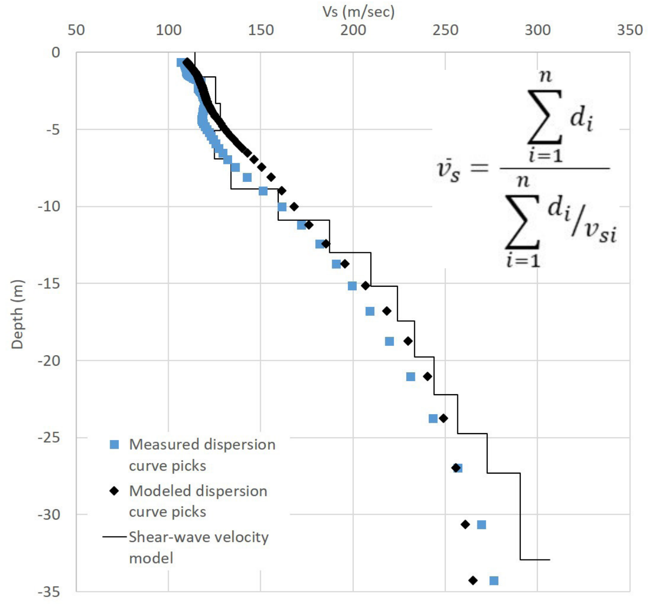
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality and the fundamental mode can also be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 6.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.5 percent. The final velocity model shows generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft) depth. Our best Vs30 measurement is 184 m/s, which places the site near the D to E boundary, at the very low end of the D class. The measured site class is significantly different than the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map shows that both school campuses and the geophone array are sitting on the Shoalwater Bay siltstone (unit Em(2sb)) which has a predicted site class of B. Mapped directly to the east of the schools is Quaternary alluvium (unit Qa) which has a predicted site class of D to E. The shear wave velocity profiles show that the measured site class is in the D range, so the location of the geologic contact between the siltstone and alluvium is inaccurate, explaining the discrepancy between the predicted and measured site class. However, this Vs30 measurement is intended to apply to both Ilwaco High school and Hilltop Middle school, which are approximately 300 m (1000 ft) apart. The Vs30 measurement was made at the lwaco High School playing field, located approximately 200 m (656 ft) away from Ilwaco Middle school. Therefore, horizontal over vertical (H/V) measurements were gathered at both schools as a check for lateral heterogeneity. All H/V measurements show consistent velocity structure, which would indicate that stratigraphy does not change significantly between the school campuses. We therefore confidently assign site class D to both Ilwaco High School and Hilltop Middle School.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

INDEX ELEMENTARY SCHOOL

FERNDALE SCHOOL DISTRICT, WHATCOM COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

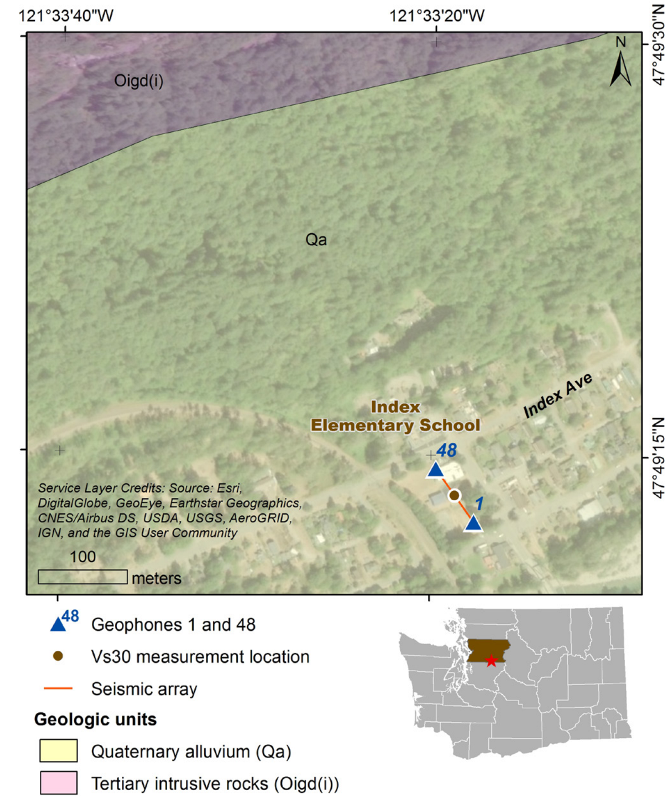
On July 31, 2018, a team from the Washington Geological Survey conducted a seismic survey at Index Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on alluvium (river sediments), a combination of silt, sand, and gravel deposited in streambeds, shown as unit Qa on the map.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

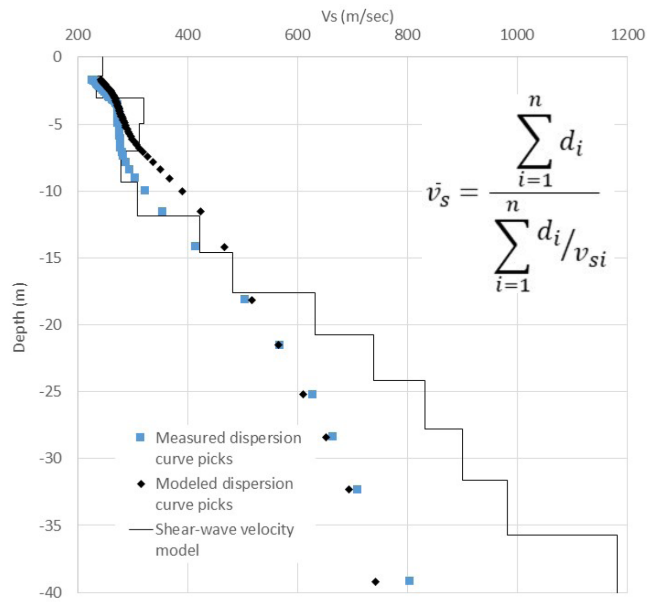
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW forward direction (located off end geophone 1). The initial model has an RMSE of 11.4 percent. The inversion was carried out for eleven iterations and resulted in a final model with an RMSE of 5.7 percent. The final velocity model shows generally constant velocity in the upper 10 m (33 ft) with a slight velocity reversal around 4 m (13 ft). Below 10 m (33 ft) the model shows generally steady increasing velocity past 30 m (100 ft) depth. Our best Vs30 measurement is 419 m/s, which places the site in the C class. This is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000-scale geologic map shows the school building and the geophone array are sitting on Quaternary alluvial river sediments, which have a predicted site class of D to E. Mapped directly to the north and south of the school are outcrops of the Index Batholith granodiorite (unit Oigd(i)). The velocity model suggests that the Quaternary alluvium extends down to approximately 15 m (49 ft) where there is a contact with a higher-velocity material, likely granodiorite. A contact between the alluvium and the granodiorite would explain the discrepancy between the measured and predicted site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

LA CONNER HIGH SCHOOL AND MIDDLE SCHOOL

LA CONNER SCHOOL DISTRICT, SKAGIT COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

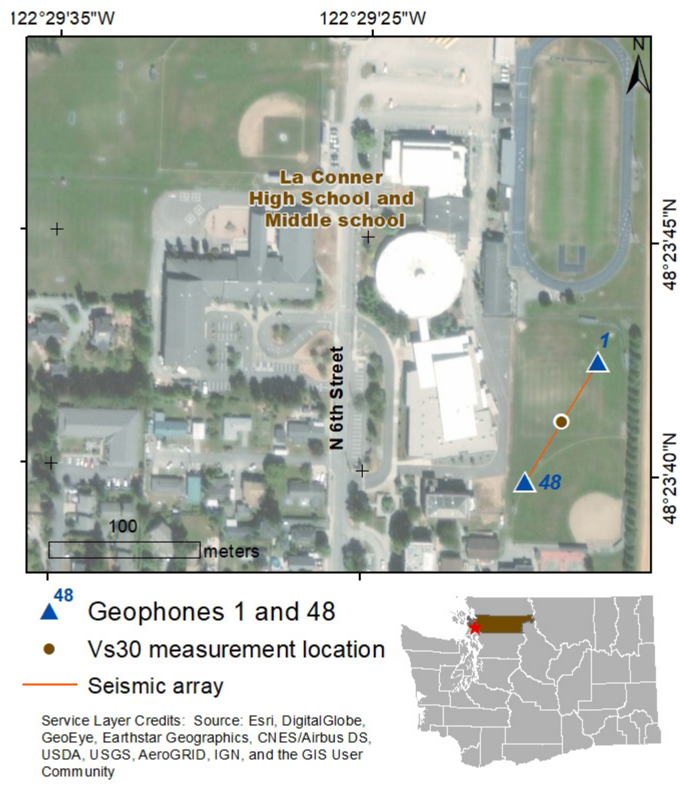
On July 11, 2018, a team from the Washington Geological Survey conducted a seismic survey at the La Conner High School and Middle School campus. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on predominantly fine sand, silt, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

TECHNICAL OVERVIEW OF RESULTS

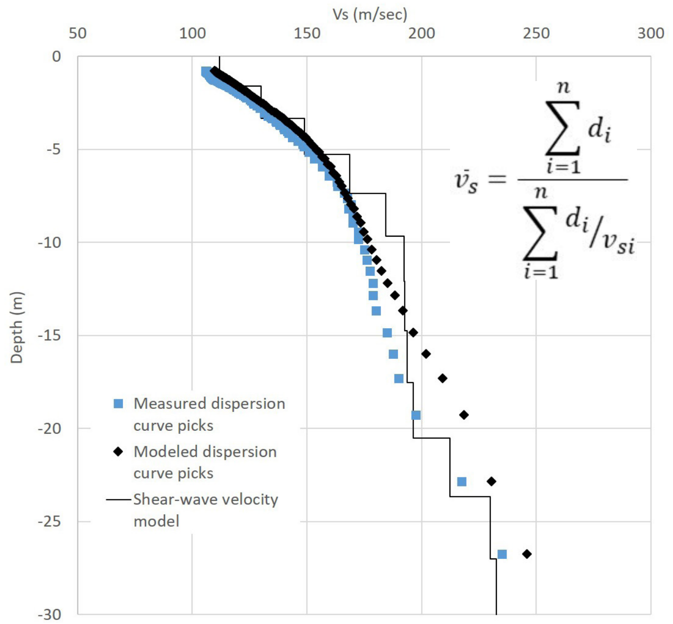
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 8.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.3 percent. The final velocity model shows a generally steady increase in velocity with depth from 1 to 17 m (3 to 56 ft), a constant velocity down to 20 m (66 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 184 m/s, which places the site in the low end of the D class. The predicted site class is either E or D, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

LACAMAS HEIGHTS ELEMENTARY SCHOOL

LACAMAS SCHOOL DISTRICT, CLARK COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

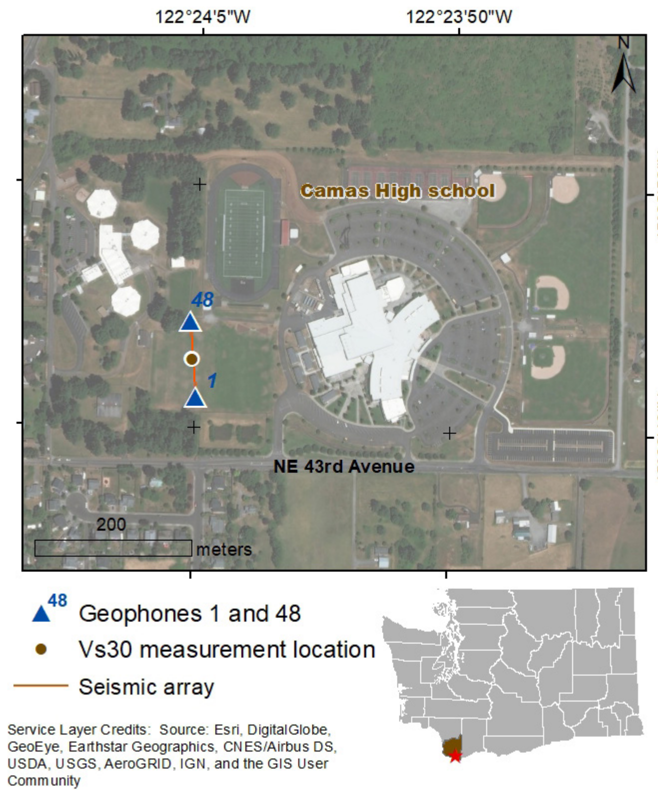
On September 10, 2018, a team from the Washington Geological Survey conducted a seismic survey at Lacamas Heights Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on weathered conglomerate that is variable in terms of sorting and cementation.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Landslide
Hazard present

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

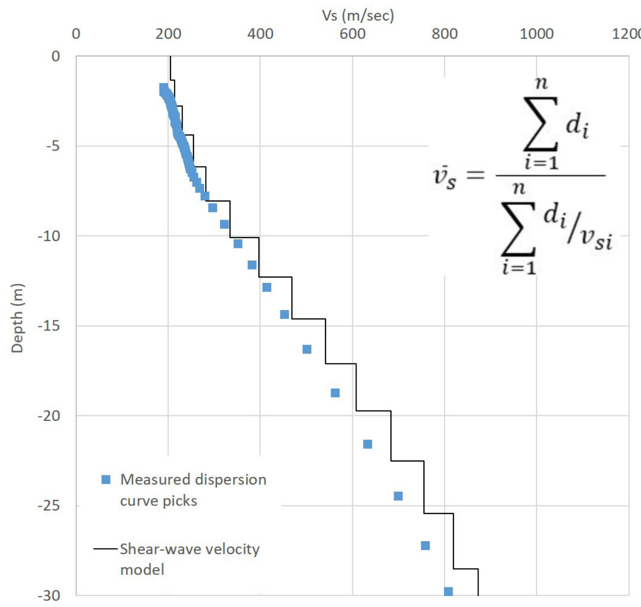
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality, with a fundamental mode that can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The combined analysis did not converge to below 5 percent RMSE without forcing artifically high velocities in the upper 5 m (16 ft). The resulting best estimate for Vs30 is 415 m/s and is based on the initial model. Despite the lack of convergence, all intial models resulted in a Vs30 in the middle of the C class, so we are confident in the measured site class of C. The predicted site class is D or C, which correlates with the measured C site class.

GEOLOGY

The 1:24,000-scale geologic map shows that both the school and geophone array are mapped to be on a Pleistocene to Pliocene conglomerate (unit QTc) that is up to 90 m (295 ft) thick. Mapped just south of the campus are Tertiary volcanic rocks with a mapped site class of B. However, the velocity model shows a fairly steady increase in velocity with depth from 10 m (33 ft) to 30 m (100 ft), which suggests the conglomerate unit extends to at least 30 m (100 ft) below the array.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

LAKE ROOSEVELT K-12 SCHOOL

GRAND COULEE DAM SCHOOL DISTRICT, OKANOGAN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

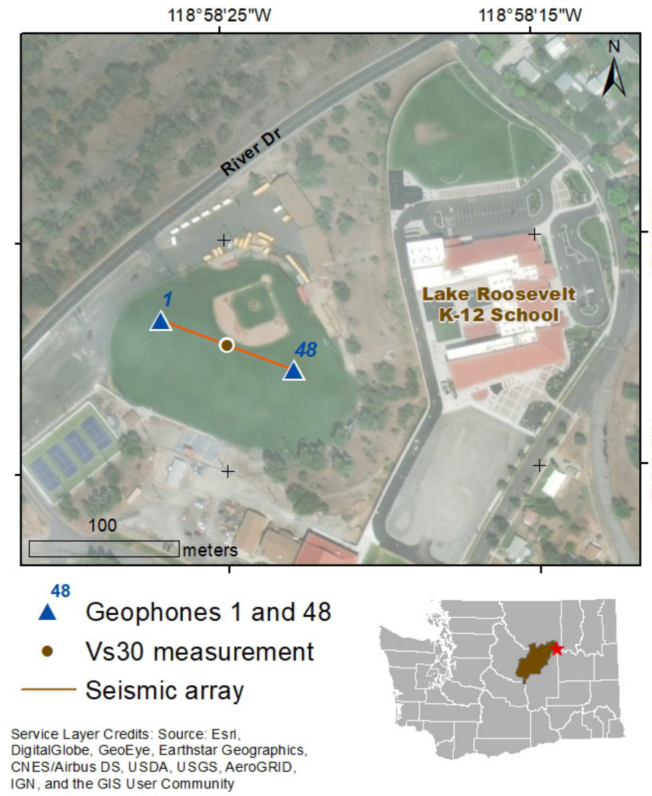
On May 17, 2017, a team from the Washington Geological Survey conducted a seismic survey at Lake Roosevelt K-12 school for an earlier project. The team measured measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- ☐ The school is built on stiff soil, which would amplify ground shaking relative to rock.
- ☐ Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene outburst flood deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Very Strong

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

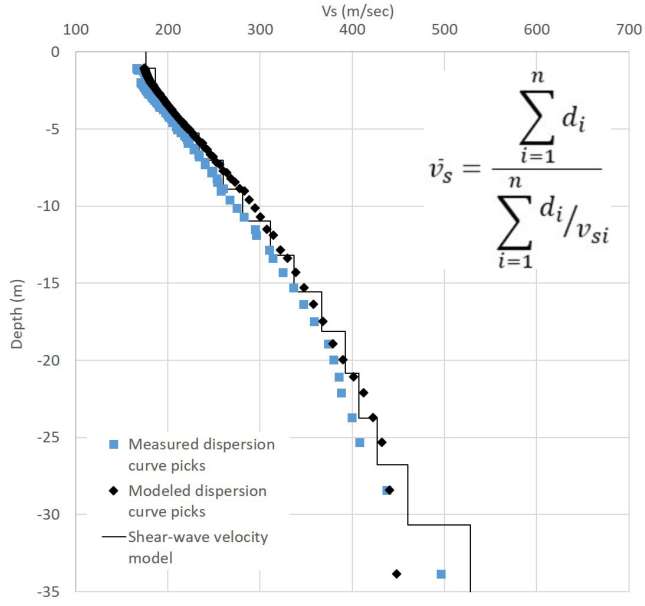
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 9.3 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.9 percent. The velocity profile shows steadily increasing velocity from 2 m (7 ft) down to 30 m (100 ft) depth. Our best Vs30 measurement is 304 m/s, which places the site in the D class. The measured site class is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

LIBBY CENTER SCHOOL

SPOKANE SCHOOL DISTRICT, SPOKANE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

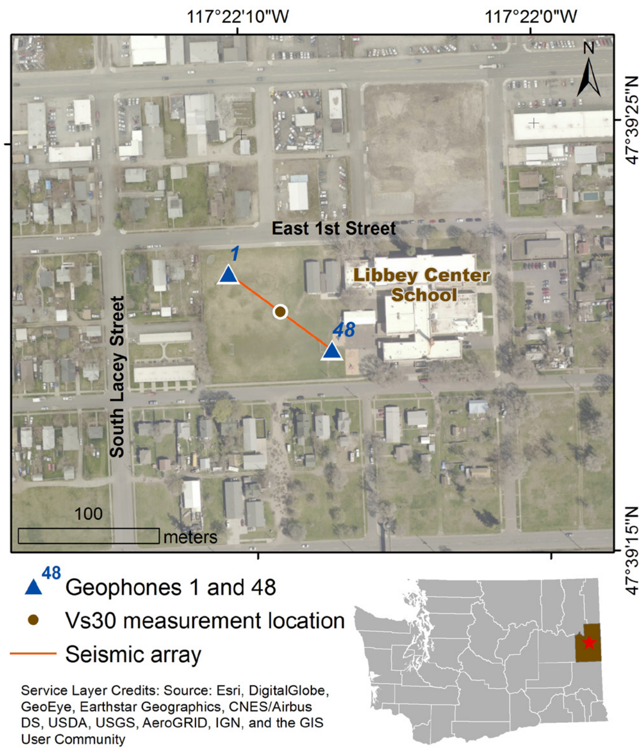
On July 17, 2018, a team from the Washington Geological Survey conducted a seismic survey at Libby Center school. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock and very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial flood-channel deposits, consisting predominantly of gravel, with sand and cobbles.

GEOLOGIC HAZARD AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

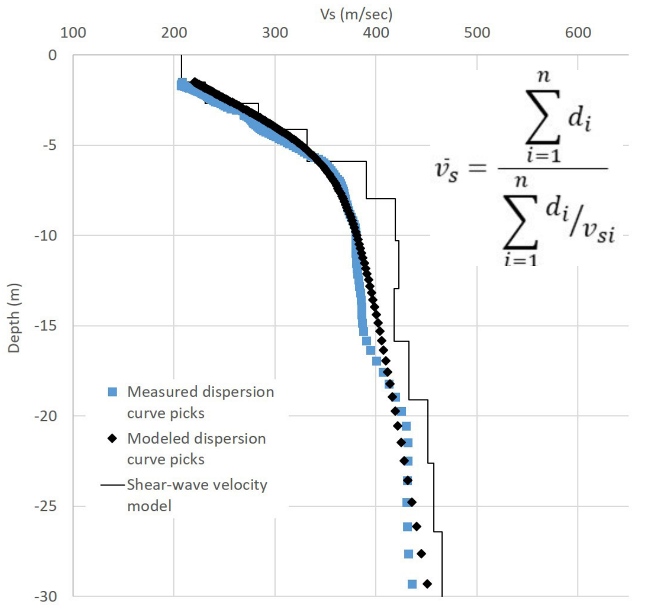
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be identified. Overall, the MASW and MAM dispersion curves agree well above 28 Hz frequency so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The combined dispersion curves were averaged and then smoothed before the initial model was constructed with an RMSE of 7.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.2 percent. The final velocity model shows steadily increasing velocity to a depth of 8 m (26 ft) and fairly constant velocity from 8 m (26 ft) to approximately 15 m (49 ft). Below 15 m (49 ft), the model shows slightly increasing velocity to 30 m (100 ft). Our best Vs30 measurement is 385 m/s which places the site on the low side of the site class C. The Vs30 values derived from the combined MASW and MAM measurements are all within the C class, so the site can be confidently classified. This Vs30 measurement and site class is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

LIBERTY ELEMENTARY SCHOOL AND MARYSVILLE MIDDLE SCHOOL

MARYSVILLE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

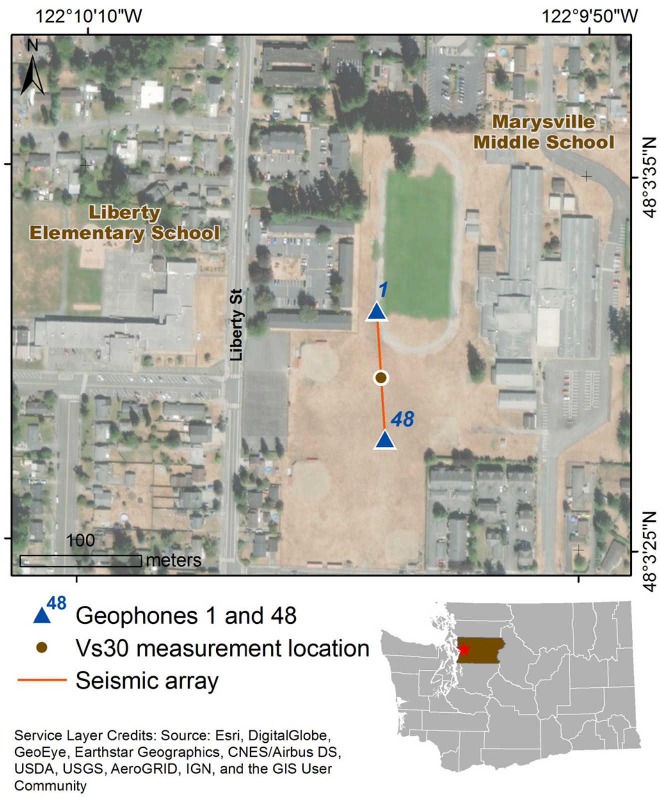
On November 8, 2018, a team from the Washington Geological Survey conducted a seismic survey at Liberty Elementary School and Marysville Middle School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on outwash sand deposited by glaciation.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate hazard

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

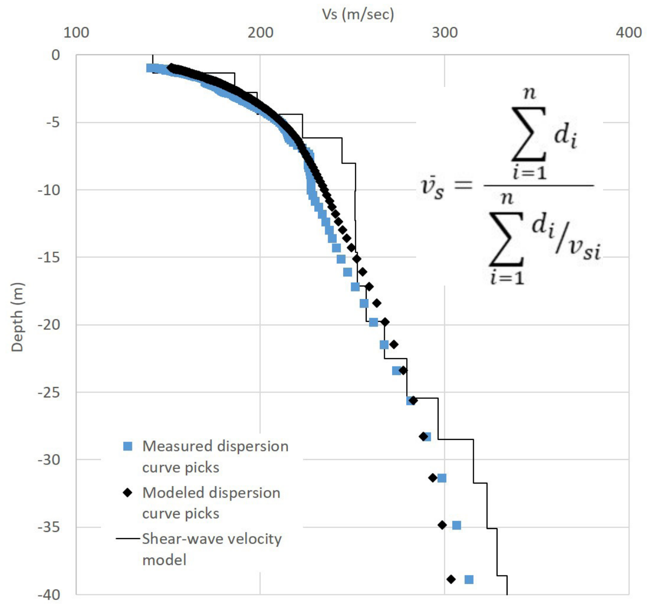
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 6.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.6 percent. The final velocity model shows a general increase in velocity down past 30 m (100 ft). Our best Vs30 measurement is 245 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

LIBERTY MIDDLE SCHOOL

LACAMAS SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

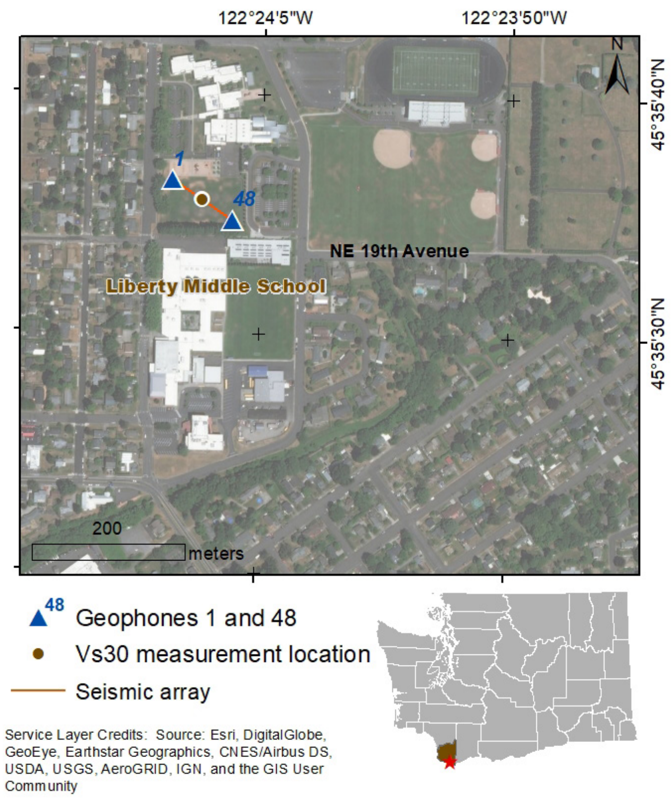
On August 22, 2018, a team from the Washington Geological Survey conducted a seismic survey at Liberty Middle School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on sandstone and weathered conglomerate that varies in sorting and cementation.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

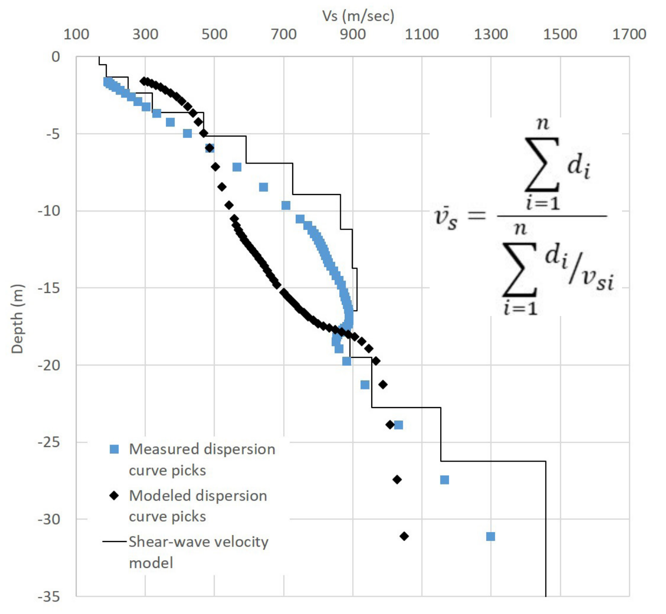
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of low quality but the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of low quality, but the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 27.4 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 9.8 percent. The final velocity model shows a steady increase in velocity with depth from 3 to 12 m (10 to 39 ft), then a slight velocity reversal around 17 m (56 ft) and increasing velocity below. Although the final model has a high RMSE, the inversion does not force an unrealistic velocity structure, so we are confident in the final model and the measured site class of C. Our best Vs30 measurement is 667 m/s, which places the site in the middle of the C class. The predicted site class is D or C, which correlates with the measured C site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

LINCOLN ELEMENTARY SCHOOL

MOUNT VERNON SCHOOL DISTRICT, SKAGIT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

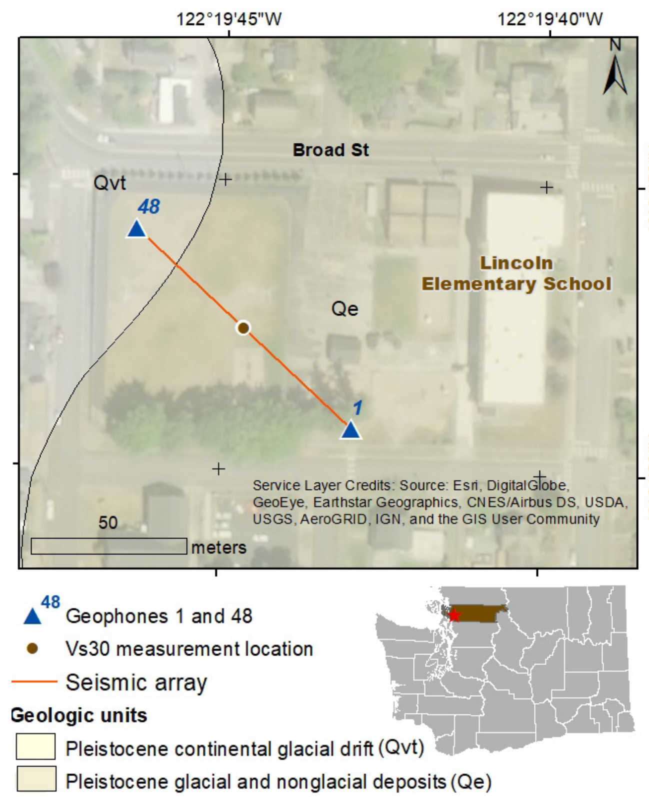
On July 3, 2018, a team from the Washington Geological Survey conducted a seismic survey at Lincoln Elementary school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock
- This site class differs from the predicted D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene glacial and nonglacial deposits (Qe) consisting of silt, sand, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

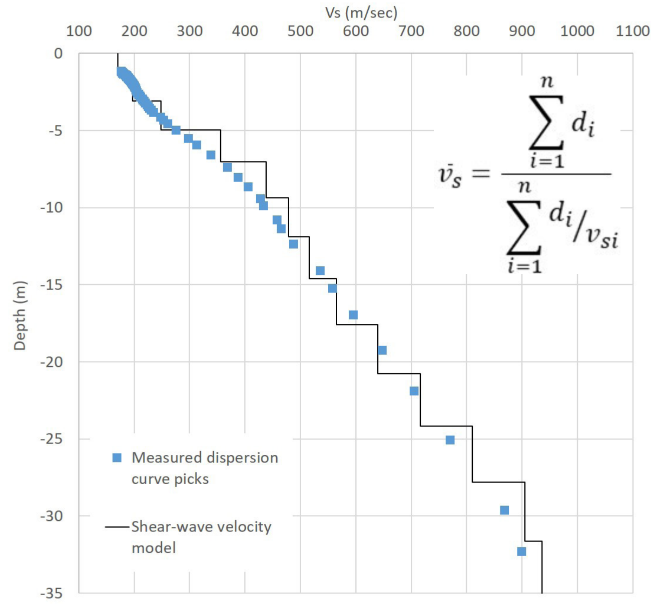
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as a check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

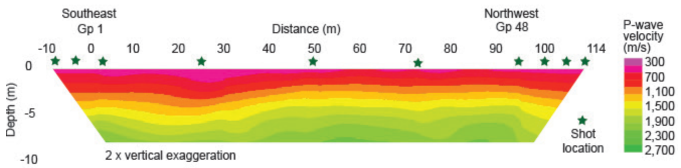
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 12.3 percent. The combined analysis did converge to a high RMSE. The resulting best estimate for Vs30 is 463 m/s and is based on the initial model, which places the site in the C class. The velocity profile shows steadily increasing velocity from 2 m (7 ft) down to 30 m (100 ft) depth. Although the inverted model did not converge to below 5 percent RMSE, all initial and final models were in the middle of the C class, so the site can be confidently classified. The site was predicted to have a site class of D for the eastern portion of the campus and site class D-E on the western portion, which differ from the measured site class of C.

GEOLOGY

The 1:24,000-scale geologic map shows the school building is sitting on Pleistocene glacial and nonglacial deposits (unit Qe). The geophone array crosses a mapped contact at around geophone 38, where unit Qe is mapped to the east and Pleistocene continental glacial drift (unit Qvt) is mapped to the west. Unit Qe is described as overlying recessional outwash (unit Qvr) or till (unit Qvt) in most places, with thicknesses that range from 8 m (26 ft) to more than 15 m (49 ft) in the Mount Vernon area. However, the final model does not show velocity structure that would indicate a contact between units Qe and Qvt at depth, nor is any significant change in lithology observed in nearby boreholes. This suggests that the difference between the measured and predicted site class is due to local variation in the unit Qe. Due to the proximity of the array to the building and a lack of evidence for significant heterogeneous velocity structure in the 2D P-wave refraction or 2D MASW results, we deem the assignment of site class C as appropriate.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.



2D refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth across the geophone array from the farthest off end shot from both ends. For this model, velocity is fairly consistent, with no significant observed heterogeneity.

LINCOLN ELEMENTARY SCHOOL

HOQUIAM SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

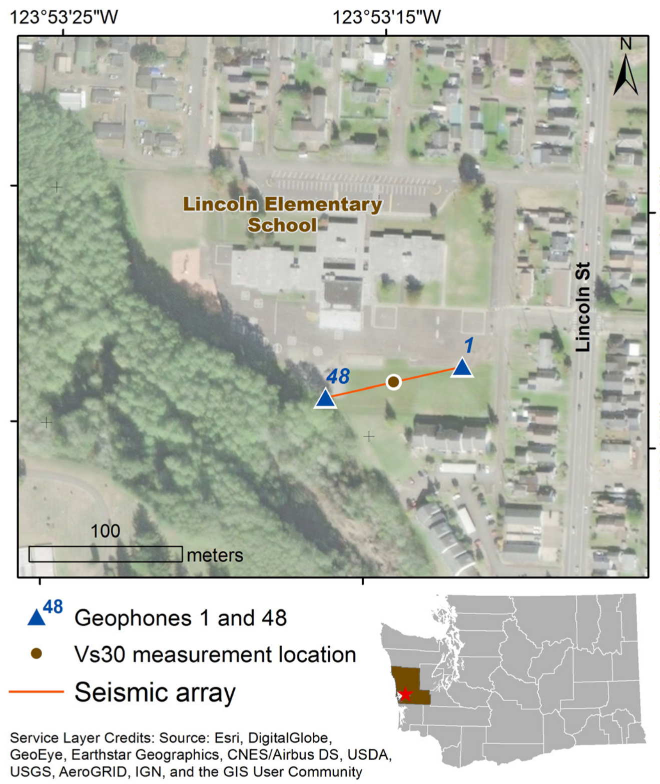
On July 19, 2018, a team from the Washington Geological Survey conducted a seismic survey at Lincoln Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

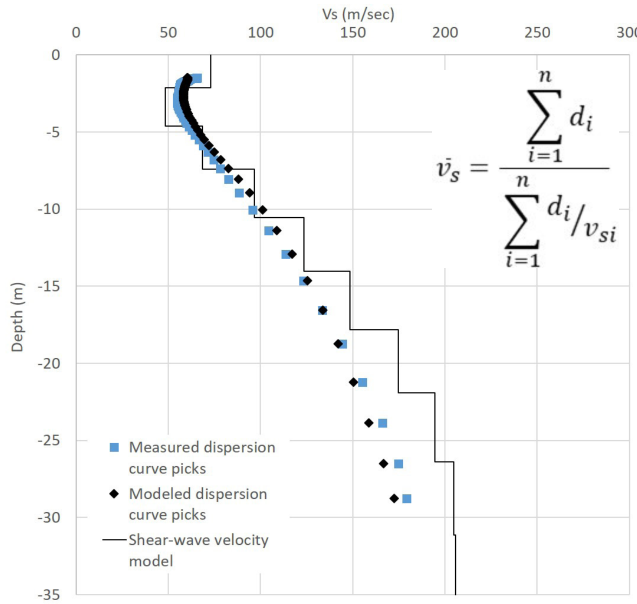
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curve contains higher modes but the fundamental mode can be still picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 10.4 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 4.6 percent. The final velocity model shows a small velocity reversal in the top layers of the model, then generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft) depth. Our best Vs30 measurement is 111 m/s, which places the site in the E class. The predicted site class is D or E, which correlates with the measured E site class.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

LONG BEACH ELEMENTARY SCHOOL

OCEAN BEACH SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

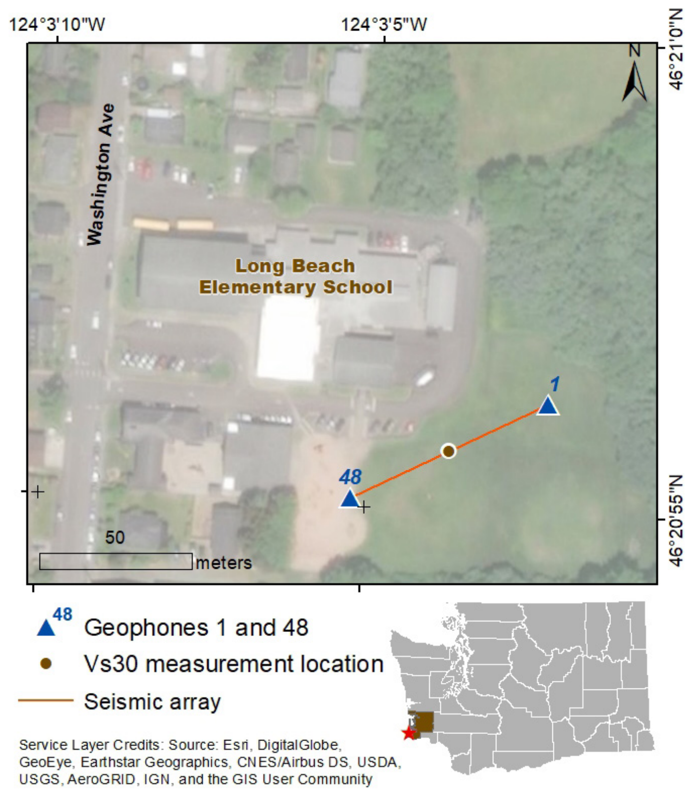
On August 2, 2018, a team from the Washington Geological Survey conducted a seismic survey at Long Beach Elementary school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 231-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS: D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on beach deposits of fine to coarse sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

TECHNICAL OVERVIEW OF RESULTS

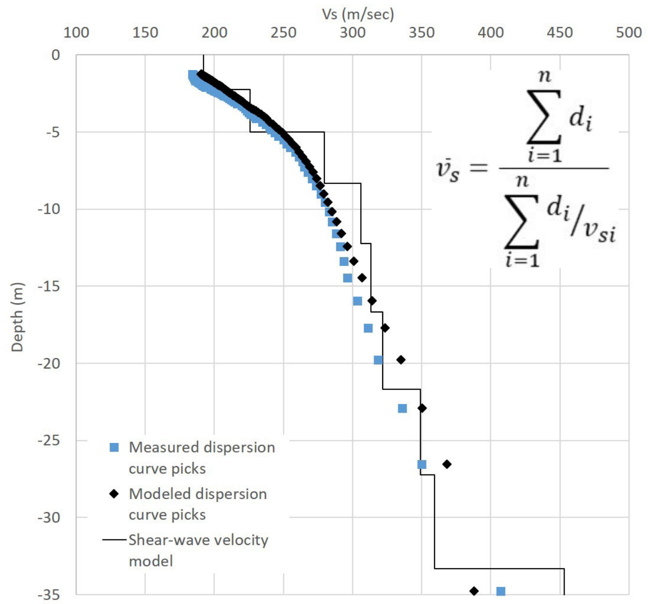
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curve. The inital model has an RMSE of 9.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.8 percent. The final velocity model shows generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft). Our best Vs30 measurement is 212 m/s, which places the site in the D class. The measured site class is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

MABTON JUNIOR—SENIOR HIGH SCHOOL

MABTON SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

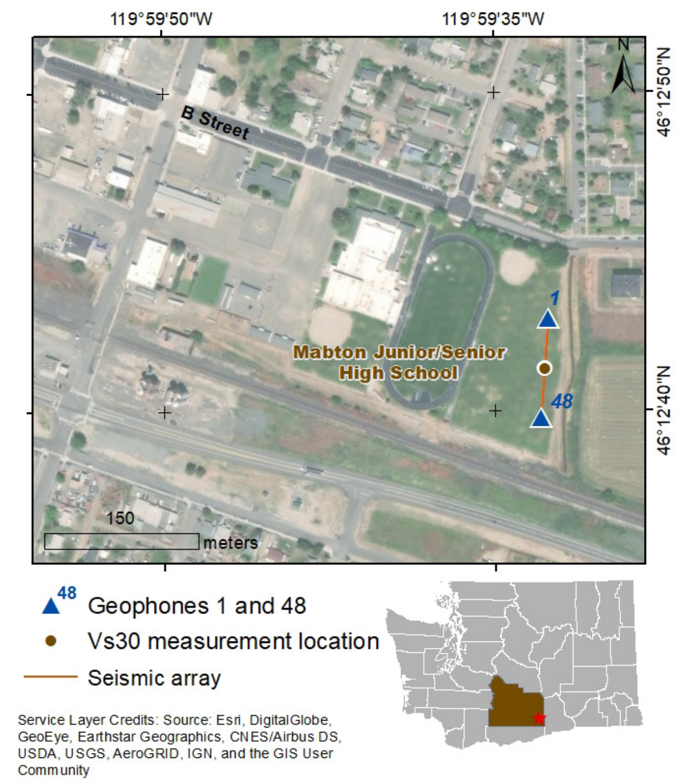
On August 7, 2018, a team from the Washington Geological Survey conducted a seismic survey at Mabton Junior—Senior High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on eolian deposits, loess.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Very Strong

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

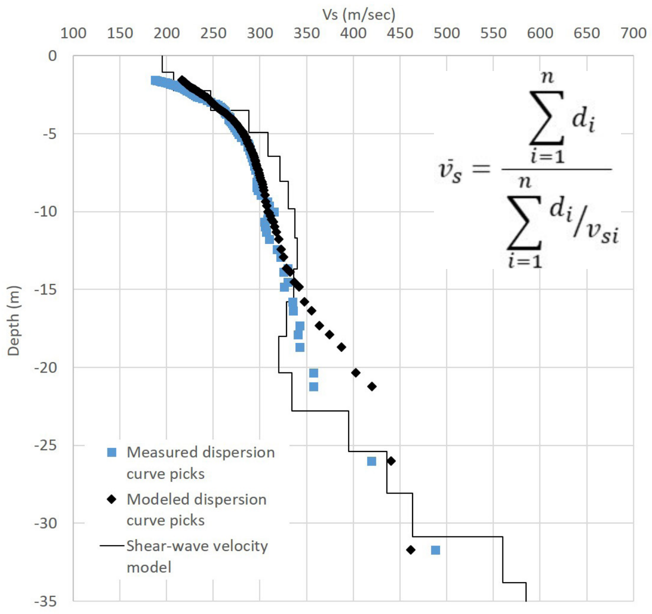
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are good quality and the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is also of good quality, with a fundamental mode that can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 7.6 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 3.4 percent. The final velocity model shows a generally steady increase in velocity from 1 m (3 ft) down to 5 m (16 ft) depth, constant velocity from 15 m (49 ft) to 25 m (82 ft), and steadily increasing velocity below. Our best Vs30 measurement is 326 m/s, which places the site in the D class. This Vs30 measurement and site class is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

MANSFIELD ELEMENTARY AND HIGH SCHOOL

MANSFIELD SCHOOL DISTRICT, DOUGLAS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

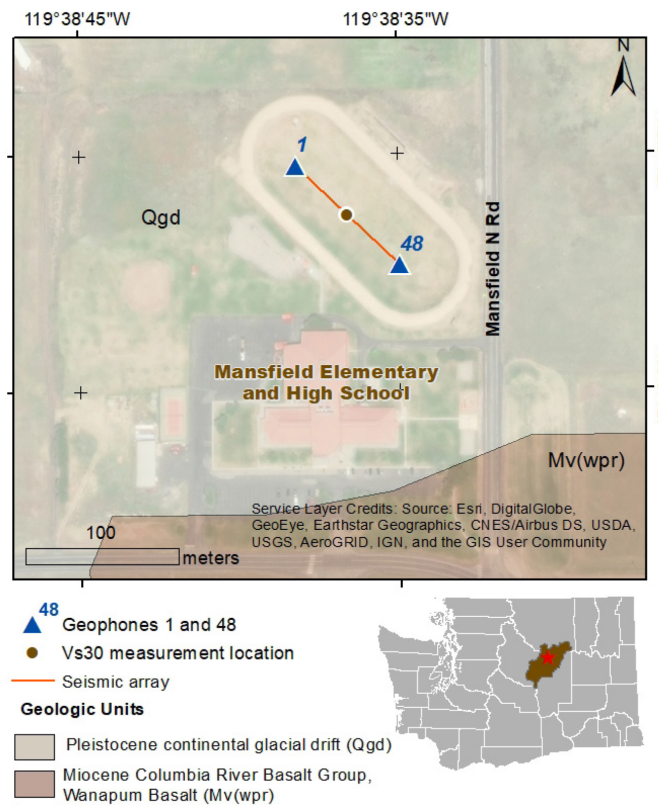
On June 26, 2018, a team from the Washington Geological Survey conducted a seismic survey at Mansfield Elementary and High school. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on rock.
- This site class differs from the predicted C or D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS: B



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, unit Qgd. An exposure of Wanapum basalt, unit Mv(wpr) is mapped to the south.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low hazard

Ground Shaking
Very strong

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

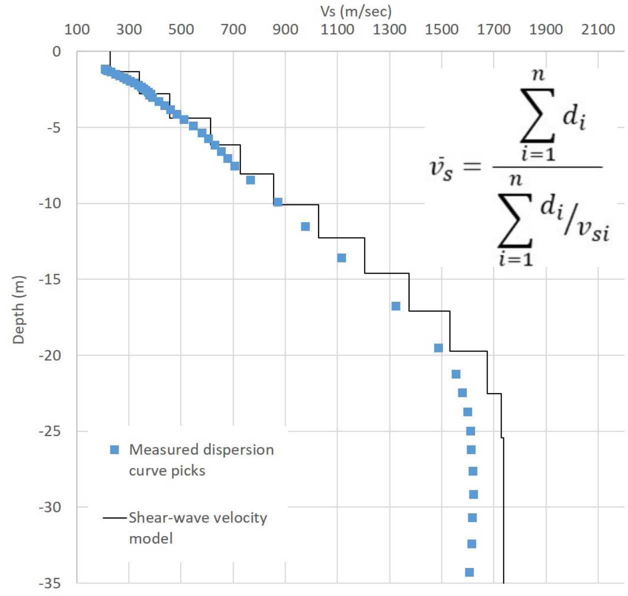
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are dominated by higher modes but the fundamental mode can be picked. The MASW dispersion curves adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of poor quality and is not used in the analysis.

VELOCITY MODEL

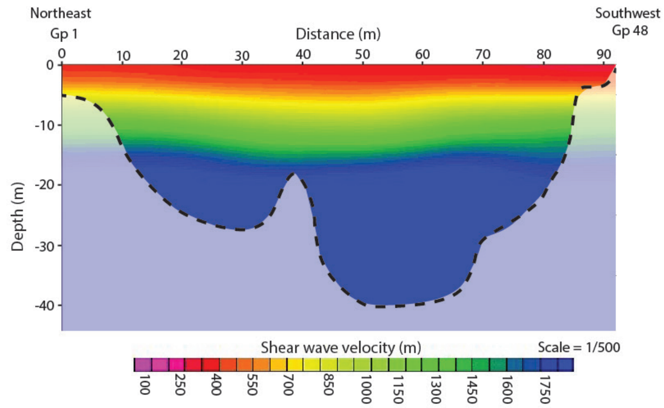
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves from the forward and reverse MASW (off end geophone 1 and geophone 48). The combined dispersion curves were averaged and smoothed before the initial model was constructed. The combined analysis did not converge to below 5 percent RMSE. Our best estimate for Vs30 is at 864 m/s and is based on the initial model. The final velocity model shows a steady increase in velocity with depth down to approximately 20 m (66 ft) and continuous velocity below 20 m (66 ft). Despite the lack of convergence, all intial models resulted in a Vs30 in the middle of the B class, so we are confident in the measured site class of B. This is significantly different than the predicted site class of C or D.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school building and the geophone array are sitting on Pleistocene continental glacial drift, unit Qgd, which has a predicted site class C to D. Mapped directly to the south of the building is the Priest Rapids Member, Wanapum Basalt, unit Mv(wpr), which has a predicted site class of B. The P-wave tomographic model suggests that there is a hard contact between a slow material and a fast material no deeper than 8 m (26 ft). The 2D MASW shows higher velocity at similar depths. This would be consistent with a Quaternary alluvium layer overlaying an unweathered basalt flow, which suggests that the difference between the measured and predicted site class is due to change in subsurface materials. Thus, due to a lack of evidence for significant heterogeneous velocity structure along the array, we assign site class B to the campus. However, we recommend further geotechnical investigation to verify the thickness of unit Qgd at the site.



Final inverted velocity model with measured dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.



Pseudo 2D MASW shear-wave velocity model with locations for Geophones 1 and 48. Dashed line approximately delineates the model's reliability in the vertical extent. Portions of the model at depths below the dashed line (shaded area) are not constrained.

MAPLE GROVE K–8 AND RIVER HOMELINK SCHOOLS

BATTLE GROUND SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

On June 26, 2018, a team from the Washington Geological Survey conducted a seismic survey at the Maple Grove and River Homelink campus. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted C site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**

Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on medium to fine sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

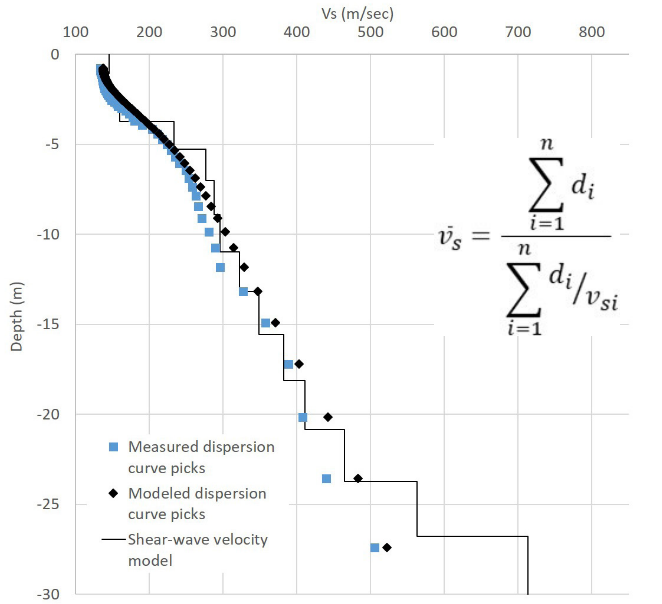
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are generally of good quality and sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of poor quailty, so the only MASW dispersion curves are used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1). The initial model has an RMSE of 10.8 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.0 percent. The final velocity model shows a generally steady increase in velocity with depth from 2 to 30 m (7 to 100 ft). Our best Vs30 measurement is 320 m/s, which places the site in the high end of the D class. The measured site class is different than the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school site and the geophone array are sitting on Pleistocene outburst flood deposits (unit Qfs) which has a predicted site class C in this area. However, the more detailed 1:24,000 geologic maps show that the site and geophone array are actually on fine-grained catastrophic flood deposits outburst deposits (unit Qf), which are described as medium to fine sand in the area. These finer-grained materials would likely lead to lower velocities. Therefore, a mis-mapping in surficial geology between unit Qfs and lower velocity unit Qf could help explain the discrepancy between the predicted and measured site classes at the school campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

MAPLEWOOD ELEMENTARY SCHOOL

PUYALLUP SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

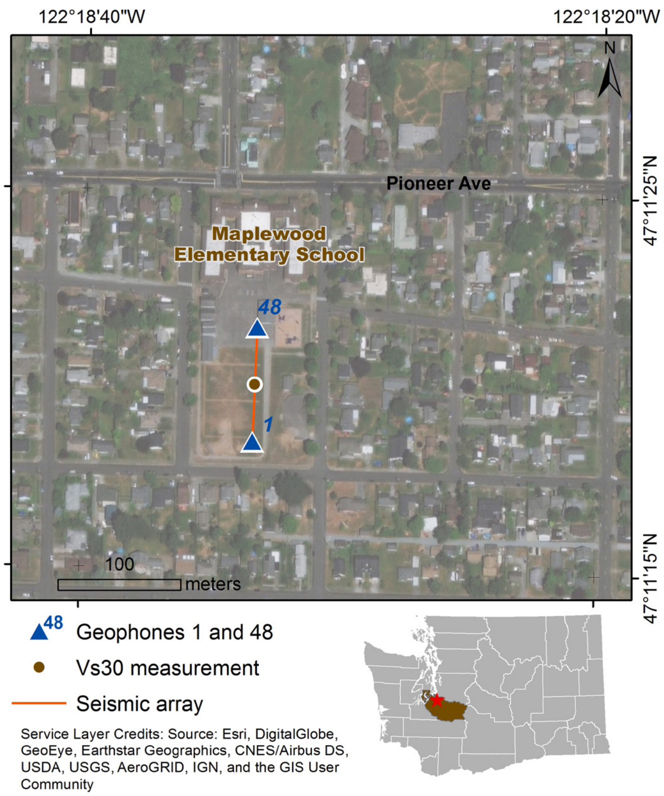
On August 8, 2018, a team from the Washington Geological Survey conducted a seismic survey at Maplewood Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mostly sand deposited by the river system.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
High hazard

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

TECHNICAL OVERVIEW OF RESULTS

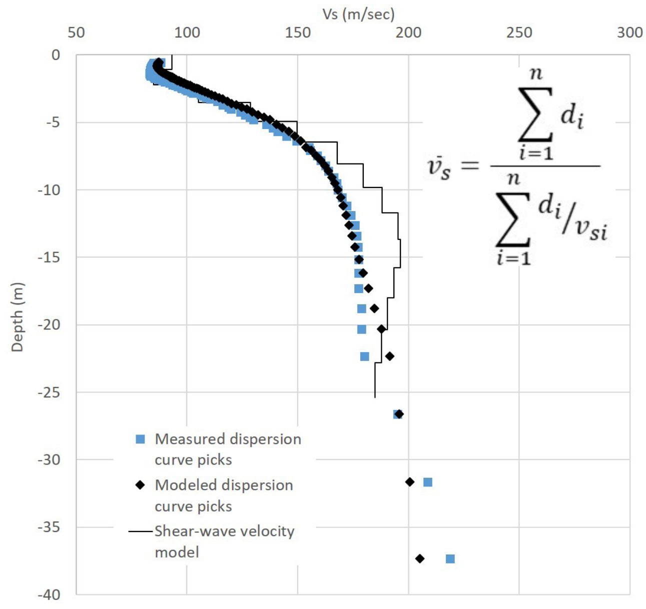
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves combined. The initial model has an RMSE of 7.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.3 percent. The final velocity model shows a slight velocity reversal in the upper 1 m (3 ft), then rapidly increasing velocity down to 15 m (49 ft), and another slight velocity reversal below. The final model then shows generally steady increase in velocity with depth to 30 m (100 ft). Our best Vs30 measurement is 165 m/s, which places the site in the E class. The predicted site class is either D or E, which correlates with the measured E site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

METHOW VALLEY ELEMENTARY SCHOOL AND LIBERTY BELL HIGH SCHOOL

METHOW VALLEY SCHOOL DISTRICT, OKANOGAN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

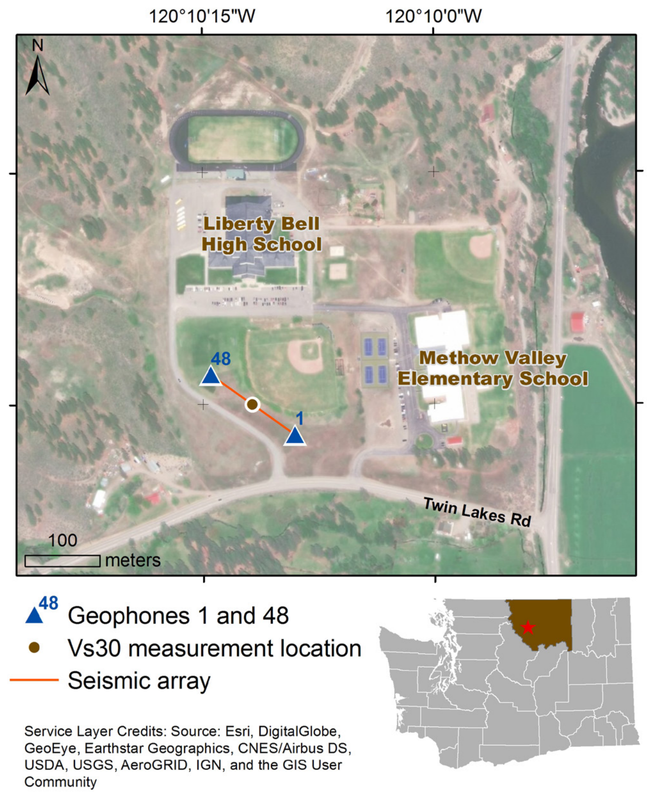
On April 18, 2017, a team from the Washington Geological Survey conducted a seismic survey at Methow Valley Elementary School and Liberty Bell High School for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments composed of sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low hazard

Ground Shaking
Very strong

TECHNICAL OVERVIEW OF RESULTS

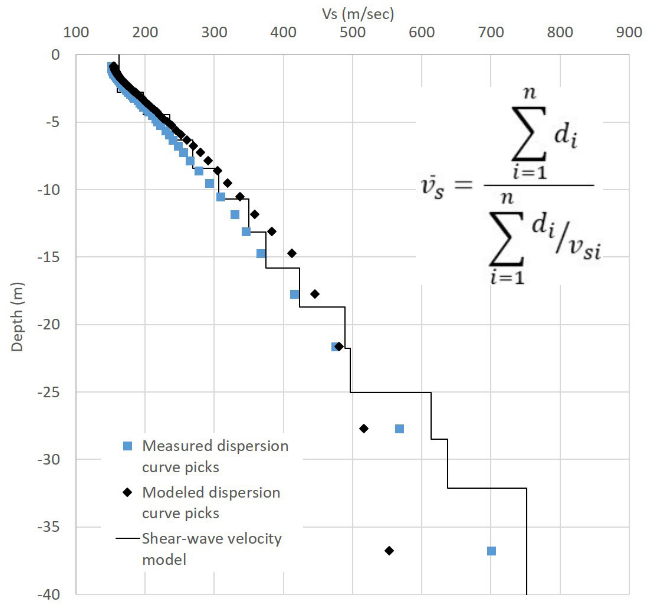
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image The multi-channel analysis of surface wave (MASW) dispersion image is generally of good quality, but does not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of poor quality, so is not used for the analysis. In order to enhance the surface wave signal, the MASW are stacked into common mid-point (CMP) cross-correlation gathers.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the CMP gather located at 60 m along the geophone array. The inital model has an RMSE of 10.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.6 percent. The final velocity model shows a general increase in velocity down past 30 m (100 ft). Our best Vs30 measurement is 333 m/s, which places the site in the D class. This is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

MORTON ELEMENTARY SCHOOL

MORTON SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

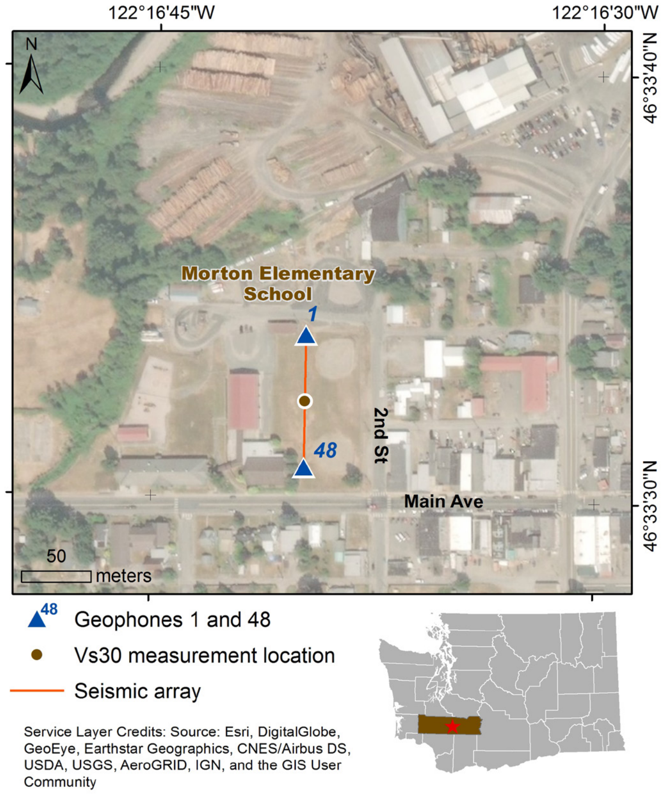
On September 5, 2018, a team from the Washington Geological Survey conducted a seismic survey at Morton Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class is differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on silt, sand, and gravel deposited in streambeds.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

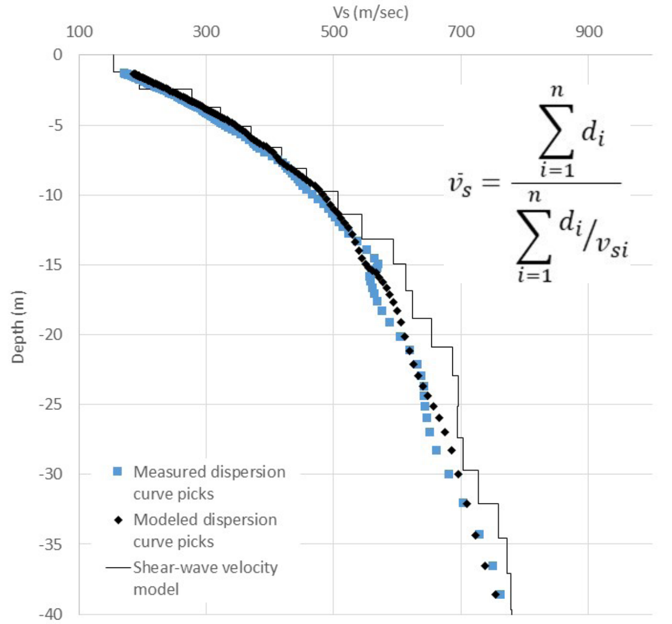
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves contain higher modes and generally low quality but the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 11.3 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 3.8 percent. The final velocity model shows a general steady increase in velocity with depth. Our best Vs30 measurement is 455 m/s, which places the site in the C class. This site class is the different than the predicted site class of D or E.

GEOLOGY

The 1:100,000-scale geologic map shows the school building and geophone array are sitting on Quaternary alluvium (unit Qa) which has a predicted site class of D to E. However, there is an outcrop Pleistocene alpine glacial drift (unit Qapt(h)) mapped just to the north, which has a predicted site class of C. The discrepancy between the measured and predicted could be due to a change in the subsurface geology.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

MORTON JUNIOR AND SENIOR HIGH SCHOOL

MORTON SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

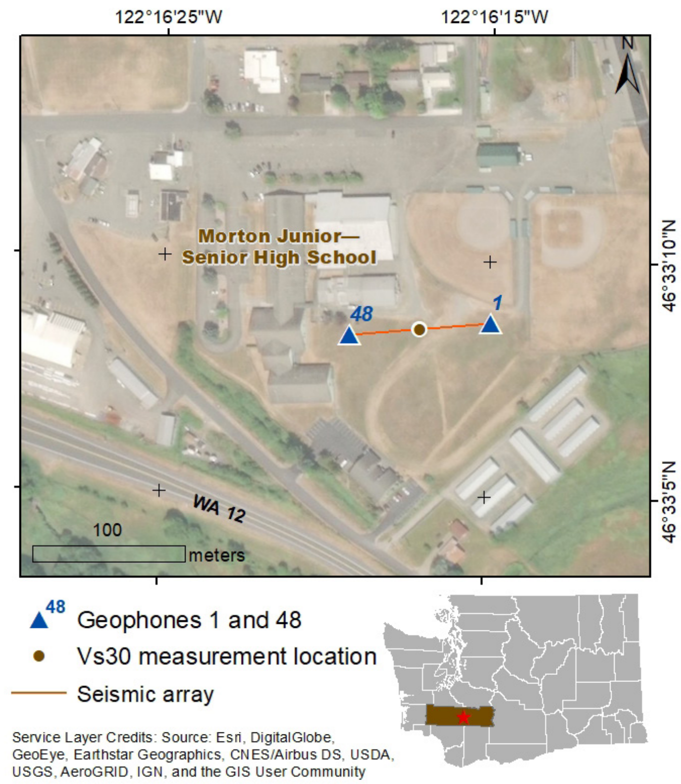
On July 25, 2018, a team from the Washington Geological Survey conducted a seismic survey at Morton Junior and Senior High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The site is sitting on Quaternary alluvium consisting primarily of silt, sand, and gravel deposited in streambeds.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

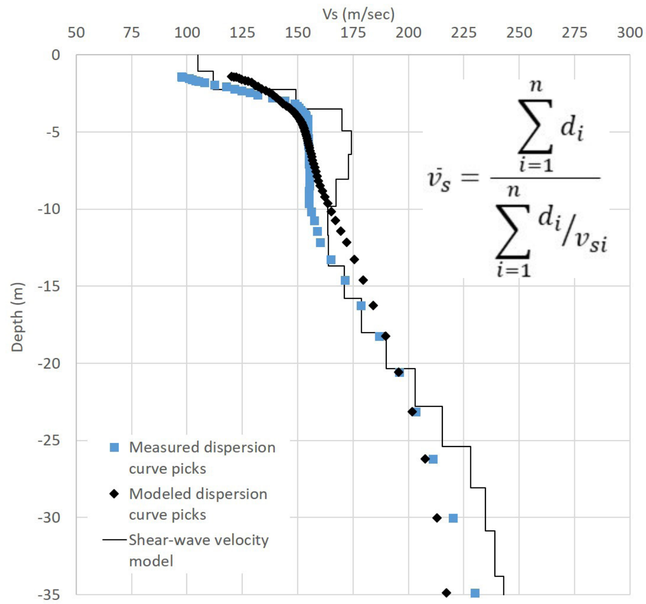
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes, but the fundamental mode can still be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality and the fundamental mode can be picked from 2 to 13 Hz. Overall, the MASW and MAM dispersion curves agree well from 2 to 13 Hz frequency, so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 7.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.7 percent. The final velocity model shows a general steady increase in velocity from 1 m (3 ft) down to 5 m (16 ft) depth, then a small velocity reversal at 10 m (33 ft) and a steadily increasing velocity from 15 m (49ft) to 30 m (100 ft) depth. Our best Vs30 measurement is 175 m/s, which places the site in the E class. The predicted site class is D or E, which correlates with the measured E site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity ($\bar{v}_s$) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. v_{si} = Shear wave velocity in (m/s) of the layer.

MOUNT BAKER JUNIOR HIGH SCHOOL AND MOUNT BAKER SENIOR HIGH SCHOOL

MOUNT BAKER SCHOOL DISTRICT, WATCOM COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

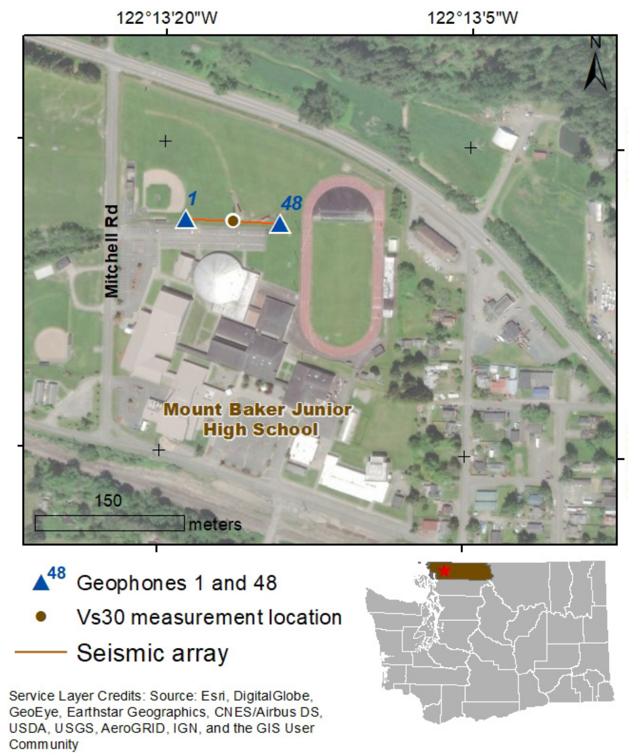
On July 3, 2018, a team from the Washington Geological Survey conducted a seismic survey at Mount Baker Junior and Senior High schools. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium consisting of gravel, sandy gravel, gravelly sand, silt, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low hazard

Ground Shaking
Moderate hazard

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

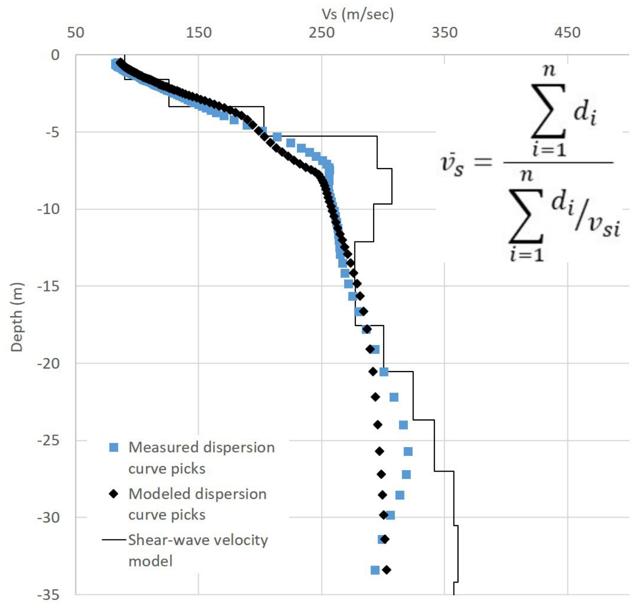
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves contain higher modes but the fundamental mode can still be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 9.6 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.7 percent. The velocity profile shows rapidly increasing velocity from 1 m (3 ft) to 5 m (16 ft), then a slight velocity reversal around 8 m (26 ft), and steadily increasing velocity below to 30 m (100 ft) depth. Our best Vs30 measurement is 248 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity ($\bar{v}_s$) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. v_{si} = Shear wave velocity in (m/s) of the layer.

NACHES VALLEY HIGH SCHOOL

NACHES VALLEY SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

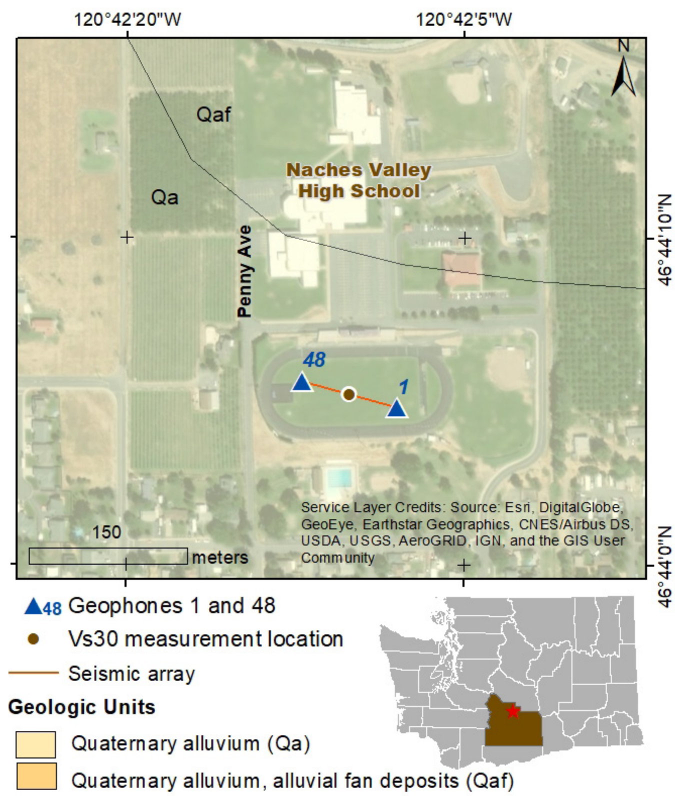
On June 25, 2018, a team from the Washington Geological Survey conducted a seismic survey at Naches Valley High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the similar to as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting partially on Quaternary alluvium (unit Qa) and partially on Quaternary alluvium, alluvial fan deposits (unit Qaf).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Very strong

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

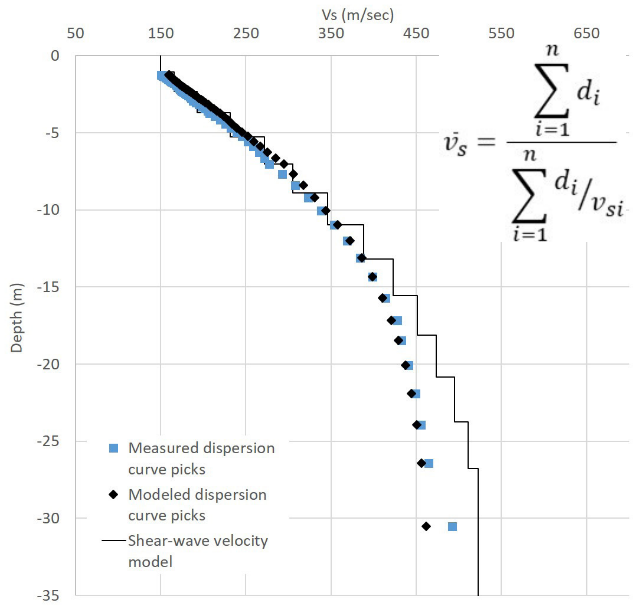
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are dominated by higher modes but the fundamental mode can be identified. The microtremor analysis method (MAM) dispersion image is of good quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft). The MASW dispersion curves from the forward and reverse directions do indicate some variability. In order to enhance the surface wave signal, the MASW are stacked into common mid-point (CMP) cross-correlation gathers.

VELOCITY MODEL

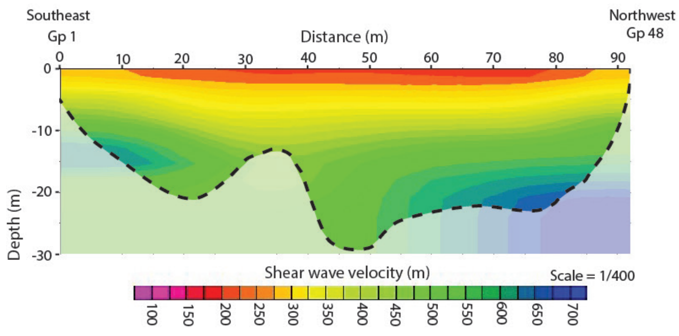
An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the CMP gather located at 44 m along the geophone array. The initial model has an RMSE of 11.5 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.3 percent. The final velocity model shows velocity generally increasing with depth. Our best Vs30 measurement is 343 m/s, which places the site on the high side of the D class. Our measurement of 343 m/s is taken from the middle of the array and is the same as was predicted.

GEOLOGY

The 1:100,000-scale geologic map shows the school building sitting on alluvial fan deposits (unit Qaf) to the northeast of campus and the Quaternary alluvium (unit Qa) to the southwest of campus. The predicted site class for unit Qaf is D, while the predicted site class for unit Qa is D-E. Our array was placed entirely within unit Qa, so our measured site class should be considered best representative of unit Qa. Laterally heterogeneous velocity structure is confirmed in the 2D MASW model, which shows lower velocity layer along the array between 20 m (66 ft) and 60 m (200 ft), the 2D model shows slightly higher velocity towards the ends of the geophone array. In fact, Vs30 measurements from the forward and reverse directions are actually slightly higher than 360 m/s, which would result in the site being classified a C. However, we take a conservative approach by taking the measured Vs30 value from the center of the array where the 2D MASW model confirms lower velocity and assigning site class of D to the school campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.



Pseudo 2D MASW shear-wave velocity model with locations for geophones 1 and 48. Dashed line approximately delineates the model's reliability in the vertical extent. Portions of the model at depths below the dashed line (shaded area) are not constrained.

NACHES VALLEY MIDDLE SCHOOL

NACHES VALLEY SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

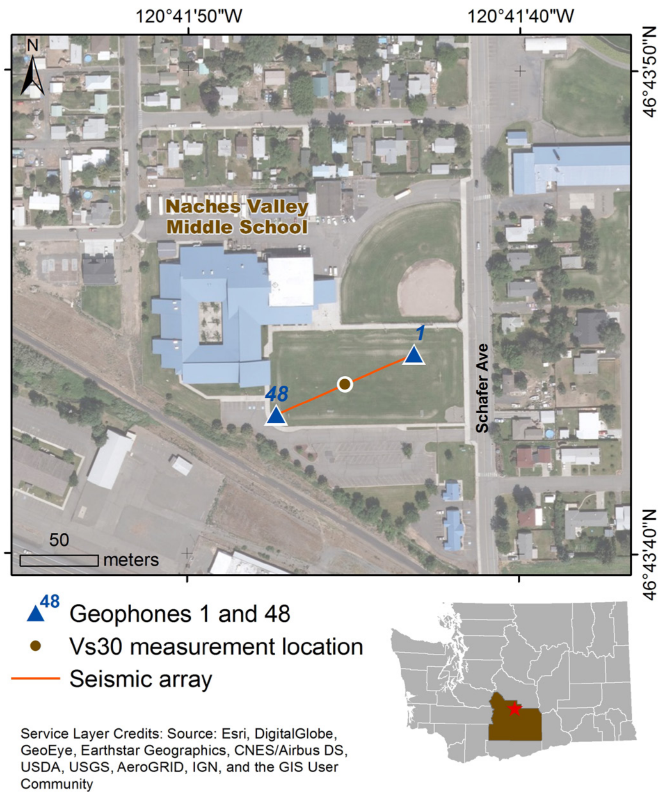
On June 25, 2018, a team from the Washington Geological Survey conducted a seismic survey at Naches Valley Middle School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

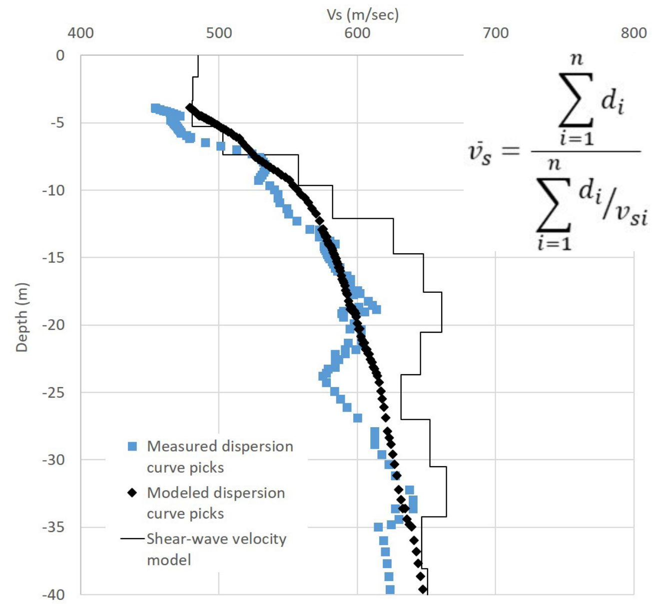
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 4.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.6 percent. The final velocity model shows constant velocity in the upper 4 m (13 ft), then shows a general increase in velocity down to 15 m (49 ft) and a generally constant velocity below 15 m (49 ft). Our best Vs30 measurement is 587 m/s, which places the site in the C class. This is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000-scale geologic map shows the school building and the geophone array are sitting on Quaternary alluvium (unit Qa) which have a predicted site class of D or E. However, mapped to the north and east of the school are outcrops of the Ellensburg formation, middle to upper Miocene sedimentary rocks, which have a predicted site class of B. The rapid increase in velocity between 7 m (23 ft) and 15 m (49 ft) could be the contact between the alluvium and Ellensburg formation and could explain why the predicted and measured site classes differ. However, it could also be heterogeneity in the alluvial sediments. Nearby boreholes do show contacts with sandstone, but at depths greater than 30 m (100 ft). This suggests that the difference between the measured and predicted site class is more likely due to local varation in the Quaternary alluvium.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

NEAH BAY JUNIOR—SENIOR HIGH SCHOOL AND NEAH BAY ELEMENTARY SCHOOL

CAPE FLATTERY SCHOOL DISTRICT, CALLAM COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

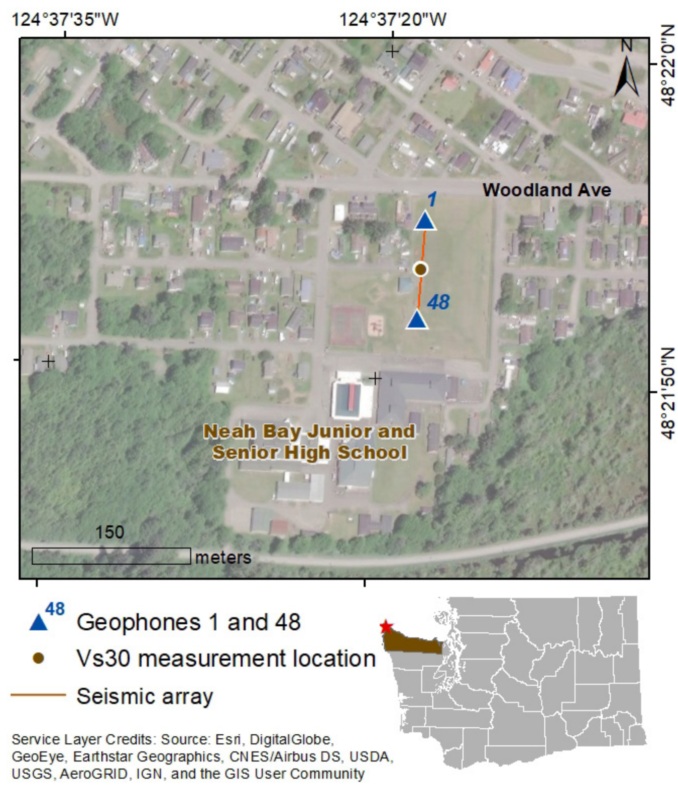
On August 1, 2018, a team from the Washington Geological Survey conducted a seismic survey at Neah Bay Junior—Senior High school and Neah Bay Elementary school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

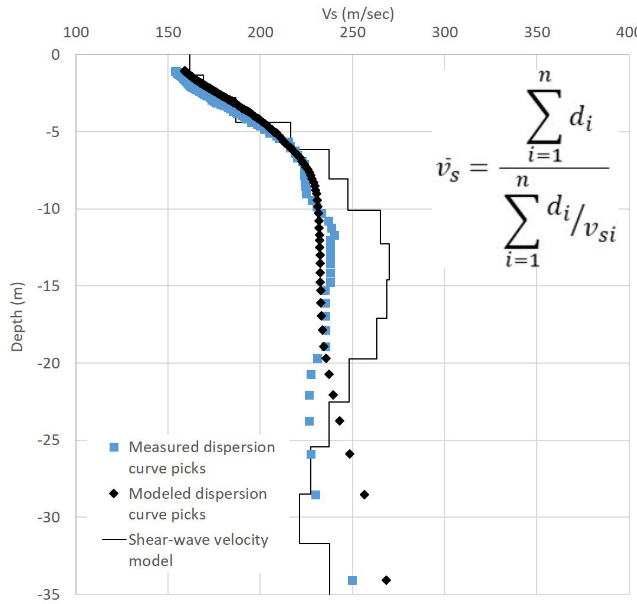
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality but the fundamental mode cannot be picked below 10 Hz. As a result, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of excellent quality and the fundamental mode can be picked down to 2 Hz frequency. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 7.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.9 percent. The final velocity model shows generally increasing velocity with depth from 1 m (3 ft) to 12 m (39 ft), then a slight velocity reversal from 15 m (49 ft) to 30 m (100 ft). Our best Vs30 measurement is 232 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

NEWPORT HIGH SCHOOL

NEWPORT SCHOOL DISTRICT, PEND OREILLE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

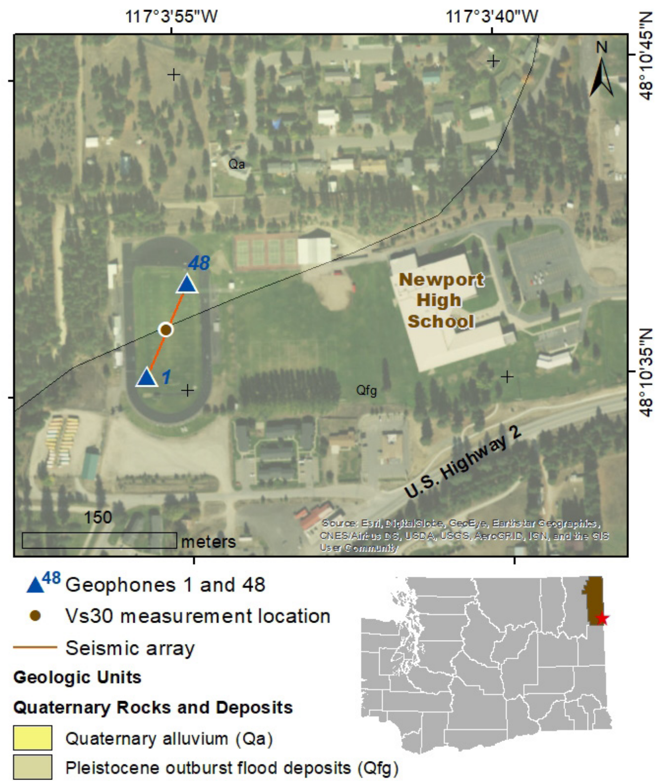
On July 19, 2018, a team from the Washington Geological Survey conducted a seismic survey at Newport High school. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock and very dense soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on outburst flood deposits (unit Qfg), consisting predominantly of gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

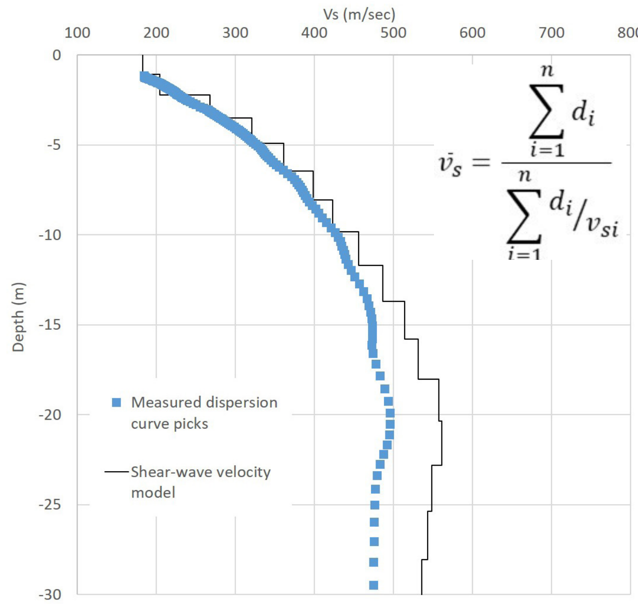
IThe term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality, with a fundamental mode that can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves from the reverse MASW (offend geophone 48) and the MAM. The combined analysis did not converge to below 5 percent RMSE. The final velocity model shows steadily increasing velocity to a depth of approximately 22 m (72 ft) and slightly decreasing velocity to below. Our best Vs30 measurement is 427 m/s with places the site on the middle of the site class C. Despite the lack of convergence, all intial models resulted in a Vs30 in the middle of the C class, so we are confident in the measured site class of C. This is the same as the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows the school building is sitting on Pleistocene outburst flood deposits (unit Qfg), which have a predicted site class of C. The geophone array crosses a mapped contact at around geophone 24, where unit Qfg is mapped to the south and Quaternary Alluvium (unit Qa) is mapped to the north, which has a predicted site class of D or E. However, the velocity model shows a fairly steady increase in velocity with depth from 1 m (3 ft) down to 22 m (72 ft), which suggests that there isn't a contact between the Qa and Qfg along the geophone array.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i/v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

OAKLAND HIGH SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

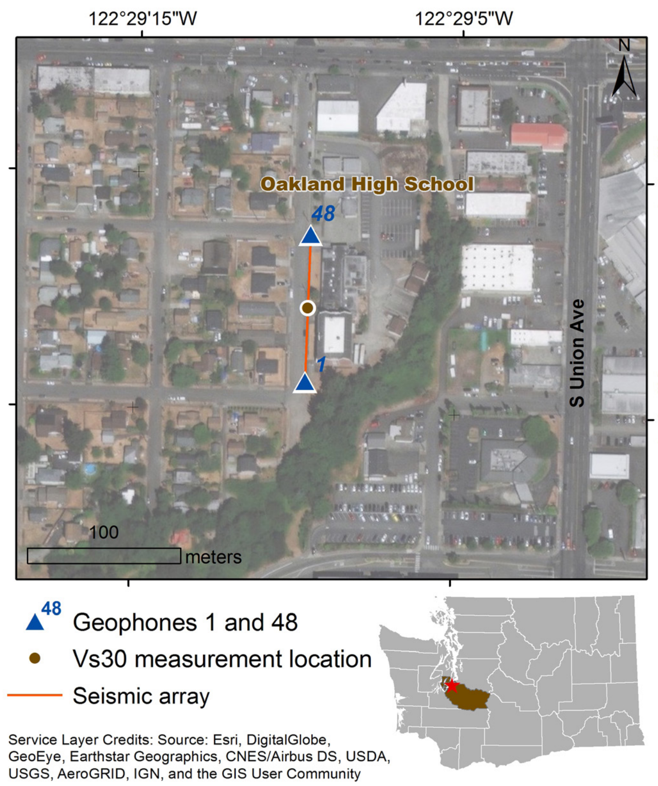
On September 5, 2018, a team from the Washington Geological Survey conducted a seismic survey at Oakland High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- ☐ The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- ☐ Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting continential glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Landslide
Hazard present

TECHNICAL OVERVIEW OF RESULTS

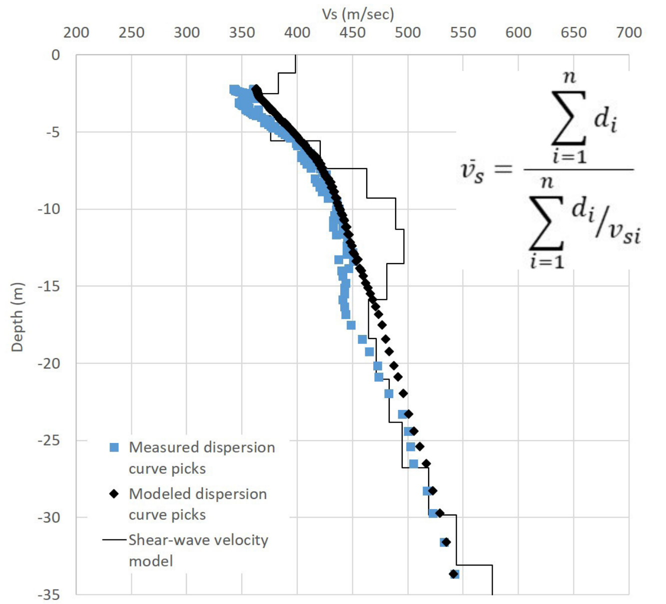
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse and forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 6.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.2 percent. The final velocity model shows a small unconstrained velocity reversal in the top layers of the model. The model then shows generally increasing velocity with depth from 2 m (7 ft) to 10 m (33 ft) depth, then another slight velocity reversal at 13 m (43 ft), and a steadily increasing velocity below. Our best Vs30 measurement is 458 m/s, which places the site in the C class. The predicted site class is C or D, which correlates with the measured C site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

OCEAN PARK ELEMENTARY SCHOOL

OCEAN BEACH SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

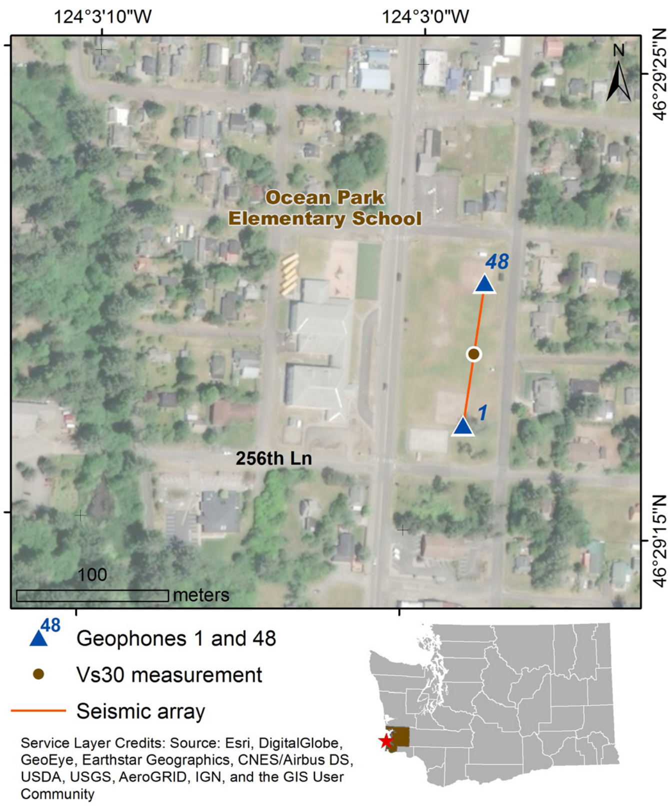
On August 2, 2018, a team from the Washington Geological Survey conducted a seismic survey at Ocean Park Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on beach deposits of fine to coarse sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

Tsunami
In a mapped tsunami hazard zone

TECHNICAL OVERVIEW OF RESULTS

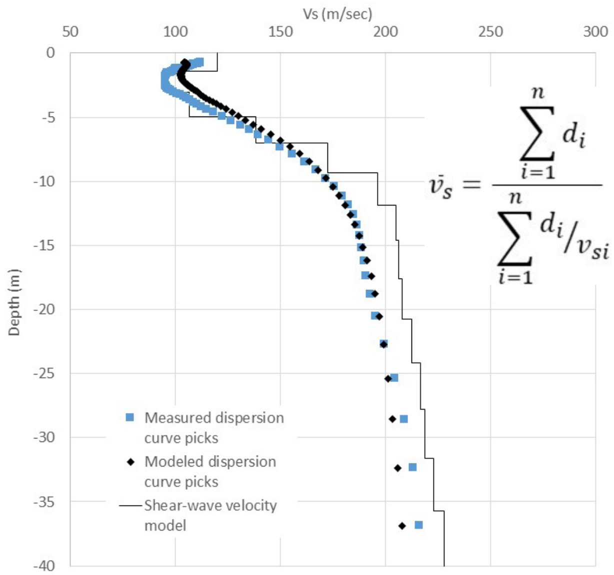
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 7.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.9 percent. The final velocity model shows a slight velocity reversal in the upper 1 m (3 ft), then a rapid increase in velocity to 10 m (33 ft) and a generally steady increase in velocity with depth below. Our best Vs30 measurement is 250 m/s, which places the site in the D class. The predicted site-class is D or E, which is correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

OCOSTA ELEMENTARY SCHOOL AND OCOSTA JUNIOR SENIOR HIGH SCHOOL

OCOSTA SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

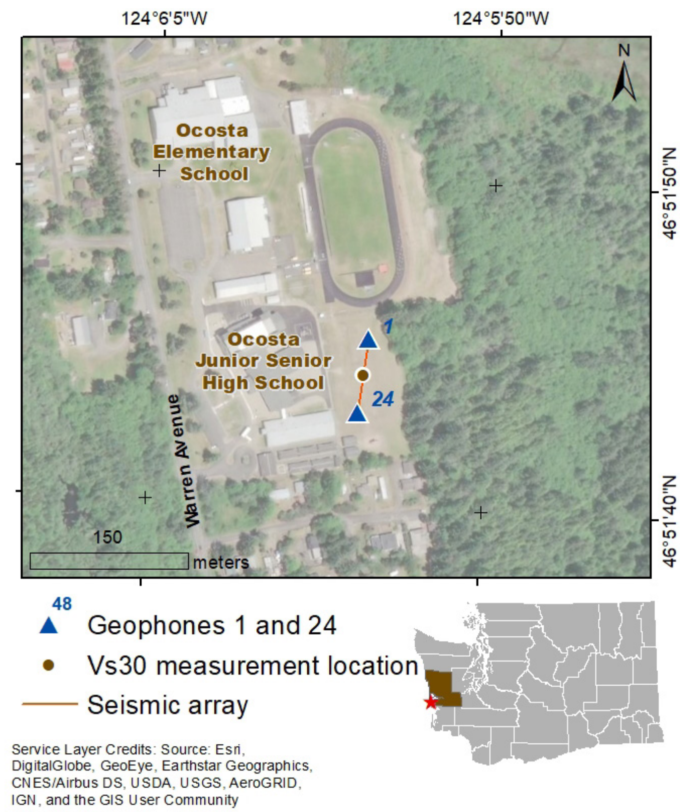
On January 3, 2013, a team from the Washington Geological Survey conducted a seismic survey at Ocosta Elementary and Junior Senior High schools for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 226-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene alpine glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

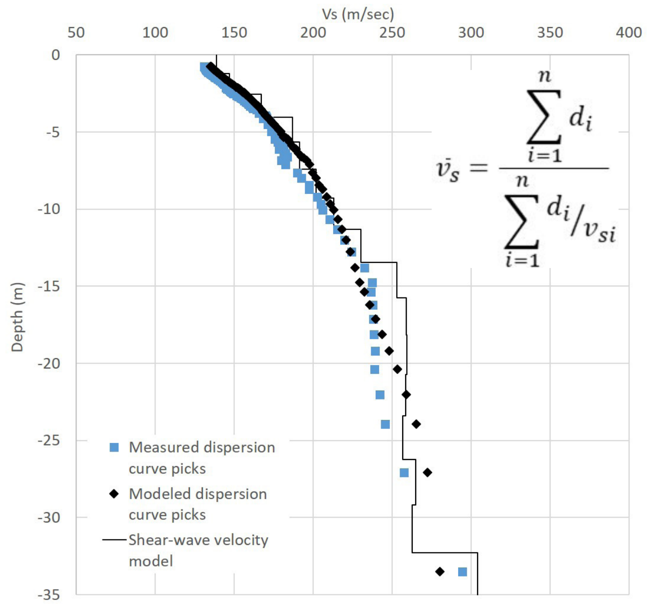
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse and forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 7.3 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.0 percent. The final velocity model shows generally increasing velocity with depth from 1 m (3 ft) to 30 m (100 ft). Our best Vs30 measurement is 220 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

OROVILLE ELEMENTARY SCHOOL

OROVILLE SCHOOL DISTRICT, OKANOGAN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

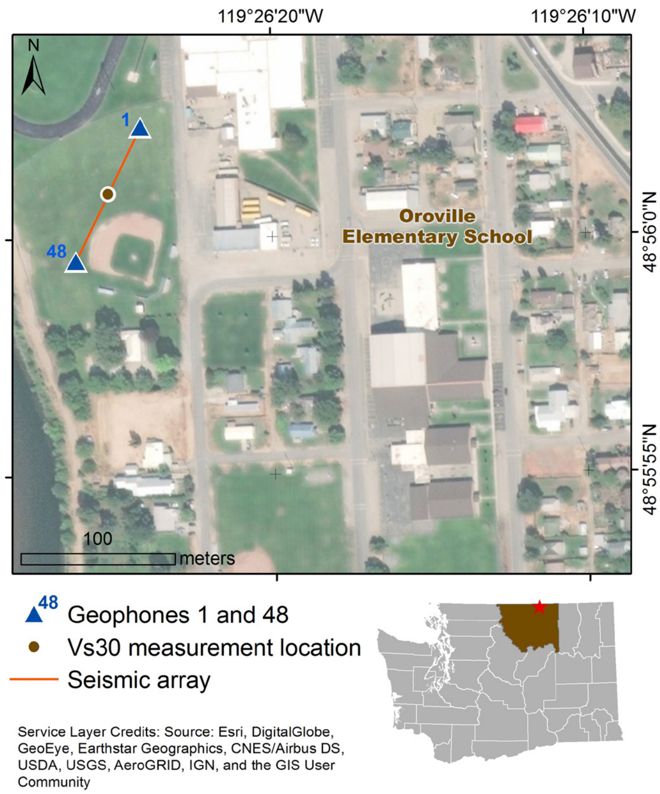
On May 16, 2017, a team from the Washington Geological Survey conducted a seismic survey at Oroville Elementary School for an earlier project. The team measured measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on undifferentiated glacial till, outwash, and glacial lake deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low hazard

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

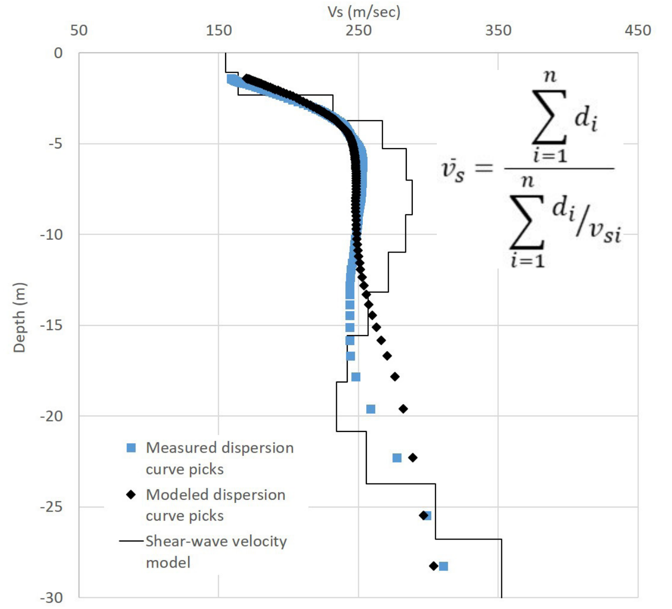
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 7.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.1 percent. The final velocity model shows a rapid increase in velocity down to 5 m (16 ft), then a velocity reversal, and a gradual increasing velocity from 20 m (66 ft) down to 30 m (100 ft). Our best Vs30 measurement is 258 m/s, which places the site in the D class. This correlates with the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

OUTLOOK ELEMENTARY SCHOOL

SUNNYSIDE SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

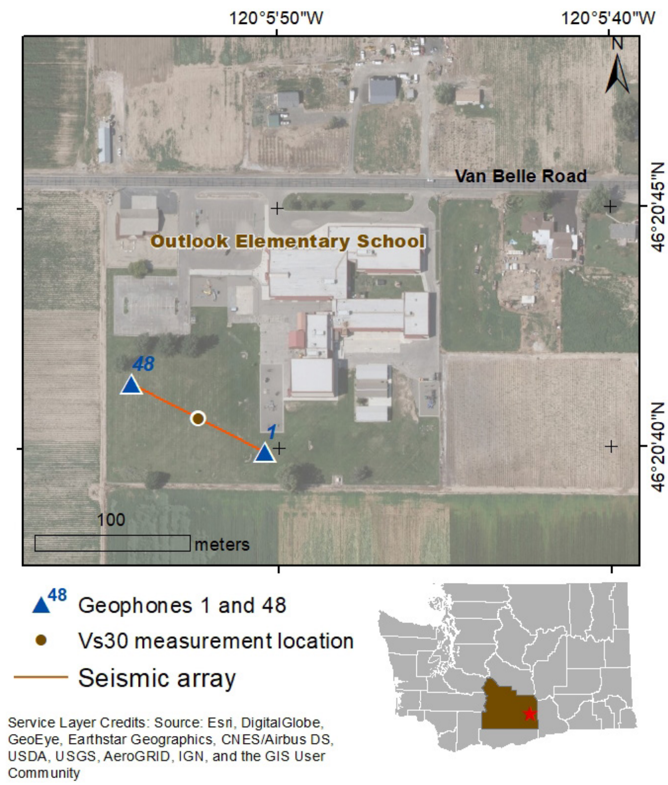
On August 28, 2018, a team from the Washington Geological Survey conducted a seismic survey at Outlook Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on outburst flood deposits of sand and silt.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate hazard

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

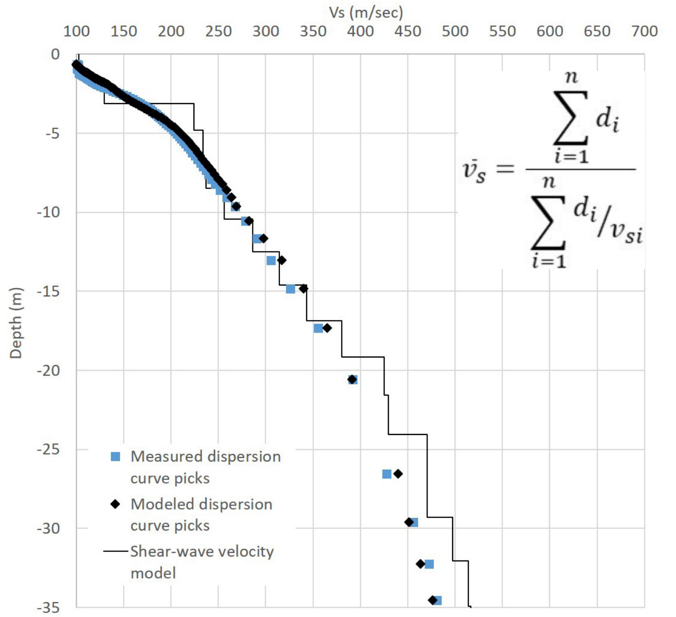
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are dominated by higher modes but the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality except between 5 and 9 Hz, but the fundamental mode can be picked above 9 Hz and below 5 Hz. Overall, the MASW and MAM dispersion curves agree well above 9 Hz, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 11.3 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 4.1 percent. The final velocity model shows a generally steady increase in velocity from 1 m (3 ft) down to 30 m (100 ft) depth. Our best Vs30 measurement is 279 m/s, which places the site in the D class. This Vs30 measurement and site class is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (s) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

PACIFIC BEACH ELEMENTARY SCHOOL

NORTH BEACH SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

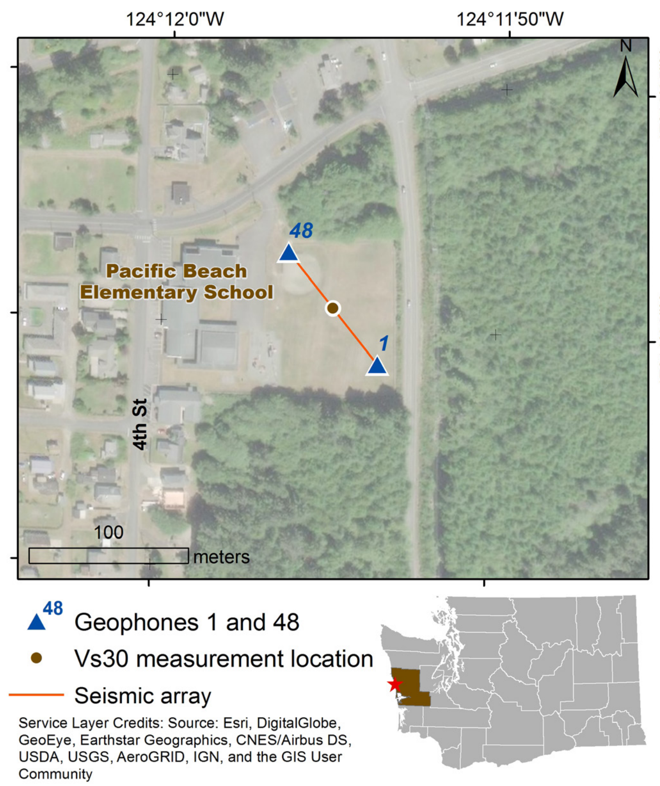
On June 20, 2018, a team from the Washington Geological Survey conducted a seismic survey at Pacific Beach Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene alpine glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

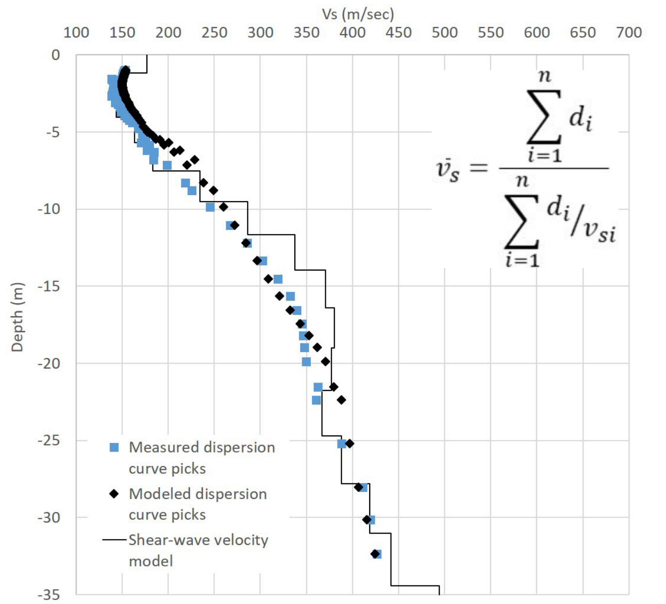
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curve contains higher modes but the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse and forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 8.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.0 percent. The final velocity model shows a small velocity reversal in the top layer of the model, then generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft). Our best Vs30 measurement is 272 m/s, which places the site in the D class. The predicted site class is C or D, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

PALISADES ELEMENTARY SCHOOL

PALISADES SCHOOL DISTRICT, DOUGLAS COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

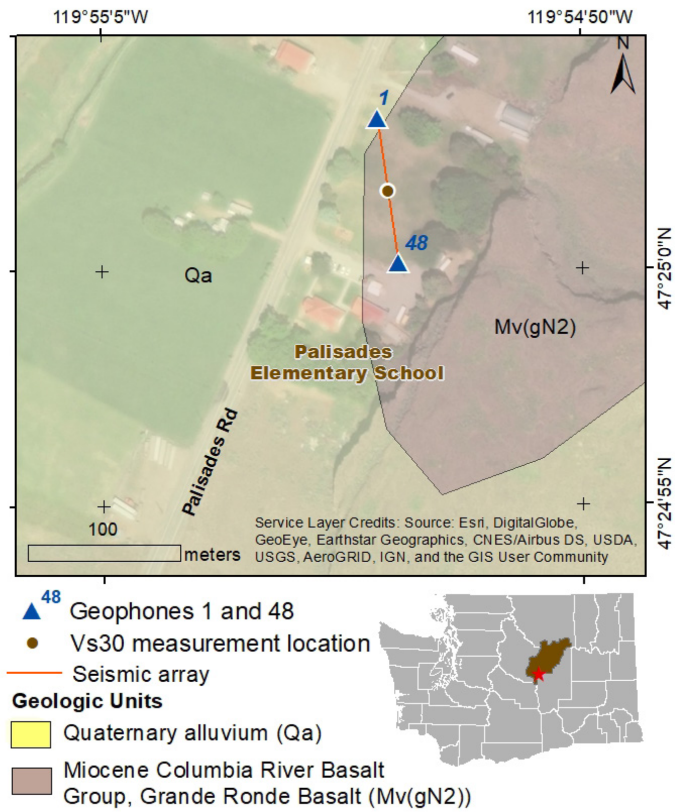
On June 28, 2018, a team from the Washington Geological Survey conducted a seismic survey at Palisades Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Very strong

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

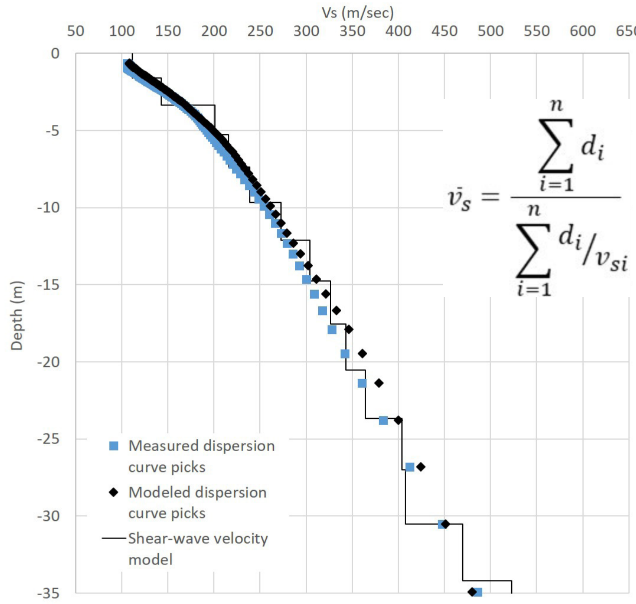
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of good quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can also be picked from 2 to 19 Hz. Overall, the MASW and MAM dispersion curves agree well from 2 to 19 Hz, so the MASW (forward and reverse directions) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 11.0 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.1 percent. The final velocity model shows generally steadily increasing velocity from 1 m (3ft) past 30 m (100 ft) depth. Our best Vs30 measurement is 263 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.

GEOLOGY

The 1:100,000-scale geologic map shows that the school buildings and geophone array are sitting partially on Quaternary alluvium (unit Qa) and partially on Columbia River Basalts, (unit Mv(gN2)). The predicted site class for unit Qa is D to E and B for unit Mv(gN2). However, the final shear wave velcoity profile does not show high velocities that would indicate hard rock and a nearby borehole does not show hard basalt until around 36 m (118 ft) depth. Finally, from the aerial photo, topographic cliff features associated with unit Mv(gN2) are east of the school buildings and the geophone array. Therefore, a mis-mapping in surficial geology may explain the discrepancy between the predicted and measured site classes across the school campus. The measured site class of D can therefore be confidently applied to the school buildings.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?
Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

PATEROS K-12 SCHOOL

PATEROS SCHOOL DISTRICT, OKANOGAN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

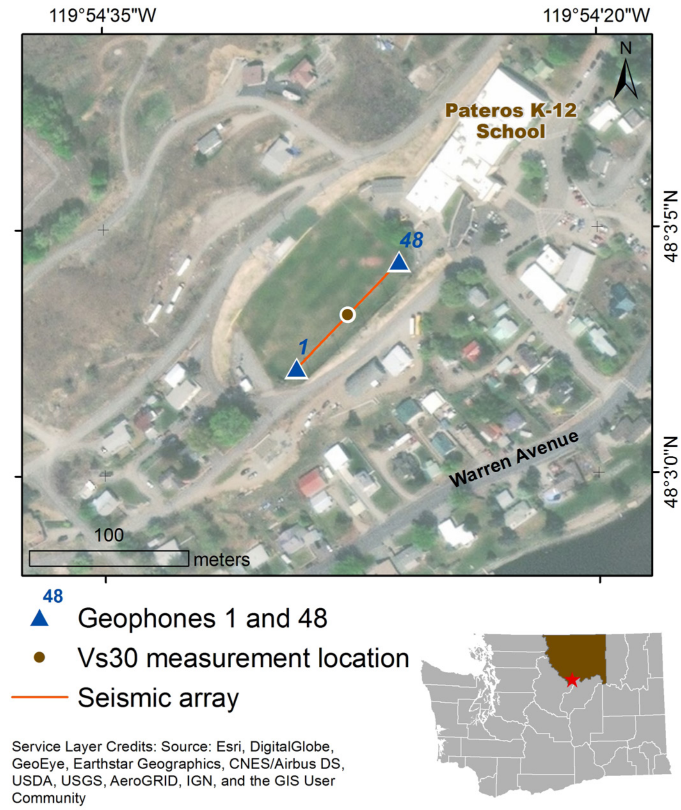
On April 20, 2017, a team from the Washington Geological Survey conducted a seismic survey at Pateros K-12 School for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Very strong

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

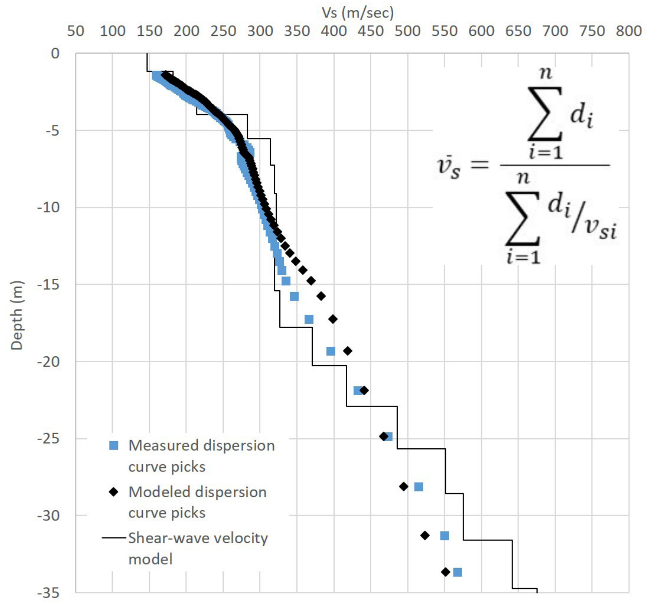
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of decent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 12.3 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.9 percent. The final velocity model shows generally steady increasing velocity from 1 m (3 ft) to 8 m (26 ft) depth, a constant velocity from 9 m (29 ft) to 17 m (55 ft), and a steadily increasing velocity past 30 m (100 ft) depth. Our best Vs30 measurement is 327 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. v_{si} = shear wave velocity of the layer in (m/s).

PATERSON ELEMENTARY SCHOOL

PATERSON SCHOOL DISTRICT, BENTON COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

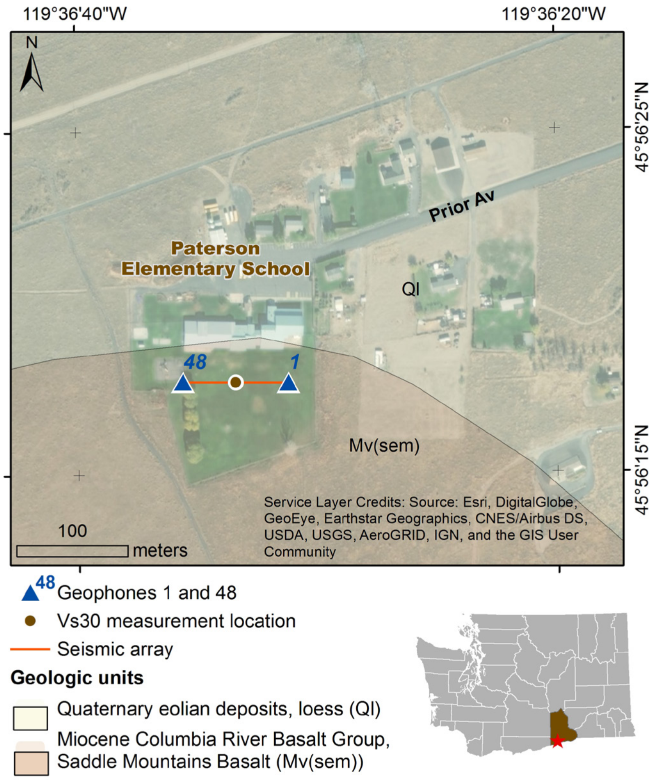
On August 8, 2018, a team from the Washington Geological Survey conducted a seismic survey at Paterson Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on rock.
- Site class is the same to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS B



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on two seperate geologic units (1) Palouse loess deposit (unit Ql) composed of wind-blown silt and fine sand and (2) Columbia River Basalt, unit Mv(sem).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Strong

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

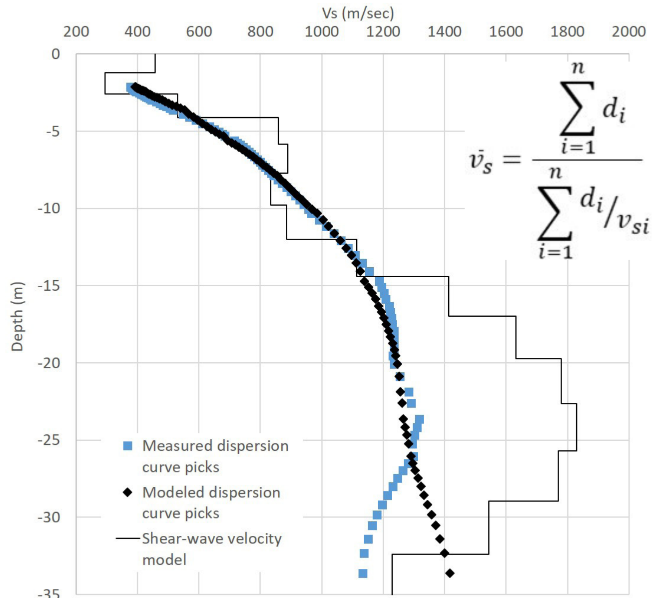
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is of reasonable quality, but the fundamental mode is broad leading to inconsistencies from shot to shot. The microtremor analysis method (MAM) dispersion image is not of good quality and was not used for analysis. The MASW adequately samples down to 30 m (100 ft) depth.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1) The initial model has an RMSE of 13.9 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 4.7 percent. The final velocity model shows a generally steady increase in velocity with depth to 25 m (82 ft) then a velocity reversal. Our best Vs30 measurement is 980 m/s, which places the site in the B class.

GEOLOGY

The 1:100,000-scale geologic map shows that the school building and the geophone array are sitting near a contact between the Palouse loess deposit (unit Ql) and a member of the Columbia River basalt (unit Mv(sem)). The site class for the unit Ql is D while the site class for unit Mv(sem) is B. Our geophone array was placed entirely within unit Mv(sem), so our measured site class should be considered best representative of unit Mv(sem). However, a borehole approximately 350 m (1,148 ft) to the northeast, shows unit Ql unit is only 1 m (4 ft) thick and overlies thick basalt flows. Therefore, it is reasonable to assume that unit Ql does not increase in thickness enough between the location of the measurement and the building footprint to lower the site class significantly. However, we recommend further geotechnical investigation to verify the thickness of loess deposits at the site.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

PORT TOWNSEND HIGH SCHOOL

PORT TOWNSEND SCHOOL DISTRICT, JEFFERSON COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

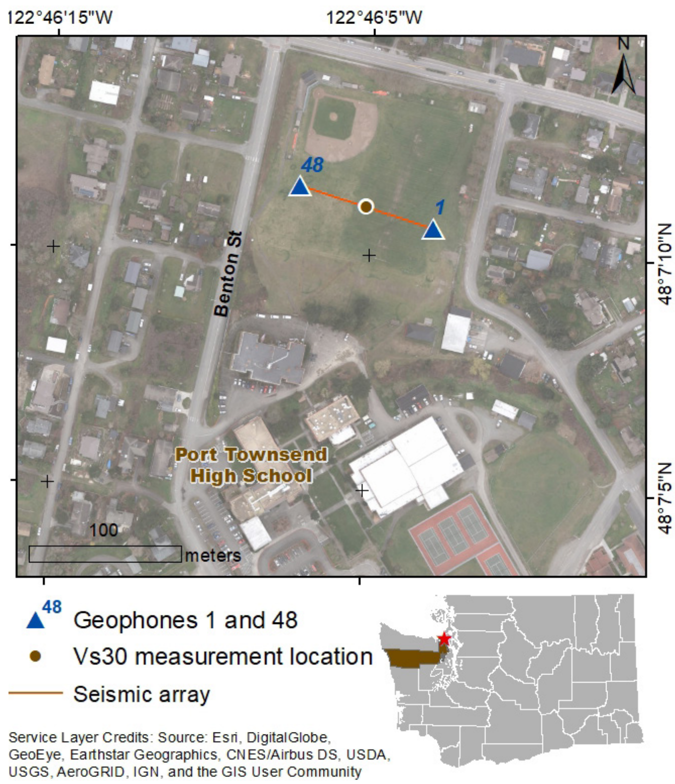
On July 30, 2018, a team from the Washington Geological Survey conducted a seismic survey at Port Townsend High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted C site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on artifical man-made fill.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

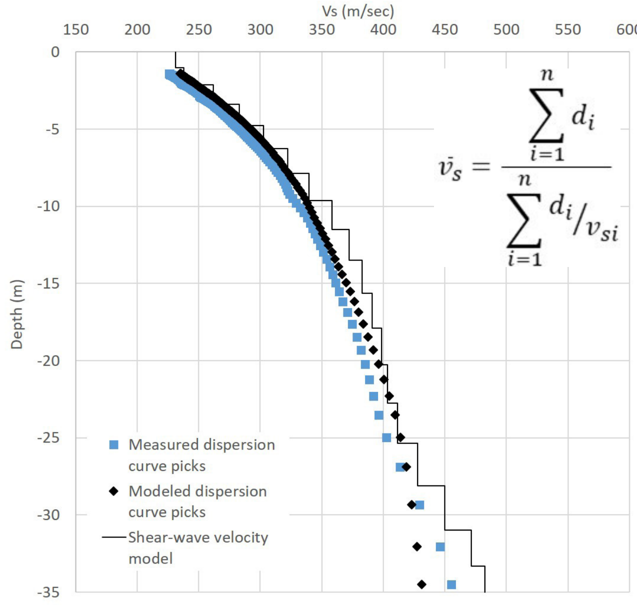
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 7.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.8 percent. The velocity profile shows steadily increasing velocity from 2 m (7 ft) down to 30 m (100 ft) depth. Our best Vs30 measurement is 355 m/s, which places the site near the D-C boundary, at the very high end of the D class. The measured site class is different than the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map shows the school building is sitting on Holocene artificial fill (unit Qml) and surrounded by Pleistocene continental glacial till (unit Qgt). Our array is completely located within unit Qml, so our measured site class should be considered best representative of unit Qml. Furthermore, the impact on Vs30 from the artifical fill cannot be completely assessed without determining the dominate materials of the artificial fill and verifying its extent. Verifying the artificial fill is beyond the scope of the project. However, for the purposes of this study, we assume the artificial fill is sitting unconformably on top of the Pleistocene continental glacial till and is only a few meters thick. Due to the proximity of the array to the building and a lack of evidence for significant heterogeneous velocity structure along the array, we assign site class D to the school campus and buildings. The presence of the lower velocity artifical fill might also be a contributing factor in the descrepancy between the measured and predicted site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

PRAIRIE HIGH SCHOOL

BATTLE GROUND SCHOOL DISTRICT, VANCOUVER, CLARK COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

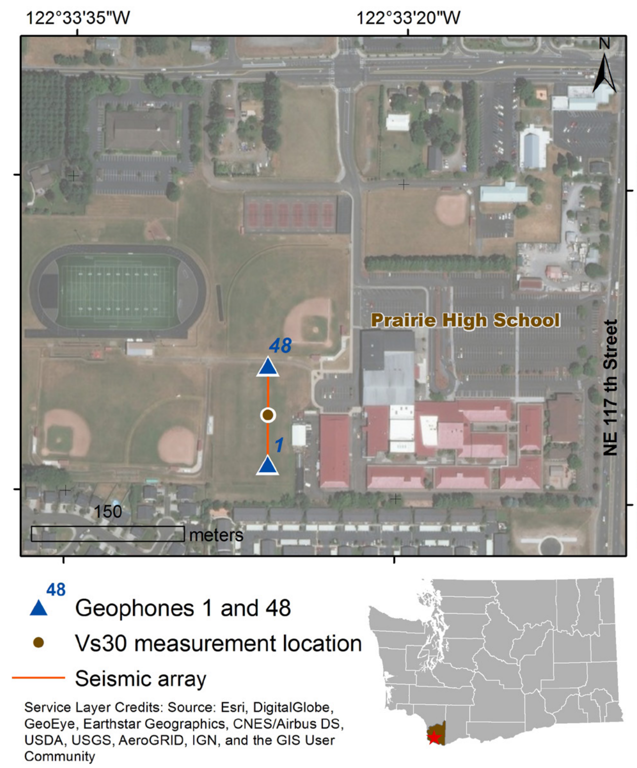
On August 22, 2018, a team from the Washington Geological Survey conducted a seismic survey at the Prairie High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted C site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on bouldery to cobbly gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Severe

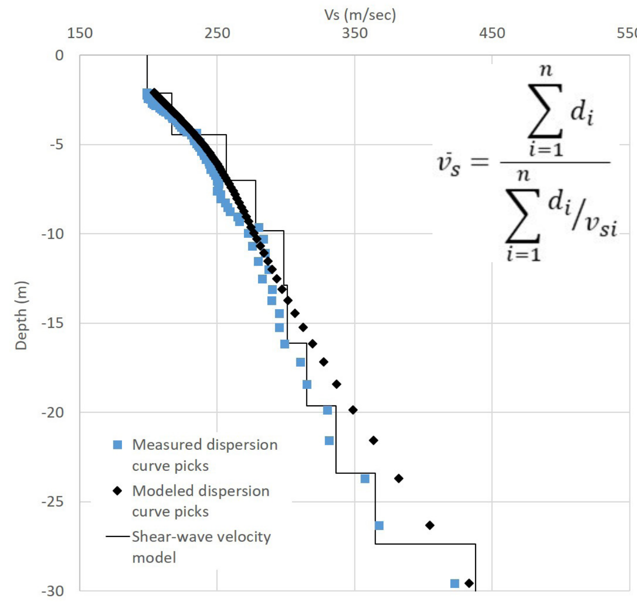
Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is of good quality, with a fundamental mode that can also be picked easily. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in m/s of the layer.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 9.0 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 3.5 percent. The final velocity model shows generally steady increase in velocity with depth from 3 to 30 m (10 to 100 ft). Our best Vs30 measurement is 297 m/s, which places the site in the middle of the D class. The measured site class is different than the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school site and the geophone array are sitting on Pleistocene outburst flood deposits (unit Qfs) which has a predicted site class C in this area. However, the more detailed 1:24,000-scale geologic maps show that the site is sitting on Pleistocene outburst flood deposits with gravel facies (unit Qfg). Unit Qfg has a predicted site class of D in this area. Therefore, a mis-mapping in surficial geology could help explain the discrepancy between the predicted and measured site classes at the school campus.

PUYALLUP HIGH SCHOOL

PUYALLUP SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

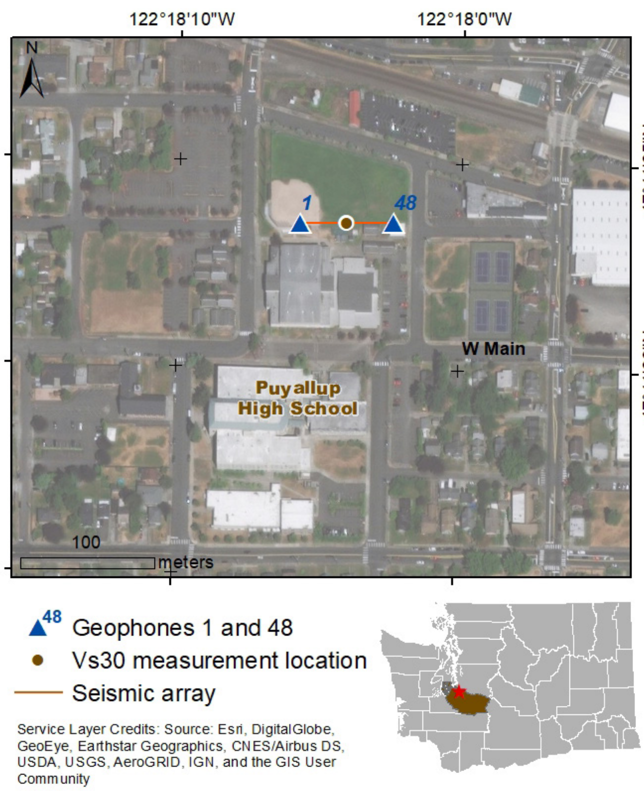
On August 15, 2018, a team from the Washington Geological Survey conducted a seismic survey at Puyallup High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mostly sand deposited by the river system.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
High hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

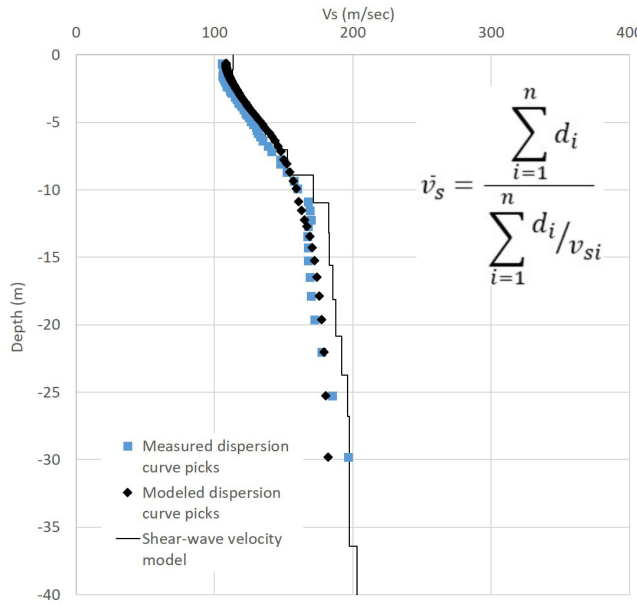
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 6.3 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.4 percent. The final velocity model shows a general increase in velocity down past 30 m (100 ft). Our best Vs30 measurement is 165 m/s, which places the site in the E class. The predicted site class is D or E, which correlates with the measured E site class.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i/v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUILCENE ELEMENTARY AND HIGH SCHOOL

QUILCENE SCHOOL DISTRICT, JEFFERSON COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

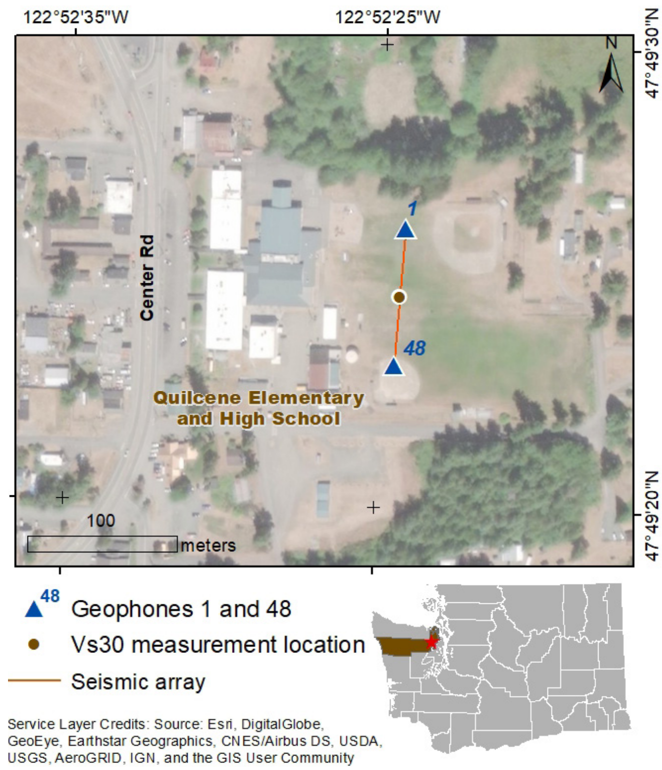
On July 30, 2018, a team from the Washington Geological Survey conducted a seismic survey at Quilcene Elementary and High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium consisting primarily of sand to cobble gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

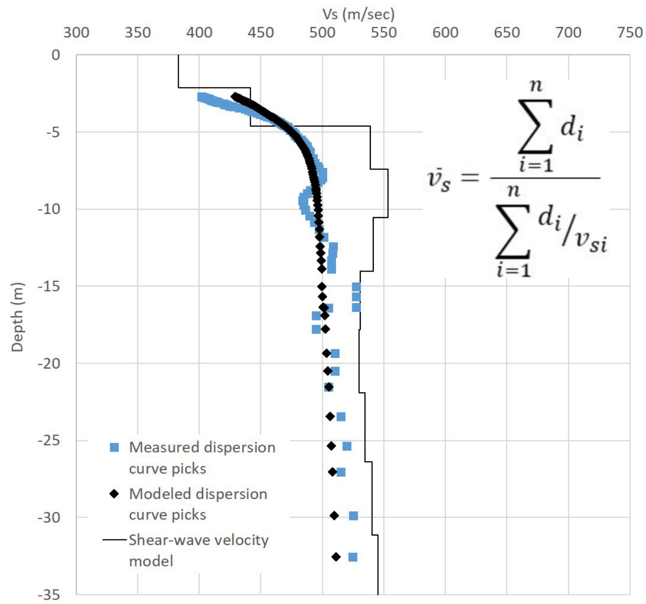
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality and the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is not of good quality and was not used for analysis. The MASW adequately samples down to 30 m (100 ft) depth.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1). The model has an RMSE of 3.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 2.2 percent. The velocity profile shows rapidly increasing velocity in the upper 5 m (16 ft) of the model, then continuous velocity down to 30 m (100 ft) depth. Our best Vs30 measurement is 514 m/s, which places the site in the C class. The predicted site class is C or D, which correlates with the measured C site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity ($\bar{v}_s$) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. v_{si} = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

R. A. LONG HIGH SCHOOL

LONGVIEW SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

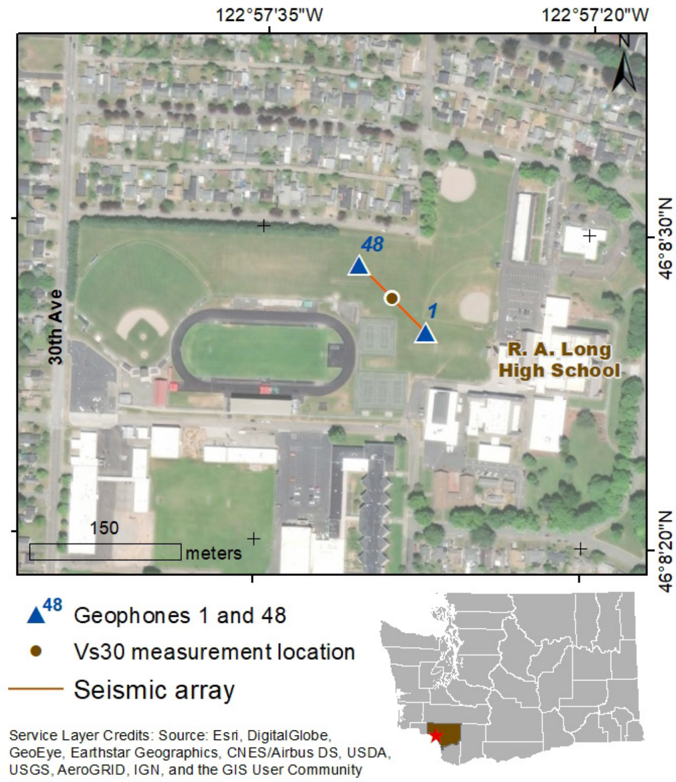
On August 2, 2018, a team from the Washington Geological Survey conducted a seismic survey at R. A. Long High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium consisting primarily of sand, gravel, silt and peat deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

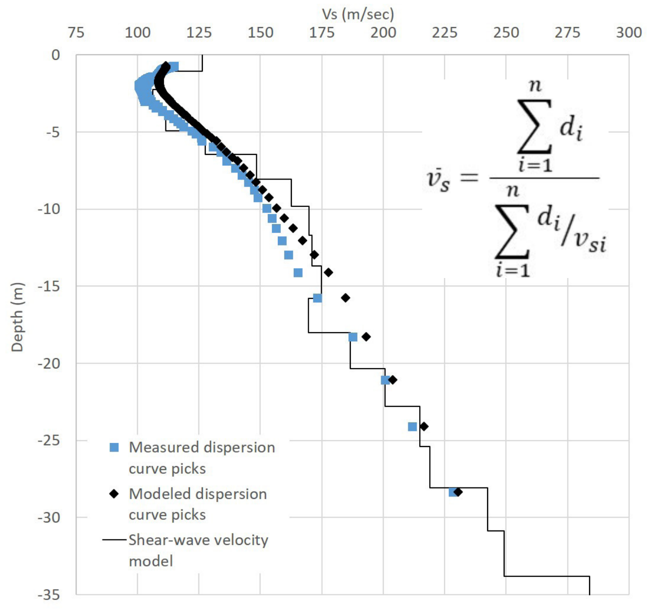
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be also be picked from 2 to 13 Hz. Overall, the MASW and MAM dispersion curves agree well from 2 to 13 Hz frequency, so the MASW (forward and reverse directions) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 6.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.1 percent. The final velocity model shows a shallow high velcoity reversal in the top layers and a generally steady increasing inversion from 3 m (10 ft) past 30 m (100 ft) depth. Our best Vs30 measurement is 166 m/s, which places the site in the E class. The predicted site class is D or E, which correlates with the measured E site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

RAYMOND ELEMENTARY JUNIOR AND SENIOR HIGH SCHOOL

RAYMOND SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

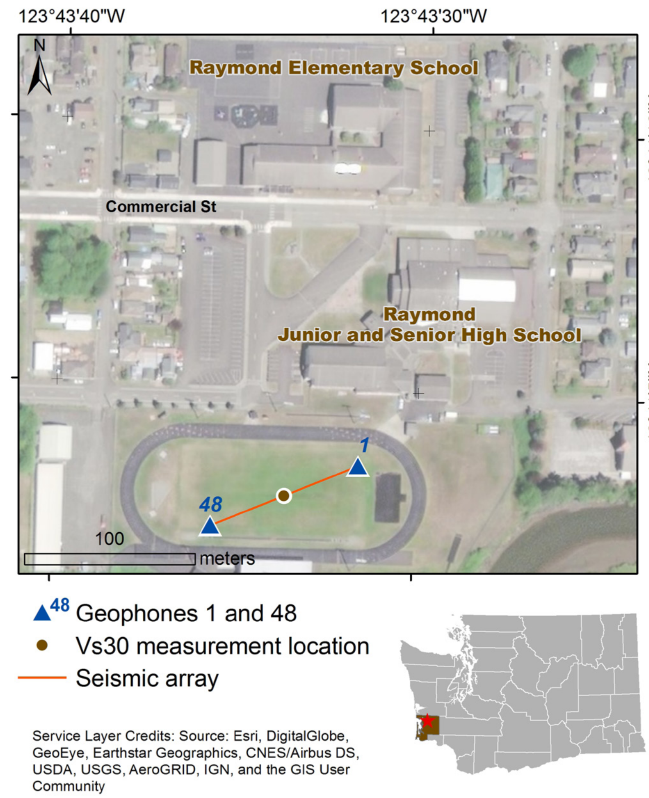
On June 19, 2018, a team from the Washington Geological Survey conducted a seismic survey at Raymond Elementary, Junior, and Senior High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on silt, sand, and gravel deposited in streambeds.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

Tsunami
In a mapped tsunami hazard zone

Landslide
Hazard present, based on terrain data

TECHNICAL OVERVIEW OF RESULTS

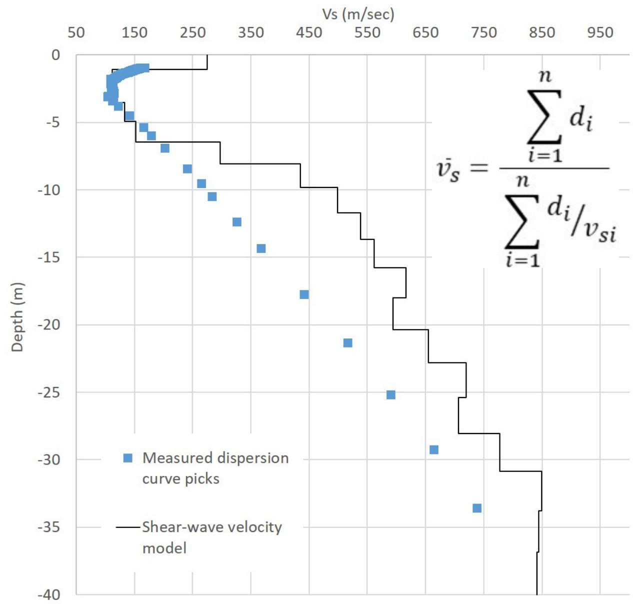
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The combined analysis did converge to a high RMSE, which suggests the model converged to a local minima. The velocity model shows a velocity inversion above 2 m (7 ft), then a rapid increase in velocity down to 10 m (33 ft), and general increasing velocities below that down to 30 m (100 ft). The resulting best estimate for Vs30 is 305 m/s and is based on the initial model. Despite the lack of convergence, all initial models resulted in a Vs30 in the middle of the D class. In addition, the inversion would have to change the Vs30 by 55 m/s or 125 m/s to change site class, so we are confident in the measured site class of D. The predicted site class is D or E, which correlates with the measured D site class.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

RAYMOND FIRE STATION

212 COMMERCIAL STREET, RAYMOND, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

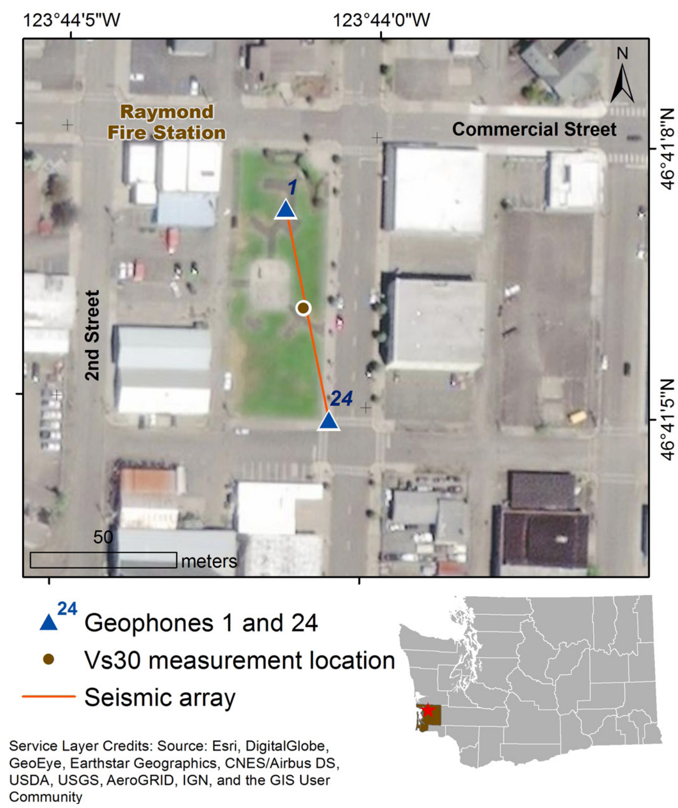
On July 29, 2010, a team from the Washington Geological Survey conducted a seismic survey near the Raymond Fire Station for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 230-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the fire station, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The fire station is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is the same as was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the fire station.

WHAT SOILS ARE UNDER THE FIRE STATION?

The fire station is sitting on silt, sand, and gravel deposited in streambeds.

GEOLOGIC HAZARDS AT THE FIRE STATION

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

TECHNICAL OVERVIEW OF RESULTS

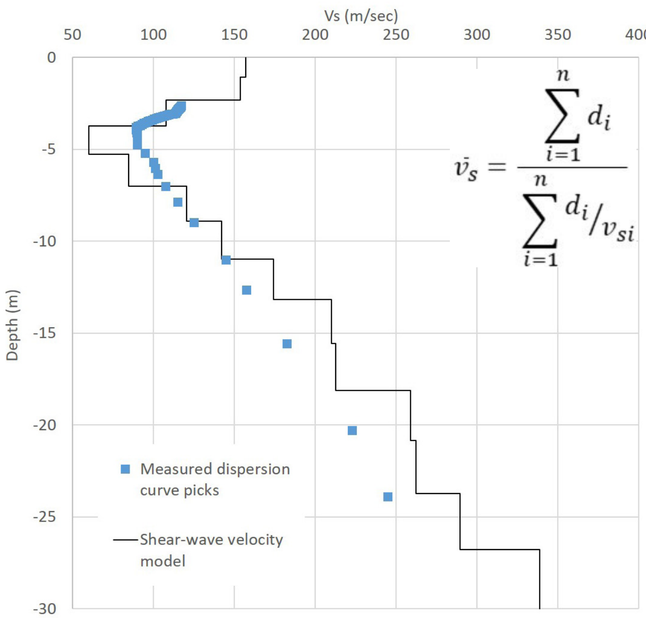
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality below 6 Hz but suspect above due to higher mode interference, making picking the fundamental mode at frequencies above 6 Hz difficult. In addition, the MASW dispersion curves do not sample below 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked from 2 Hz to 20 Hz. Although, the combined MASW and MAM dispersion curves depict a similar overall trend, the MASW does not sample at frequencies higher than sampled with the MAM. Thus, only the MAM was used.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curve from the MAM. The initial model has an RMSE of 13.9 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 6.0 percent. Both the initial and inverted model depict a near surface high velocity layer extending down to about 3 to 4 m (10 to 13 ft) with generally steady increasing velocity with depth down to 30 m (100 ft). However, the complex velocity structure in the upper 4 m (13 ft) prevents the final model from converging without forcing unrealistic velocities above 5 m (16 ft). Thus, our best estimate for Vs30 is 174 m/s and is based on the initial model, which places the site in the E class. All initial models are in the E class, so the site can confidently be classified an E. The predicted site class is D or E, which correlates with the measured E site class.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

RED ROCK ELEMENTARY SCHOOL, ROYAL MIDDLE SCHOOL, AND ROYAL HIGH SCHOOL

ROYAL SCHOOL DISTRICT, GRANT COUNTY, WA

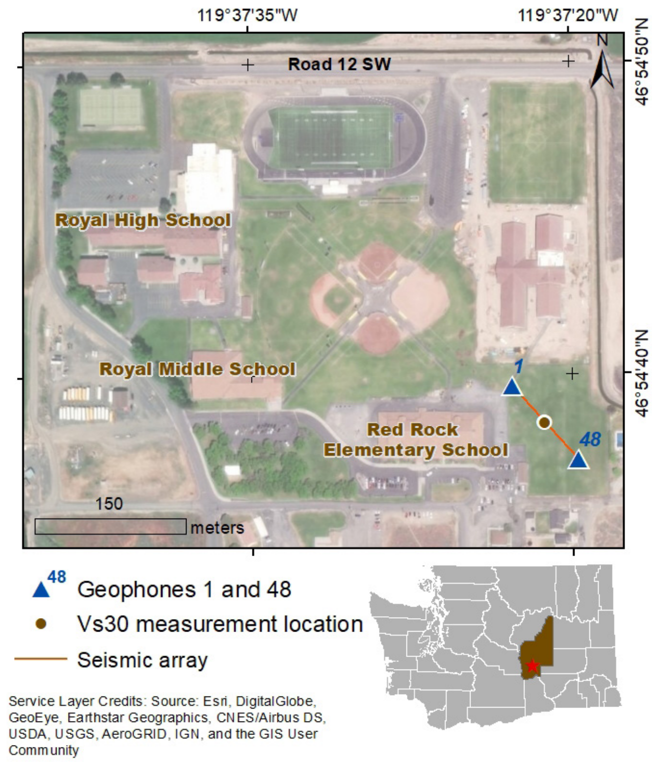
WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

On July 18th, 2018, a team from the Washington Geological Survey conducted a seismic survey at the Red Rock Elementary, Royal Middle School, and Royal High School. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.



Location of seismic array at the school campus.

WHAT DID WE LEARN?

- The school is built on soft rock and very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Tertiary sedimentary rocks and deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Very Strong

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

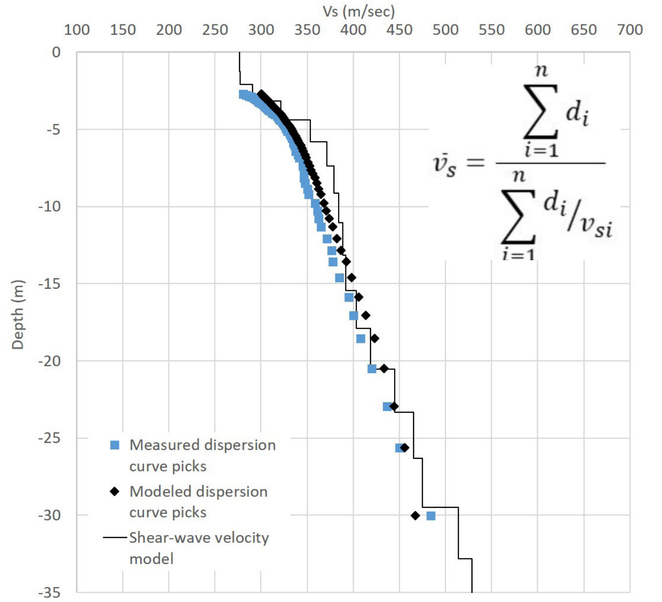
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the forward MASW (offend geophone 1). The initial model has an RMSE of 6.3 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.4 percent. The final velocity model shows constant velocity in the upper 2 m (7 ft) and generally increasing velocity below to a depth of 30 m (100 ft). Our best Vs30 measurement is 391 m/s which places the site on the low side of the site class C. This Vs30 measurement and site class is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

RIDGETOP JUNIOR HIGH SCHOOL AND SILVER RIDGE ELEMENTARY SCHOOL

CENTRAL KITSAP SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

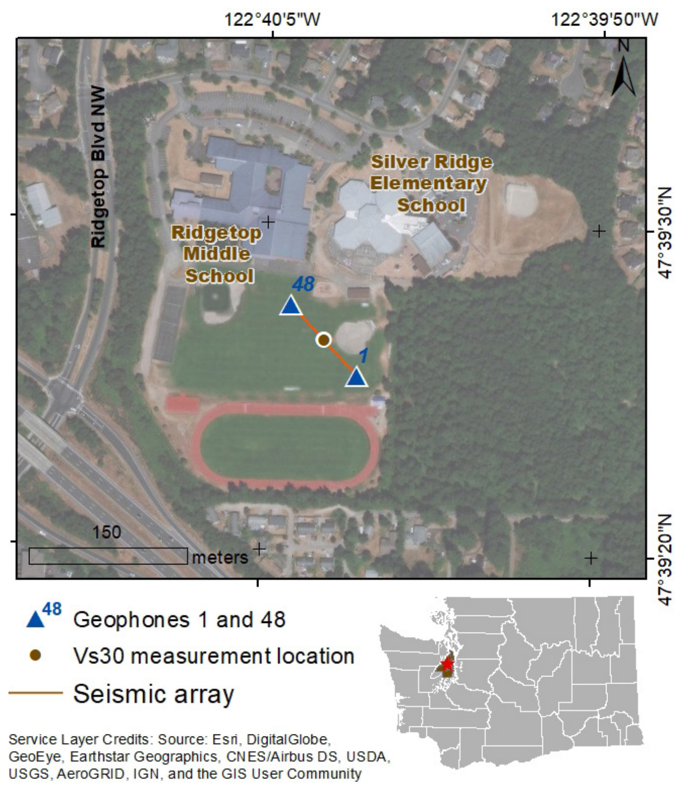
On August 7, 2018, a team from the Washington Geological Survey conducted a seismic survey at Ridgetop Junior High school and Silver Ridge Elementary school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- ☐ The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- ☐ Site class is the same as what was predicted

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on an unsorted mix of clay through boulder-size material deposited by glaciers.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

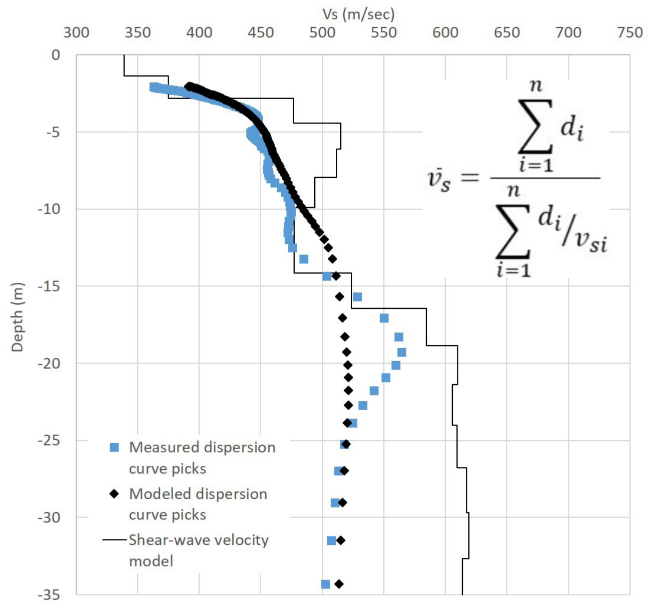
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 4.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 2.9 percent. The velocity profile shows rapidly increasing velocity in the upper 5 m (16 ft) of the model. A velocity reversal occurs from 5 m (16 ft) to 15 m (49 ft) and then a steadily increasing velocity from 15 m (49 ft) to 20 m (66 ft). Below 20 m (66 ft), there is a constant velocity. Our best Vs30 measurement is 521 m/s, which places the site in the C class. The measured site class is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

ROOSEVELT ELEMENTARY SCHOOL

PORT ANGELES SCHOOL DISTRICT, CLALLAM COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast seismic shear waves move through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

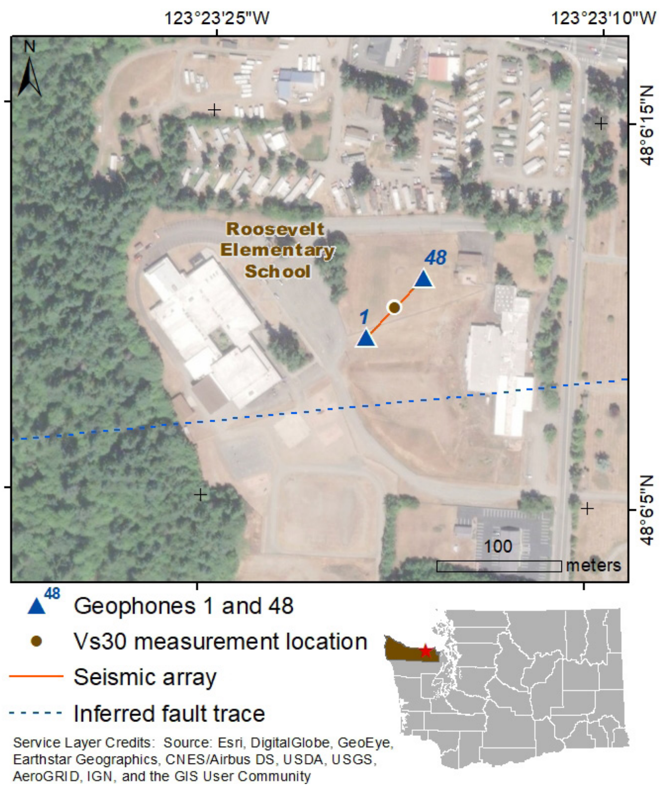
On July 31, 2018, a team from the Washington Geological Survey conducted a seismic survey at Roosevelt Elementary School. We measured seismic velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 231-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock and very dense soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on two seperate geologic units (1) artifical man-made fill, and (2) deposits primarily consisting of gravel, sand, silt, clay, and locally peat.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

Landslide
Hazard present

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of good quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality, with a pickable fundamental mode. The MASW dispersion curves from the forward and reverse directions do indicate some variability and neither adequately sample down to 30 m (100 ft). Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

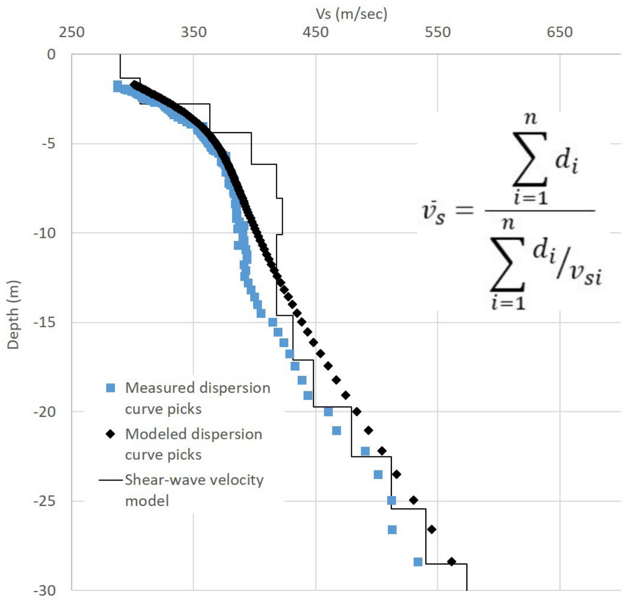
VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 6.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.4 percent. The final velocity model shows variably increasing velocity with depth over the profile. Our best Vs30 measurement is 431 m/s, which places the site in the C class. The predicted site class is D or C, which correlates with the measured C site class.

GEOLOGY

The 1:24,000-scale geologic map shows the school building sitting mostly on Holocene artificial fill (unit Qml) and partly on Pleistocene recessional outwash and glaciomarine drift (unit Qgo). The geophone array is completely located within unit Qgo. Therefore, the impact on Vs30 from the artifical fill cannot be completely assessed without determining the dominate materials of the artificial fill and verifying its extent. Verifying the artificial fill is beyond the scope of the project. However, for the purposes of this study, we assume the artificial fill is sitting unconformably on top of the unit Qgo and is only a few meters thick. Due to the proximity of the array to the building and a lack of evidence for significant heterogeneous velocity structure along the array we assign site class C to the school campus.

The school campus is crossed by an unnamed Quaternary age inferred fault (USGS reference ID 555). The fault trace is mapped at a 1:250,000 scale by Gower and others (1985) who project it through the campus directly south of the Roosevelt Elementary School.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS? **Washington Department of Natural Resources—WA Geological Survey**
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

SHAW ISLAND SCHOOL

SHAW ISLAND SCHOOL DISTRICT, SAN JUAN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

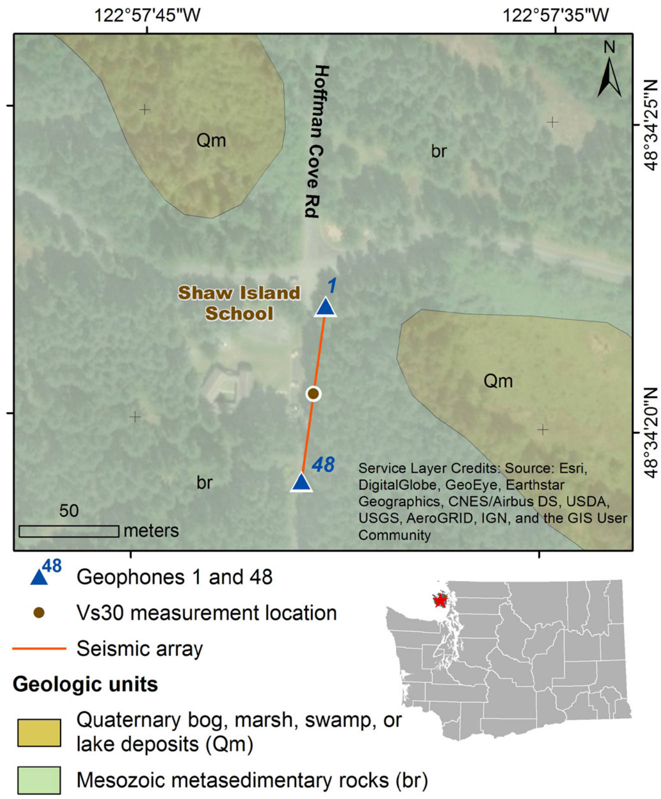
On September 5, 2018, a team from the Washington Geological Survey conducted a seismic survey at Shaw Island School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS: B



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on metamorphosed sandstone, argillite, mudstone, and conglomerate (unit br). Mapped to the northeast and west are deposits of silt and sand deposited by marshes and bogs (unit Qm).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

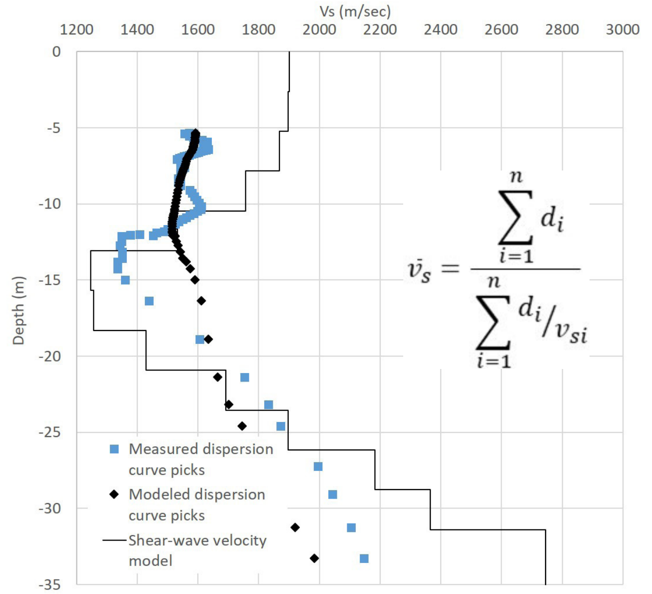
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves are slightly different, which indicates some variability across the geophone array. The microtremor analysis method (MAM) dispersion image is unusable, but is not needed because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

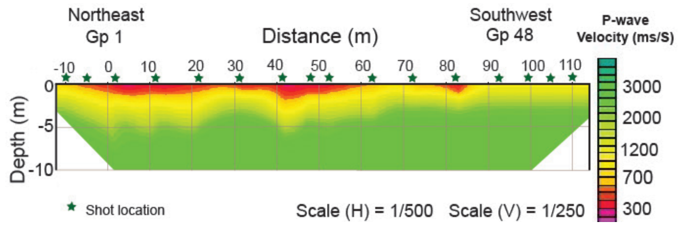
An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW reverse direction (located off end geophone 48). The initial model has an RMSE of 5.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.3 percent. The final model shows generally constant velocity from 1 m (3 ft) to 6 m (20 ft), but is unconstrained in the upper 5 m (16 ft). Below 6 m (20 ft), the velocity model shows a significant velocity reversal down to 18 m (59 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 1674 m/s, which places the site in the middle of the B site class. Although, the MASW dispersion curves from the reverse and forward directions do show some variability, the inverted models from each are in the middle of the B class, so the site can be confidently classified. This correlates with the predicted site class of B.

GEOLOGY

The 1:24,000-scale geologic map shows the school building sitting on Mesozoic metasediments (unit br) that are quite dense and have a predicted site class of B. Mapped nearby are areas of Quaternary bog, marsh, or swamp deposits (unit Qm) that could have affected our site class measurements. The 2D P-wave tomography model shows a thin, low velocity layer near the surface without significant heterogeneity below 5 m (15 ft). Due to the proximity of the array to the building and a lack of evidence for significant heterogeneous velocity structure along the array in the 2D P-wave refraction we assign a site class B to the campus. However, we recommend further geotechnical investigation to verify the depth to unit br at the site.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (VS) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.



2D refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth across the geophone array from the farthest off end shot from both ends. For this model, velocity is fairly consistent, with no observed heterogeneity.

SKYKOMISH SCHOOL

SKYKOMISH SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

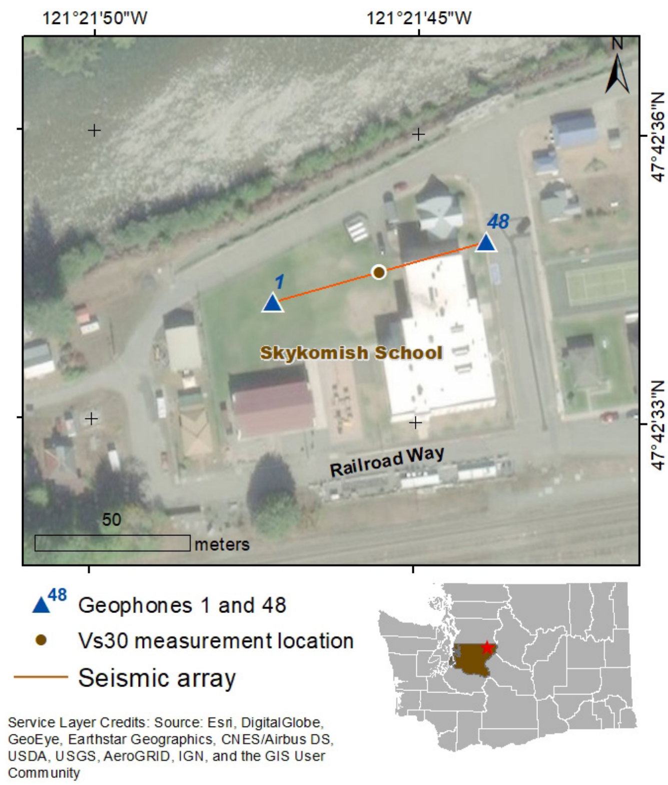
On June 19, 2018, a team from the Washington Geological Survey conducted a seismic survey at Skykomish School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 231-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

Landslide
Hazard present

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

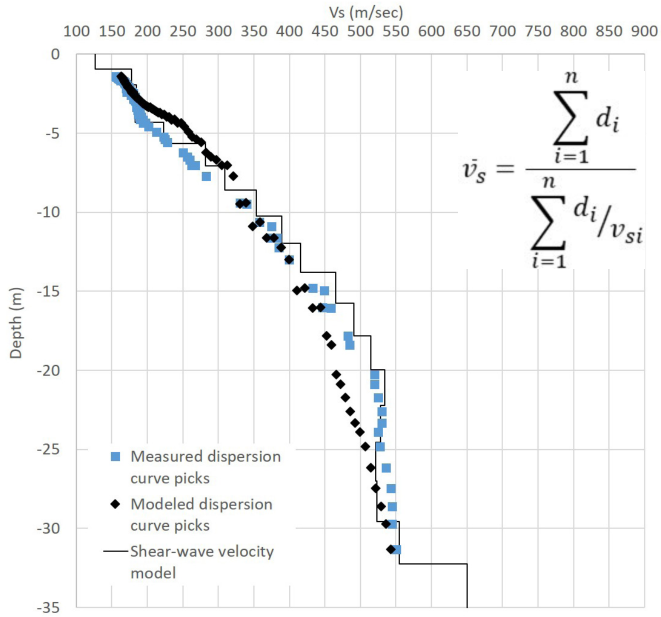
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of decent quality and the fundamental mode can be picked from 6 to 27Hz. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 13.4 percent. The inversion was carried out for fourteen iterations and resulted in a final model with an RMSE of 6.7 percent. The final velocity model shows a generally steady increase in velocity from 1 m (3 ft) down to 30 m (100 ft) depth. Our best Vs30 measurement is 347 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class,



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

SKYRIDGE MIDDLE SCHOOL

CAMAS SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

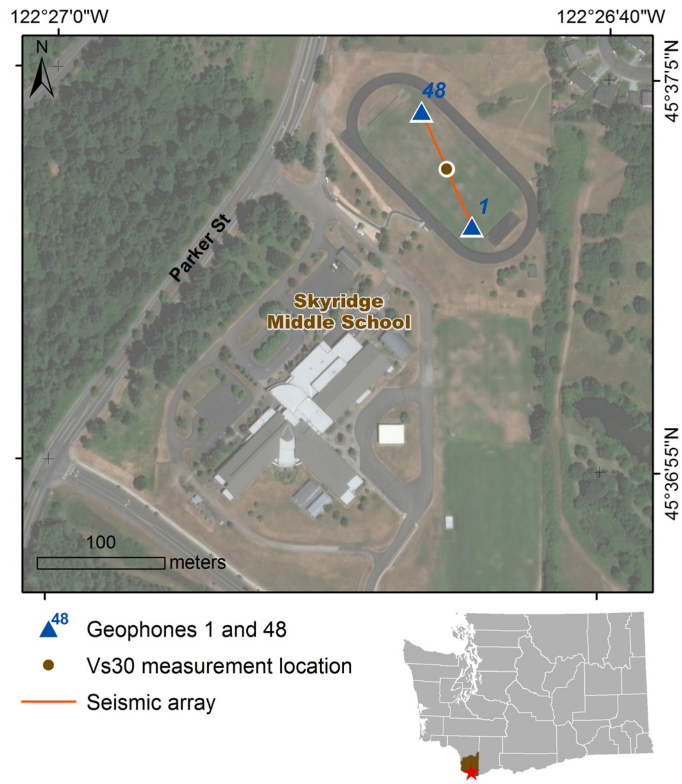
On September 10, 2018, a team from the Washington Geological Survey conducted a seismic survey at Skyridge Middle School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was previously thought.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on weathered conglomerate that varies in sorting and cementation.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

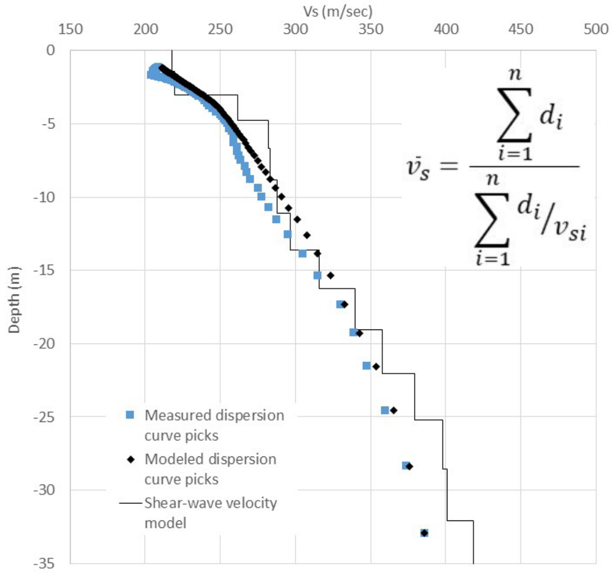
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is not of good quality and was not used for analysis. The MASW adequately samples down to 30 m (100 ft) depth.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the reverse direction (located off end geophone 48). The model has an RMSE of 6.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.5 percent. The final velocity model shows steadily increasing shear wave velocity with depth. Our best Vs30 measurement is 312 m/s, which places the site in the D class. The predicted site class is C or D, which correlates with the measured D site class.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

SOUTH BEND JUNIOR AND SENIOR HIGH SCHOOL

SOUTH BEND SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

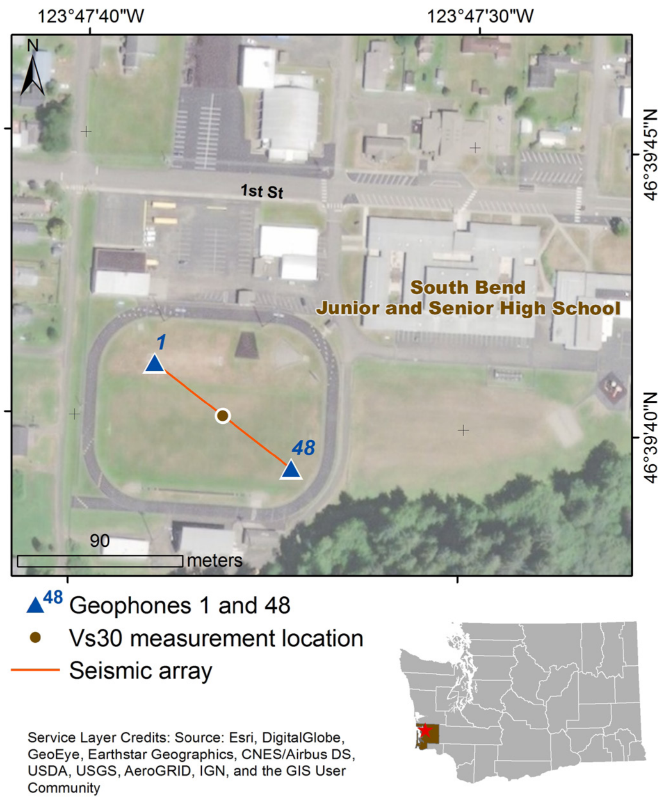
On June 19, 2018, a team from the Washington Geological Survey conducted a seismic survey at South Bend Junior and Senior High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on silt, sand, and gravel deposited in streambeds.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Landslide
Hazard present

TECHNICAL OVERVIEW OF RESULTS

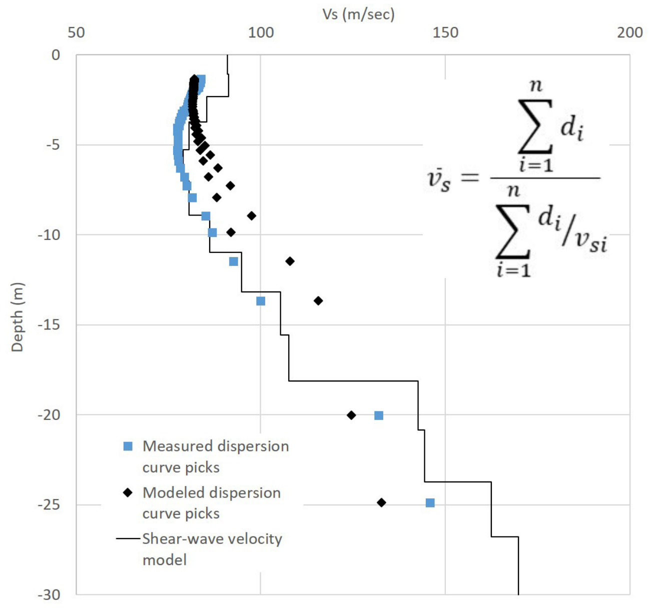
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward a direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 6.3 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 3.7 percent. The velocity models shows a slight velocity inversion above 5 m (16 ft) and increasing velocities below that down to 30 m (100 ft). The best estimate for Vs30 is 109 m/s, which places the site in the site class E. The predicted site class is D or E, which correlates with the measured E site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

SOUTH WHIDBEY ELEMENTARY SCHOOL

SOUTH WHIDBEY SCHOOL DISTRICT, ISLAND COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

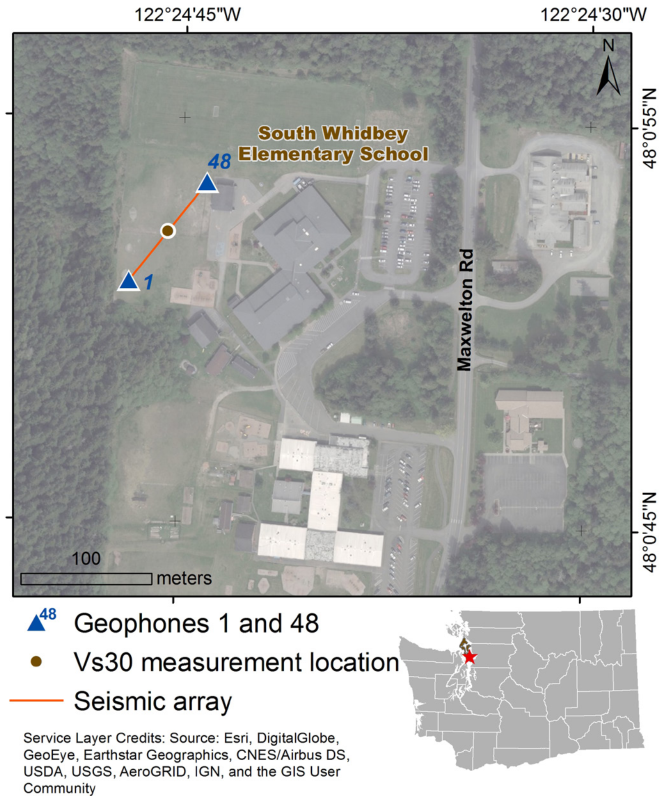
On July 31, 2018, a team from the Washington Geological Survey conducted a seismic survey at South Whidbey Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on an unsorted mix of clay to boulder-sized material, deposited by glaciers.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

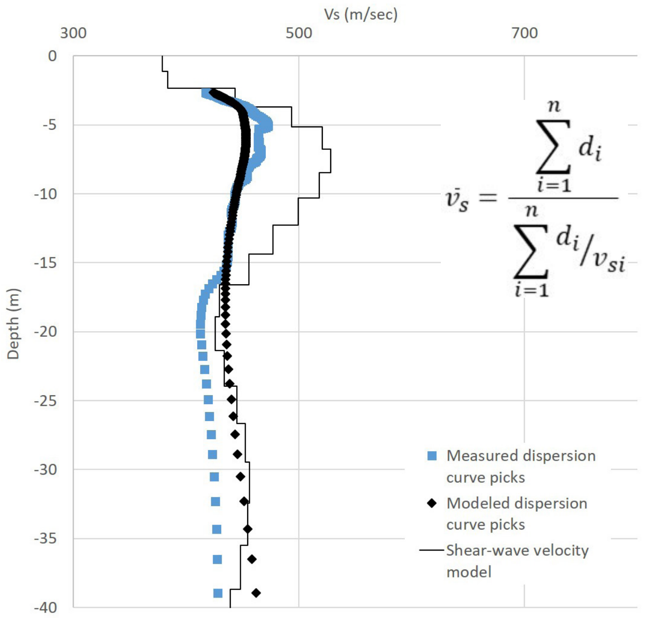
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of excellent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 3.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 2.4 percent. The velocity profile shows rapidly increasing velocity from 2 m (7 ft) down to 8 m (26 ft), with a velocity reversal below, then generally constant velocity down to 30 m (100 ft) depth. Our best Vs30 measurement is 456 m/s, which places the site in the middle of the C class, which is the same as the predicted site class C.

GEOLOGY

The 1:24,000-scale geologic map shows the school building and the geophone array are sitting on Pleistocene continental glacial till (unit Qgt(v)). The velocity profile suggests there is a higher velocity layer between 3 m (10 ft) and 17 m (56 ft). There are no obvious geologic units that could explain the high velocity layer in the surficial geology. A nearby borehole log is not detailed enough to provide an explanation. Due to the mixed clast sizes common in glacial till, it is likely that the high velocity layer represents an increase in clast size locally.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

SPINNING ELEMENTARY SCHOOL

PUYALLUP SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

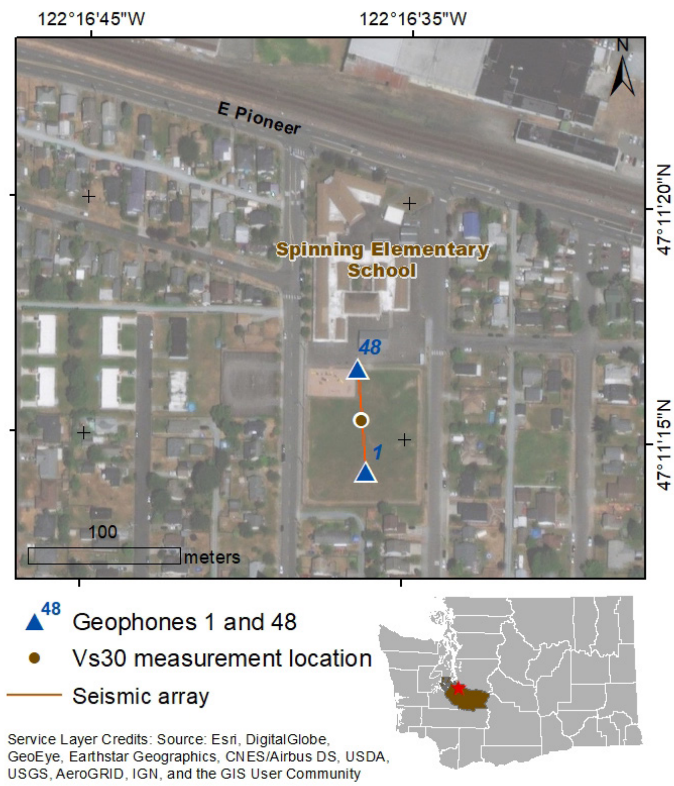
On August 15, 2018, a team from the Washington Geological Survey conducted a seismic survey at Spinning Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 231-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mostly sand deposited by a river system.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
High hazard

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

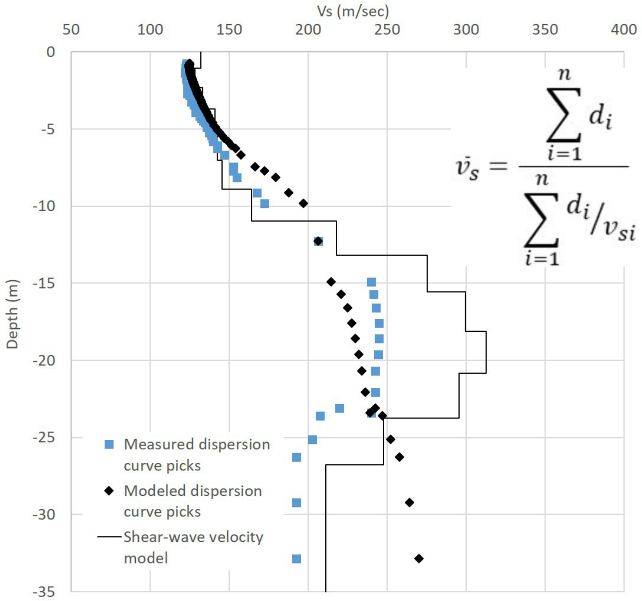
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked from 2 to 20 Hz. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 7.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.8 percent. The final velocity model shows constant velocity with depth down to 10 m (33 ft), then a sharp increase in velocity at 12 m (39 ft), and a velocity reversal below 20 m (66 ft). Our best Vs30 measurement is 200 m/s, which places the site in the low D class. The predicted site class is D or E, which correlates with the measured D site class.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

TAHOLAH ELEMENTARY SCHOOL

TAHOLAH SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

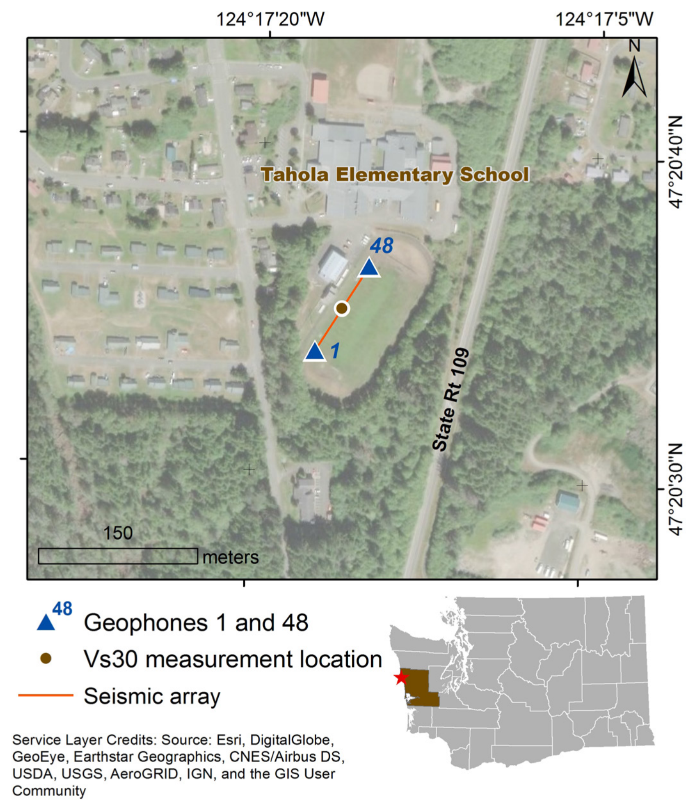
On June 20, 2018, a team from the Washington Geological Survey conducted a seismic survey at Taholah Elementary School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

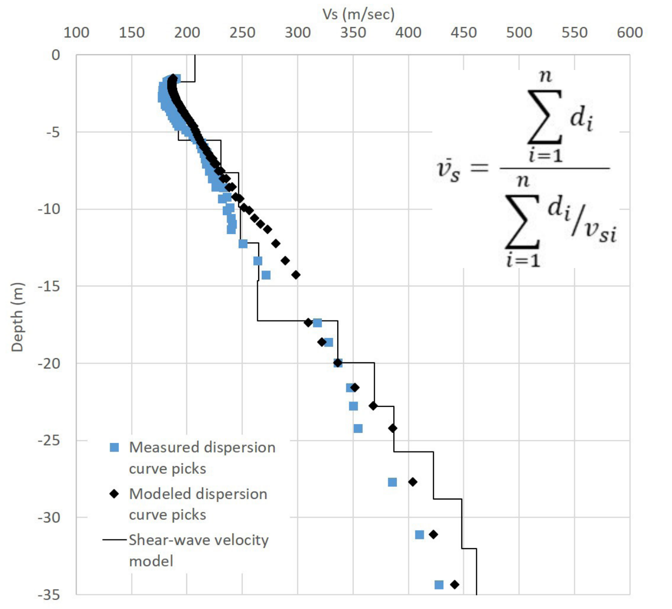
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 8.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final velocity model shows a small velocity reversal in the top layer of the model, then generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft). Our best Vs30 measurement is 278 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

THORP ELEMENTARY AND JUNIOR–SENIOR HIGH SCHOOL

THORP SCHOOL DISTRICT, KITTITAS COUNTY, WA

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

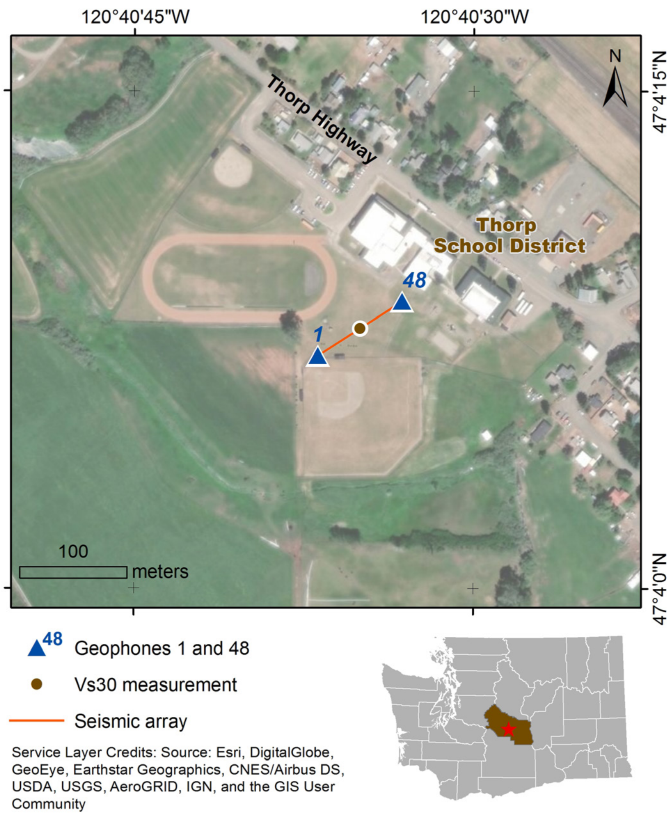
On June 16, 2018, a team from the Washington Geological Survey conducted a seismic survey at Thorp School District. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium (river sediments) composed of silt, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Very Strong

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

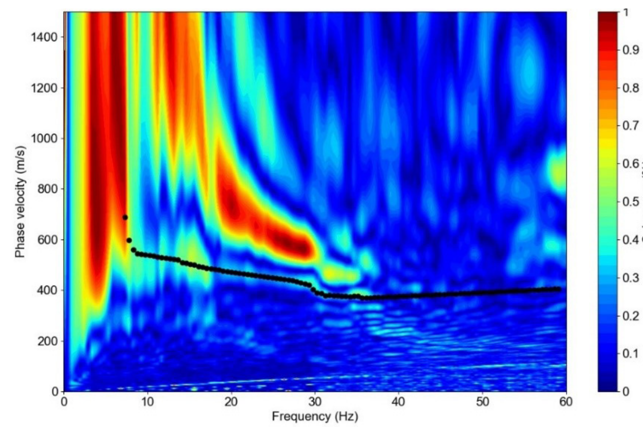
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. A strong higher mode in the multi-channel analysis of surface waves (MASW) dispersion images makes the fundamental mode difficult to pick. The microtremor analysis method (MAM) dispersion image is also of poor quality and the fundamental mode could not be picked. Ultimately, the MASW dispersion curve samples sufficiently deep to classify the site, so the MAM data is not used for analysis.

VELOCITY MODEL

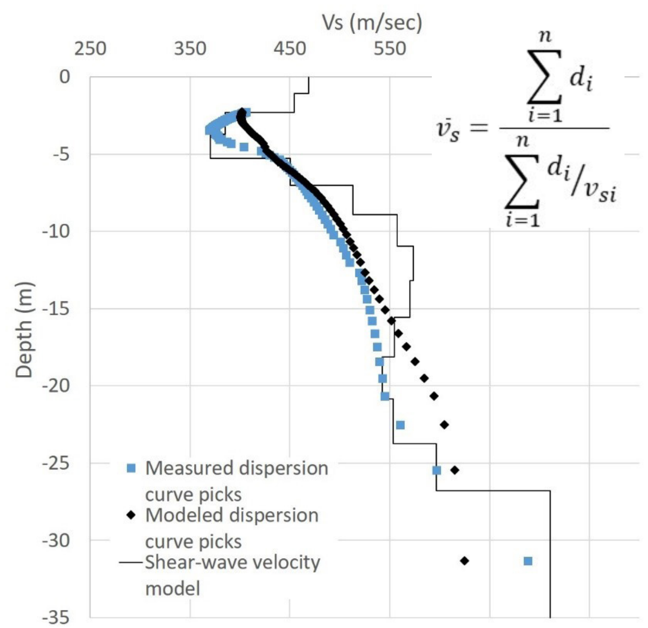
An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curves. The model has an RMSE of 8.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final velocity model shows a significant velocity reversal above 5 m (16 ft) and a rapidly increasing velocity from 5 m (16 ft) to 10 m (33 ft). The final model shows another velocity reversal between 15 m (49 ft) and 22 m (72 ft) and generally increasing velocity below. Our best Vs30 measurement is 532 m/s, which places the site in the C class The Vs30 values from the MASW measurements are all within the C site class, so this site can be confidently classified. This is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000-scale geologic map shows that both the school building and the array are sitting on Quaternary alluvium (unit Qa) which has a predicted site class of D or E. However, there are outcrops of Pliocene sedimentary rocks and deposits (unit PLcg(t)) and Pleistocene alpine glacial drift (unit Qapo(ki)) nearby. These units have a predicted site class of B and C respectively. Nearby boreholes show deposits of cemented gravel around 4 m (14 ft) overlying alternating sandy to silty gravels. Thus, it is likely that the Quaternary alluvium is underlain by one of these higher velocity units, which could help explain the difference in site class. This is further supported supported by the 2D refraction analysis, which shows a strong impedance contrast at 2 m (7 ft). Therefore, we assign site class C to the school campus.



MASW dispersion image, with warmer colors indicating high coherence. The picked fundamental mode is shown as black circles, this is the measured dispersion curve .



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

TONASKET ELEMENTARY AND HIGH SCHOOL

TONASKET SCHOOL DISTRICT, OKANOGAN COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

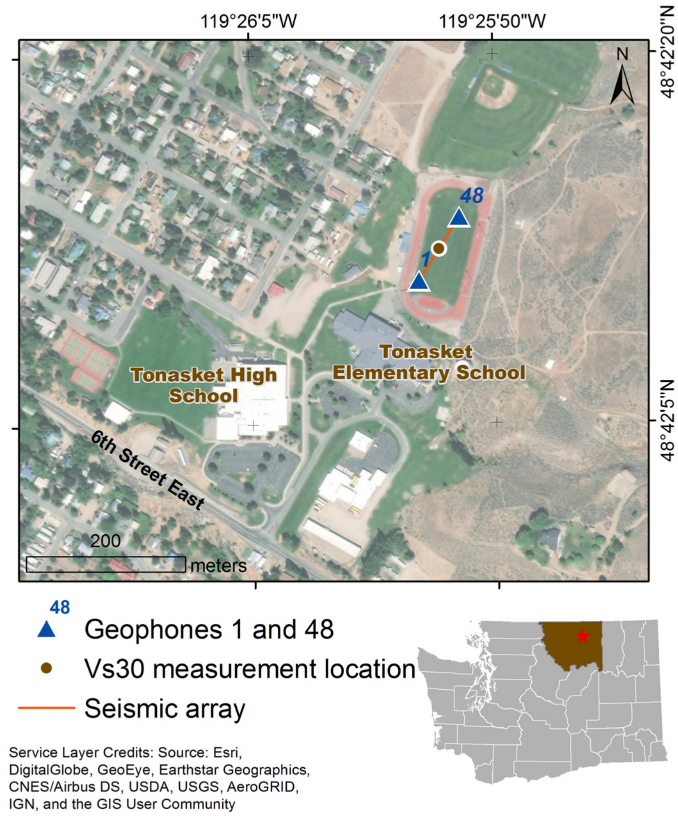
On May 16, 2017, a team from the Washington Geological Survey conducted a seismic survey at Tonasket Elementary and High School for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low hazard

Ground Shaking
Very Strong

TECHNICAL OVERVIEW OF RESULTS

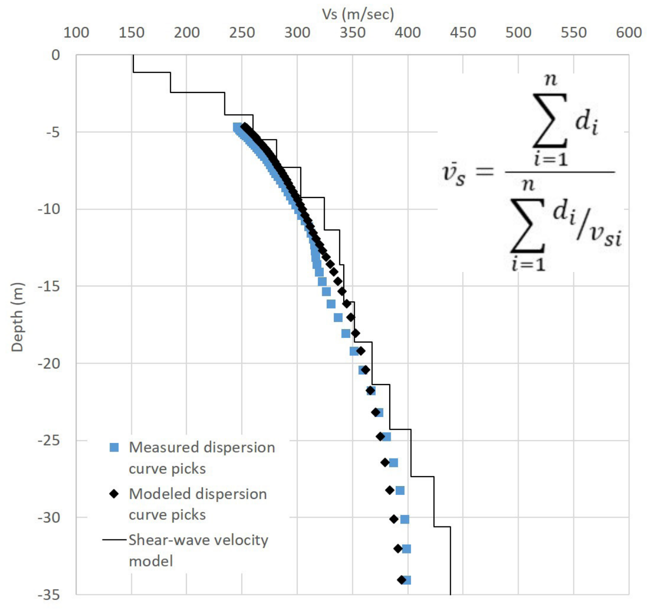
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images areof excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of excellent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 7.9 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.1 percent. The upper 5 m (16 ft) of the final velocity model is unconstrained, but the model shows generally increasing velocity from 1 m (3 ft) to a depth of 30 m (100 ft). Our best Vs30 measurement is 313 m/s, which places the site in the D class. The predicted site class is C or D, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

TOTEM MIDDLE SCHOOL

MARYSVILLE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

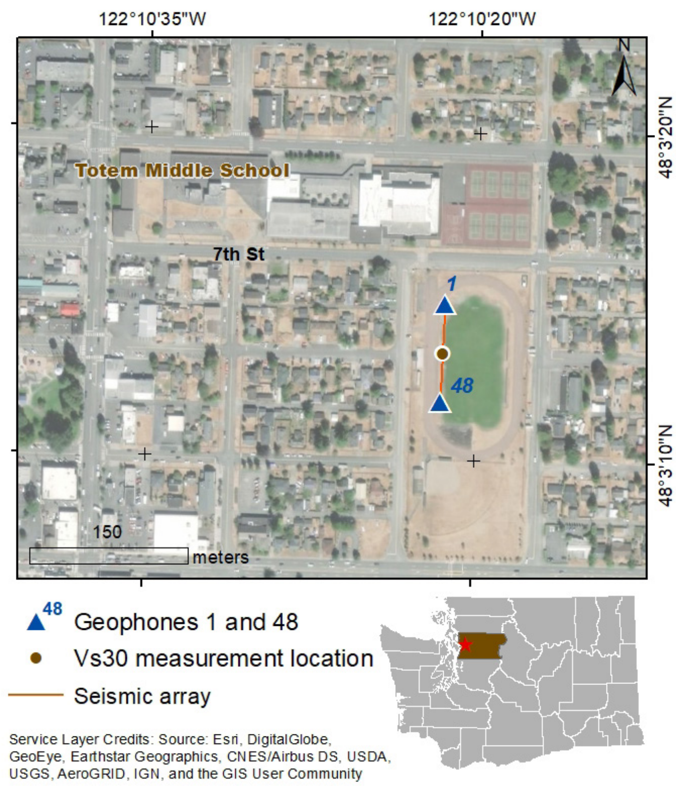
On November 8, 2018, a team from the Washington Geological Survey conducted a seismic survey at Totem Middle School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is on stratified to massive outwash sand deposited by glaciation.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate hazard

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

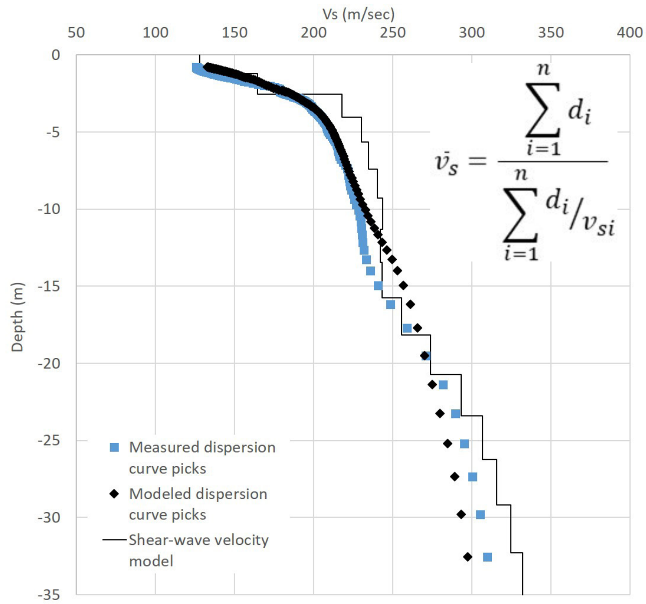
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is generally of good quality, but does not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of decent quality and the fundamental mode can be picked from 2 to 26 Hz. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 8.3 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.4 percent. The final velocity model shows a generally increasing velocity down past 30 m (100 ft). Our best Vs30 measurement is 246 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

QUESTIONS?

Washington Department of Natural Resources—WA Geological Survey
geology@dnr.wa.gov • 360.902.1450 • https://www.dnr.wa.gov/geology

TOUCHET ELEMENTARY AND HIGH SCHOOL

TOUCHET SCHOOL DISTRICT, WALLA WALLA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

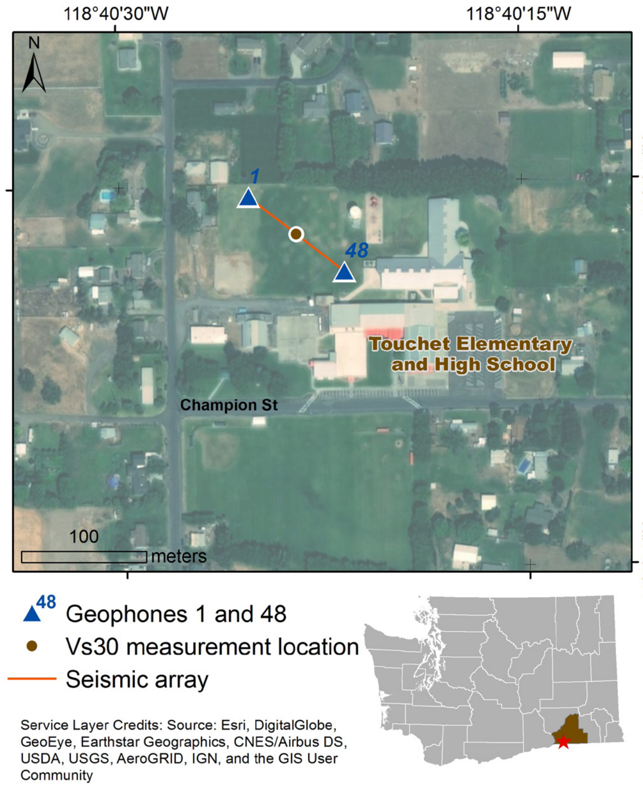
On July 2, 2018, a team from the Washington Geological Survey conducted a seismic survey at Touchet Elementary and High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on clay, silt, sand and gravel deposited by the river system.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Strong

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

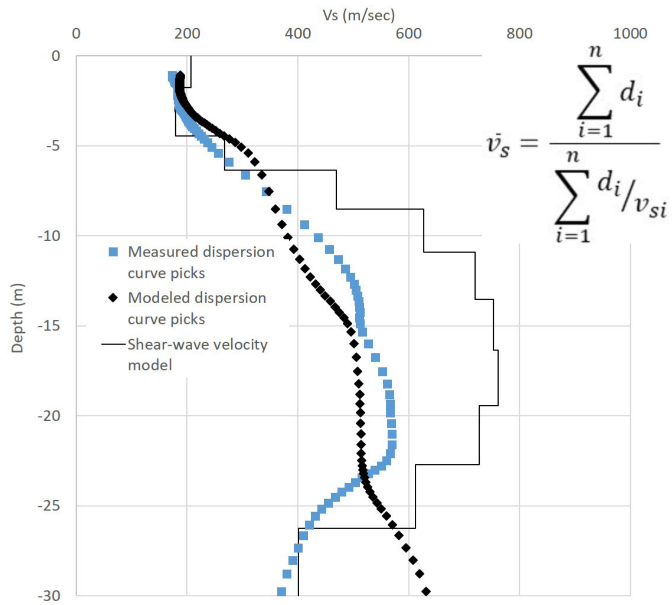
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 12.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 9.8 percent. The final velocity model shows constant velocity in the upper 5 m (16 ft), then a general increase in velocity down to 17 m (56 ft), and decreasing velocity from 17 m (56 ft) to 30 m (100 ft). Our best Vs30 measurement is best Vs30 measurement is 427 m/s, which is in the middle of the C class. Although the inverted model did not converge to below 5 percent RMSE, all initial and final models were in the middle of the C class, so the site can be confidently classified. This is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000 scale geologic map shows the school building and the geophone array are sitting on Quaternary alluvium (unit Qa) which has a predicted site class of D or E. A nearby borehole log in the surrounding area shows thick cemented gravel deposits below 15 m (48 ft) depth, which are underlain by non-cemented deposits. Cemented deposits can vary significantly in thickness over relatively short distances increasing shear wave velocities locally. Deposits of higher velocity cemented gravels underlain by non-cemented deposits could be contributing to the observed relatively high velocity with lower velocity below 17 m (56 ft). Cemented deposits could also help explain the discrepancy between the predicted and measured site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

TUMWATER FIRE DEPARTMENT HEADQUARTERS

311 ISRAEL RD SW, TUMWATER, THURSTON COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

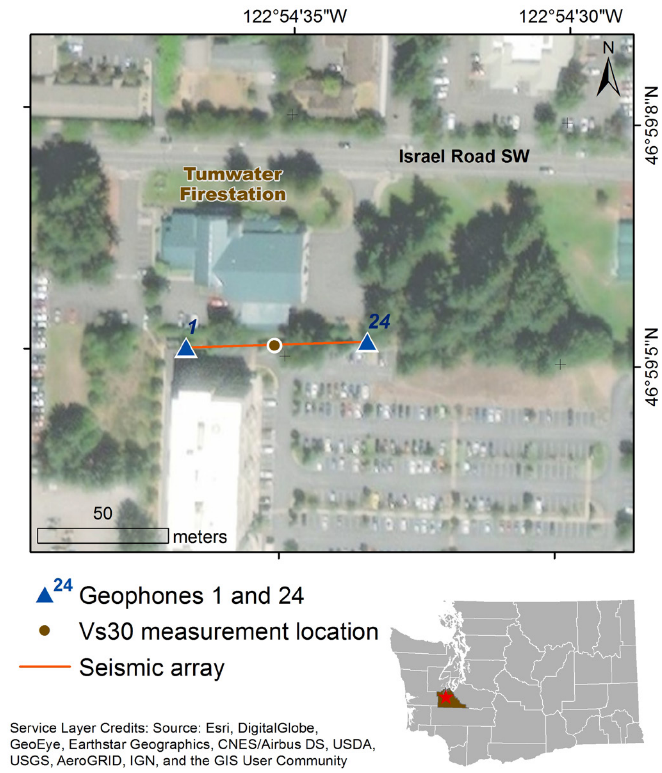
On June 7, 2010, a team from the Washington Geological Survey conducted a seismic survey at the Tumwater Fire Deparment headquarters for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 230-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the fire station, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The fire station is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array near the fire station.

WHAT SOILS ARE UNDER THE FIRE STATION?

The fire station is sitting on sand and silt with minor gravel interbeds.

GEOLOGIC HAZARDS AT THE FIRE STATION

Liquefaction
Low to moderate

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

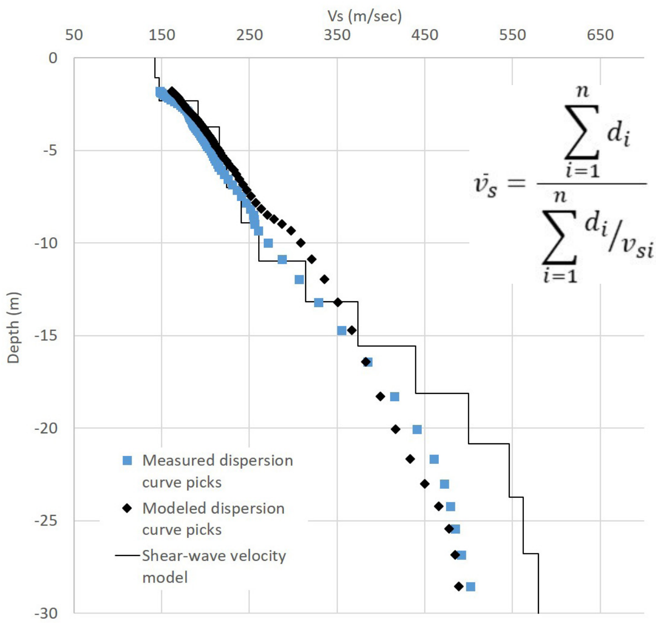
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are suspect below 6 Hz but the fundamental mode can be picked up to 28 Hz. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100-ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. The combined MASW and MAM dispersion curves diverge below 10 Hz but do depict a similar overall trend, so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves from the MASW forward direction (located off end geophone 1) and the MAM. The initial model has an RMSE of 12.5 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.9 percent. The final velocity model shows a generally steady increase in velocity with depth from 2 m (7 ft) to 30 m (98 ft). Our best Vs30 measurement is 318 m/s, which places the site in the middle of the D class. This site class is the same as the predicted site class of D.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i/v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

UNION RIDGE ELEMENTARY SCHOOL

RIDGEFIELD SCHOOL DISTRICT, RIDGEFIELD, CLARK COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

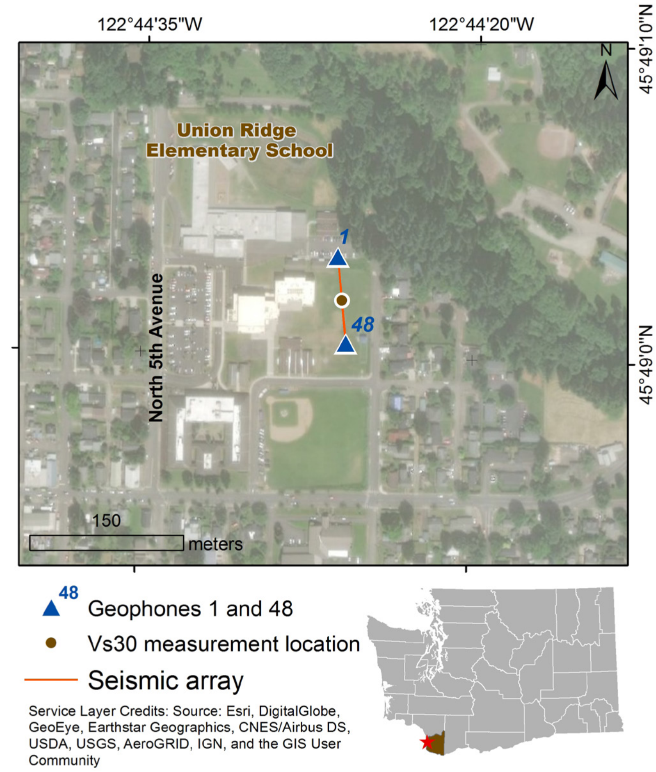
On June 26, 2018, a team from the Washington Geological Survey conducted a seismic survey at the Union Ridge elementary school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted C site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on clay, silt, and fine to medium sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

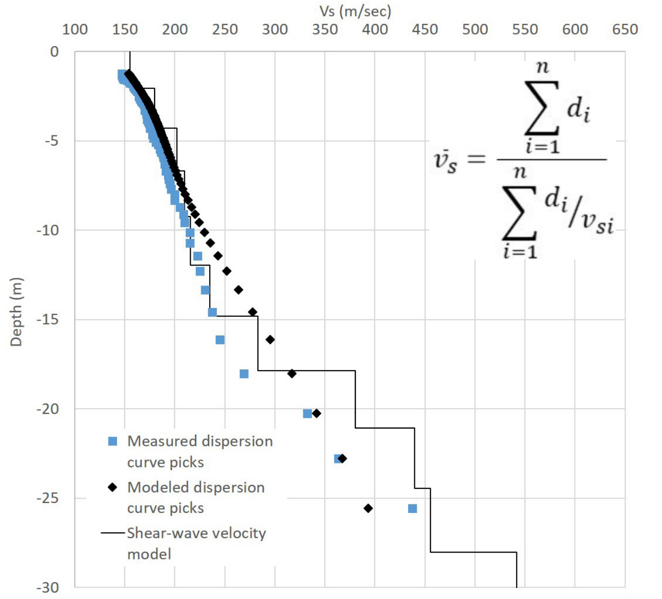
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of good quality and the fundamental mode can be easily picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 9.2 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.3 percent. The final velocity model shows a generally steady increase in velocity with depth from 2 to 30 m (7 to 100 ft). Our best Vs30 measurement is 268 m/s, which places the site in the middle of the D class. The Vs30 values derived from the combined MASW and MAM measurements are all within the D class, so we can confidently classify the site as a D. The measured site class is different than the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic maps show that the school building and geophone array are sitting on Pleistocene outburst flood deposits (unit Qfs). These fine-grained catastrophic flood deposits are described as unconsolidated clay, silt, and fine to medium sand in the area, which would lead to lower velocities. These lower velocity sediments could help explain the discrepancy between the predicted and measured site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

VANCOUVER FIRE DEPARTMENT STATION NO. 9

17408 SOUTHWEST 15TH STREET, VANCOUVER, CLARK COUNTY, WA

WHAT IS SITE CLASS?

To assess seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

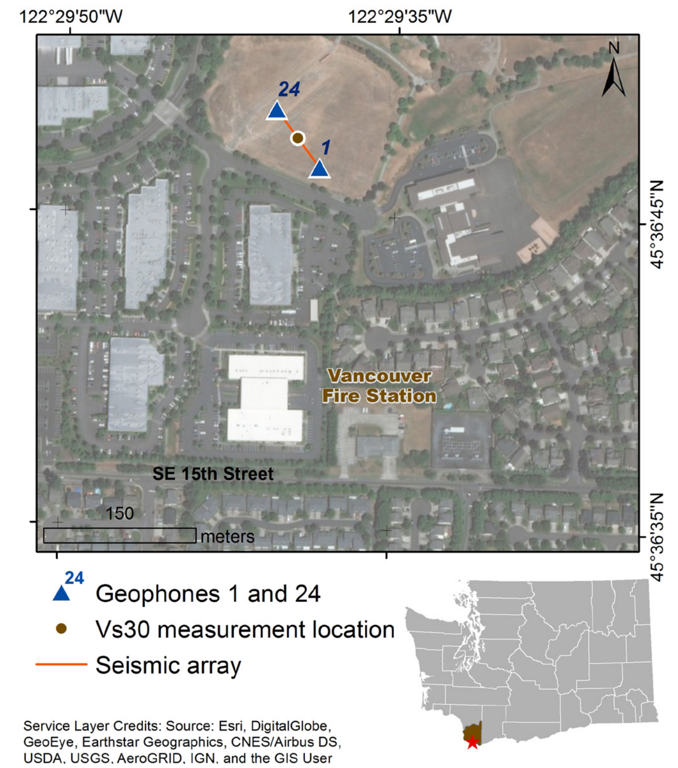
On September 3, 2010, a team from the Washington Geological Survey conducted a seismic survey near the Vancouver Fire Deparment for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 230-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The fire station is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array near the fire station.

WHAT SOILS ARE UNDER THE FIRE STATION?

The fire station is sitting on bouldery to cobbly gravel and sand.

GEOLOGIC HAZARDS AT THE FIRE STATION

Liquefaction
Low to moderate

Ground Shaking
Severe

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

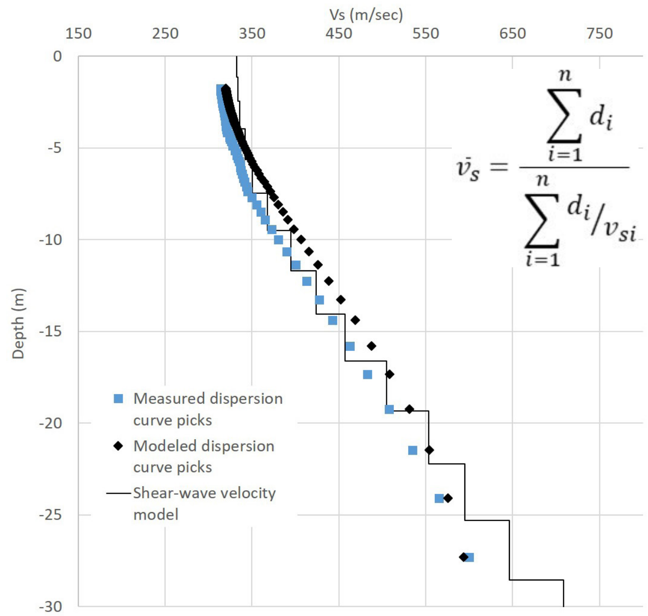
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are of excellent quality and the fundamental mode can be easily picked. However, the MASW dispersion curves are slightly different, which indicates some variability across the geophone array. The microtremor analysis method (MAM) dispersion image is not of good quality and is not used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW reverse direction (located off end geophone 24). The initial model has an RMSE of 7.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.0 percent. The final velocity model shows constant velocity in the upper 5 m (16 ft) and steadily increasing velocity with depth below. Although the forward and reverse MASW have slightly varying final models the measured Vs30 are both in the middle of the site class C, so the site can be confidently classified. Our best Vs30 measurement is 450 m/s, which is different than the predicted site class of D.

GEOLOGY

The 1:24,000-scale geologic map shows that both the fire station and geophone array are sitting on Pleistocene outburst flood deposits (unit Qfg). These deposits are described as being crudely stratified, poorly sorted, and containing boulders. Nearby borehole logs show thick layers containing boulders at varying depths below 5 m (16 ft) depth. These deposits of boulders would likely result in a bulk velocity effect that increases velocity locally and could help explain the discrepancy between the predicted and measured site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

VASHON ISLAND HIGH SCHOOL

VASHON ISLAND SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

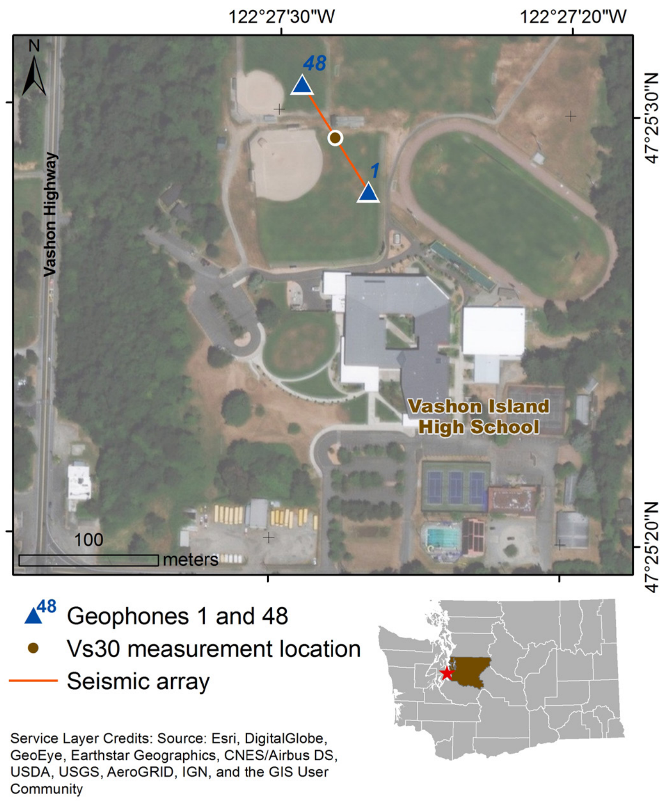
On July 17, 2018, a team from the Washington Geological Survey conducted a seismic survey at Vashon Island High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on unsorted sand and gravel in a matrix of mud that was deposited by glaciation.

GEOLOGIC HAZARDS AT THE SITE

Liquefaction
Very low hazard

Ground Shaking
Violent

Active Fault Proximity
Within five miles of an active mapped fault

TECHNICAL OVERVIEW OF RESULTS

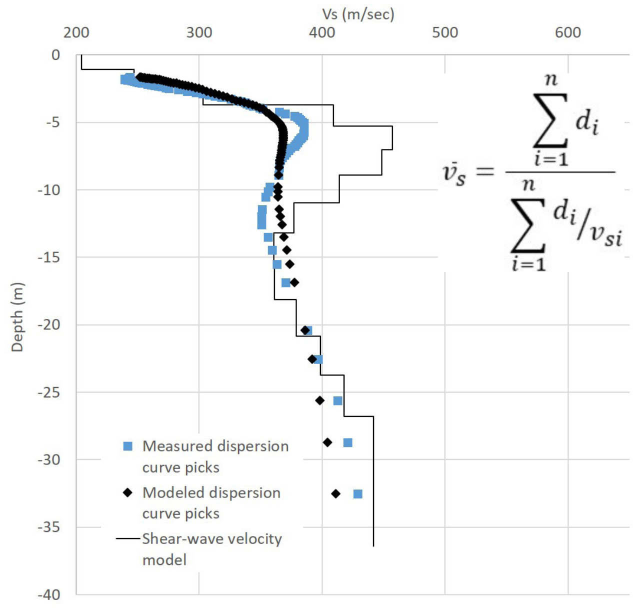
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is generally of good quality and it samples down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of poor quailty, so only the MASW dispersion curves are used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve from the forward direction (located off end geophone 1). The inital model has an RMSE of 9.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.2 percent. The final velocity model shows a rapid velocity increase down to 5 m (16 ft), then a significant velocity reversal below, and then generally a constant velocity from 15 m (49 ft) to 30 m (100 ft). Our best Vs30 measurement is 375 m/s, which places the site in the C class. This correlates with the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

WALLA WALLA COUNTY FIRE DISTRICT NO. 4

2251 SOUTH HOWARD STREET, WALLA WALLA, WALLA WALLA COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

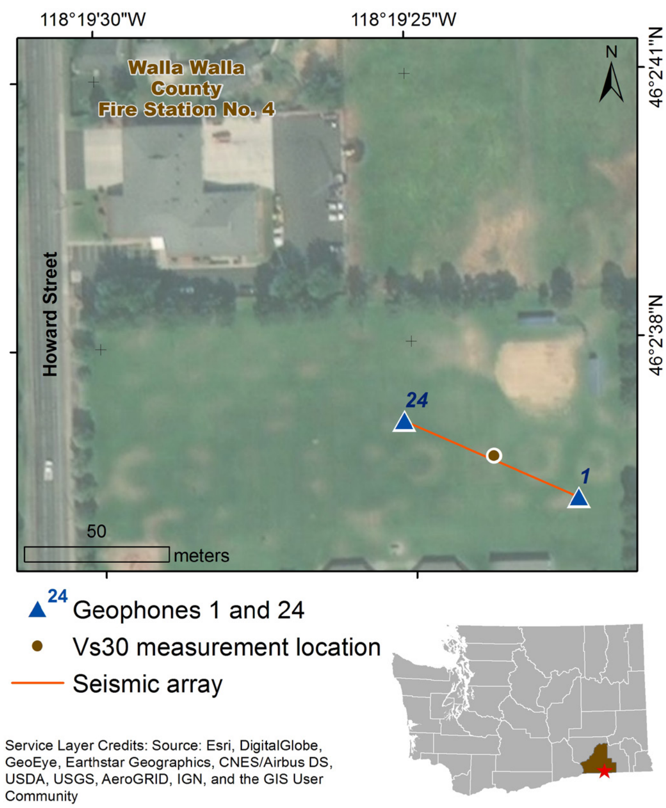
On June 24, 2010, a team from the Washington Geological Survey conducted a seismic survey near the Walla Walla County Fire Station No. 4 for an earlier project. The team measured shear wave velocity of the upper 30 m (100 ft) by laying out 24 geophones (ground motion sensors) in a 230-ft line. Then they conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the fire station, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The fire station is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D or E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the fire station.

WHAT SOILS ARE UNDER THE FIRE STATION?

The fire station is sitting on predominantly sand with minor silt, clay, sparse pebbles, and some gravel.

GEOLOGIC HAZARDS AT THE FIRE STATION

Liquefaction
Moderate to high

Ground Shaking
Strong

Active Fault Proximity
Within five miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

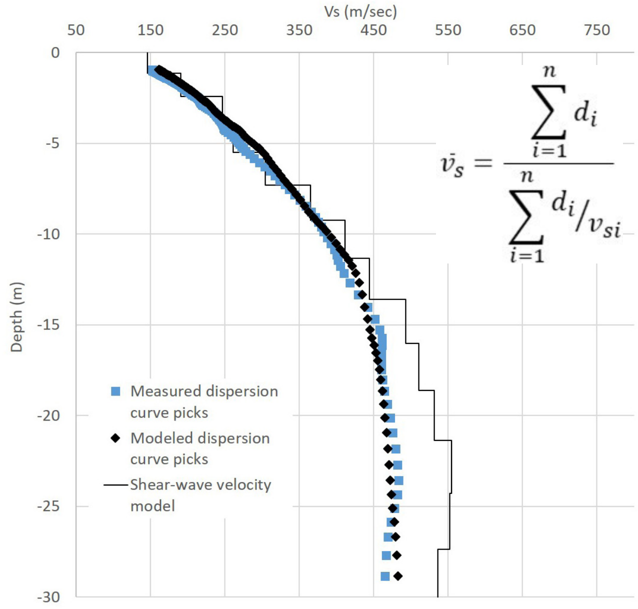
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is of reasonable quality, though the fundamental mode gets broad at low frequencies, making the fundamental mode difficult to pick at low frequencies. The microtremor analysis method (MAM) dispersion image is also of reasonable quality and the fundamental mode is easy to pick. The combined dispersion curves coorelate well with a similar overall trend, so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 10.4 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.1 percent. The final velocity model shows a generally steady increase in velocity with depth from 1 m (3 ft) to 22 m (72 ft), then a generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 382 m/s, which places the site in the low end of the C class. This is different than the predicted site class of D or E.

GEOLOGY

The 1:100,000-scale geologic map shows the fire station and the geophone array sitting on Quaternary alluvium (unit Qa) which has a prdeicted a site class D to E in this area. However, the more detailed 1:24,000-scale geologic map shows that the fire station is sitting on Pleistocene outburst flood deposits (unit Qfs(t2)). These glacial slackwater flood deposits are described as having an older sequence dominated by minor silt, clay, and sparse pebbles and ice-rafted gravel and a younger sequence dominated by fine- to medium-grained felsic to basaltic sand at the base, grading upward to felsic silt. A borehole log located close by shows thick layers containing large rocks and gravel from 1.5 m (5 ft) to 10.5 m (34 ft) depth, then gravel from 13.7 m (45 ft) to almost 30 m (100 ft) depth. These gravelly deposits would likely result in a bulk velocity effect that increases velocity locally, which could help explain the discrepancy between the predicted and measured site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

WARDEN ELEMENTARY, MIDDLE, AND HIGH SCHOOL

WARDEN PASS SCHOOL DISTRICT, GRANT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

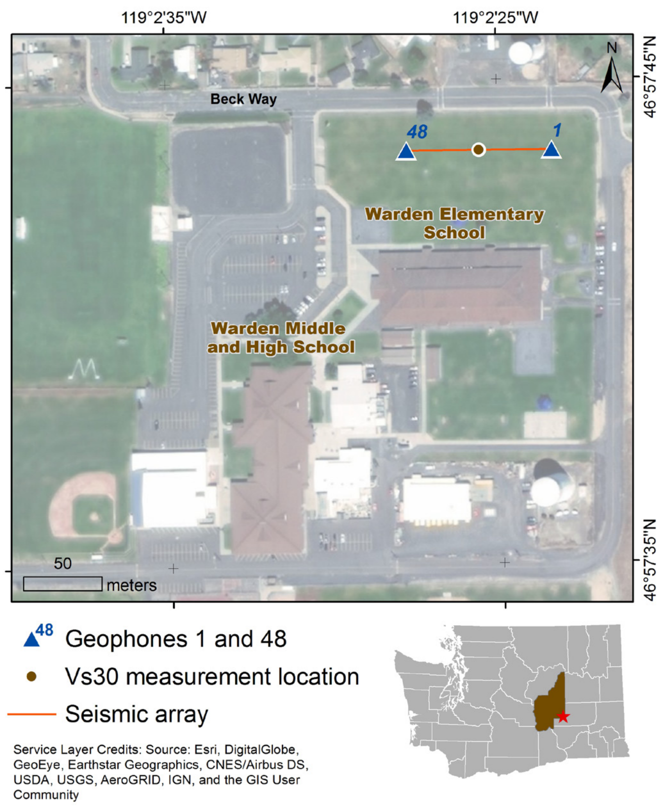
On August 27, 2018, a team from the Washington Geological Survey conducted a seismic survey at Warden Elementary, Middle, and High school. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on wind deposited silt and fine sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate hazard

Ground Shaking
Strong

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

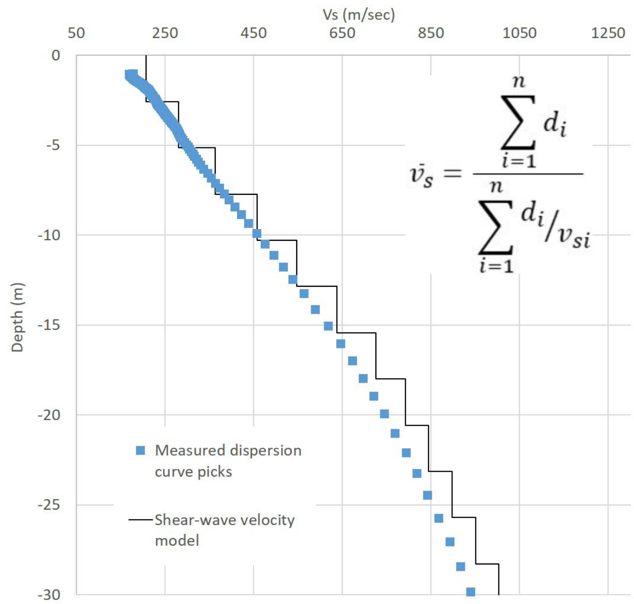
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image.The multi-channel analysis of surface wave (MASW) dispersion images are of good qaulity and the fundamental mode can be picked. However, the MASW dispersion curves from the forward and reverse directions do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is good quality, with a fundamental mode that can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse directions) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 13.5 percent. The combined analysis did not converge to below 5 percent RMSE. The final velocity model shows steadily increasing velocity to a depth of approximately 30 m (100 ft). Our best Vs30 estimate is 503 m/s with places the site on the middle of the site class C. Despite the lack of convergence, all initial models resulted in a Vs30 in the middle of the C class, so we are confident in the measured site class of C. This is different than the predicted site class of D

GEOLOGY

The 1:100,000-scale geologic map shows the school building and geophone array are sitting on Palouse formation (unit Ql), which has a predicted site class of D. To the southwest are mapped exposures of Wanapum Basalt and Touchet Beds (unit Mv(wr)), which have a predicted site class of B. Nearby boreholes encountered broken basalt between 5 m (17 ft) and 25 m (81 ft) and the velocity models do see bedrock velocities (>1000 m/s) in the upper 30 m (100 ft). Thus, it is possible that in this area the low velocity unit Ql sits on top of a high velocity basalt that is shallow enough to affect the Vs30. This suggests that the difference between the measured and predicted site class is due to local variation in unit Qe. Due to the proximity of the array to the building and a lack of evidence for significant heterogeneity we deem the assignment of site class C as appropriate.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

WASHTUCNA ELEMENTARY AND HIGH SCHOOL

WASHTUCNA SCHOOL DISTRICT, ADAMS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

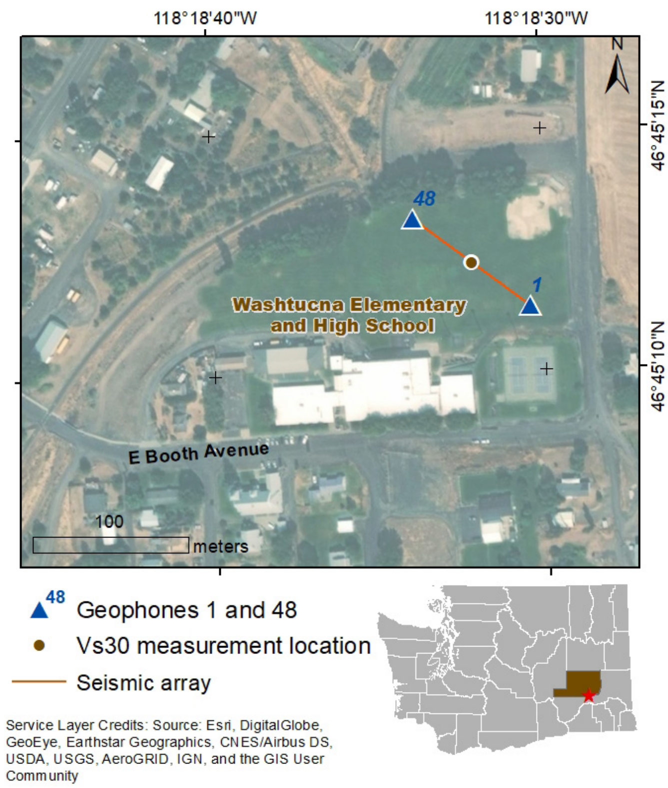
On July 4, 2018, a team from the Washington Geological Survey conducted a seismic survey at Washtucna Elementary and High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted D-E site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Severe

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

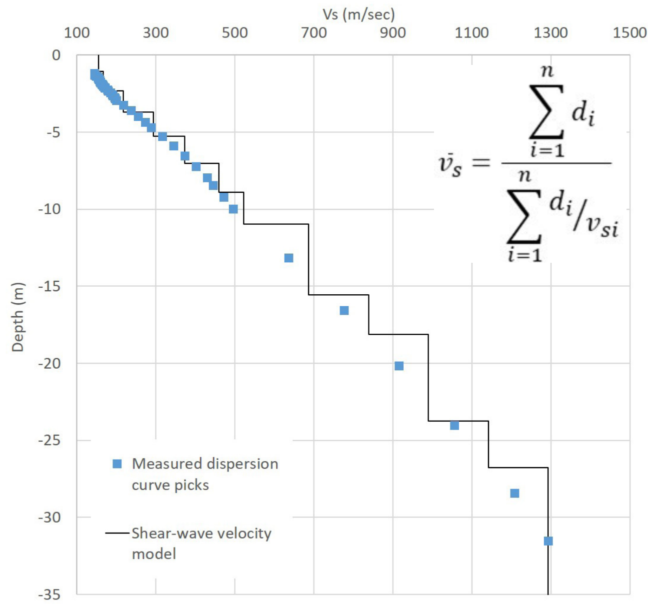
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are low quality but the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is not of good quality and is not used for analysis.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MASW dispersion curve. The combined analysis did not converge to below 5 percent RMSE without forcing artifically high velcoities. The resulting best estimate for Vs30 is 511 m/s and is based on the initial model. Despite the lack of convergence, all intial models resulted in a Vs30 in the middle of the C class, so we are confident in the measured site class of C. The initial model shows steadily increasing velcoity with depth from 1 m (3 ft) to 30 m (100 ft). The predicted site-class is a D-E class, which is significantly different than what we measured.

GEOLOGY

The 1:100,000 geologic maps show that the school building and geophone array are sitting on Quaternary alluvium (unit Qa) which are mapped as a site class D-E. However, there is an outcrop of Pleistocene outburst flood deposits (unit Qfg) mapped just to the south of the school campus. In this area, unit Qfg has a mapped site class of C. The discrepancy between the measured and predicted is likely due to a change in the subsurface geology.



$$\bar{v_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

WAYNE M. HENKLE MIDDLE SCHOOL AND COLUMBIA HIGH SCHOOL

WHITE SALMON SCHOOL DISTRICT, KLICKITAT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

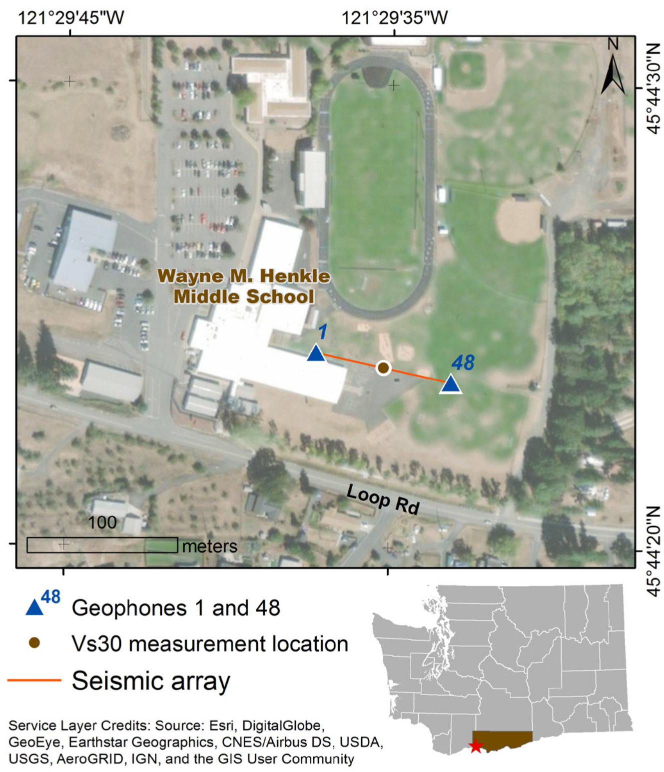
On July 9, 2018, a team from the Washington Geological Survey conducted a seismic survey at the Wayne M. Henkle Middle School and the Columbia High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS: C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on outburst flood deposits of gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Very Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

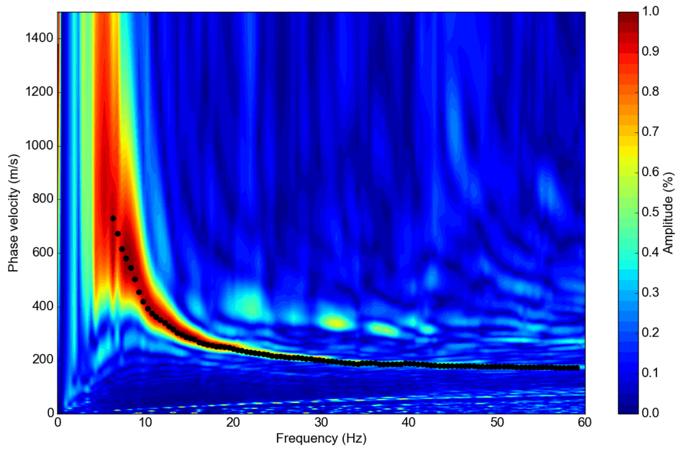
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

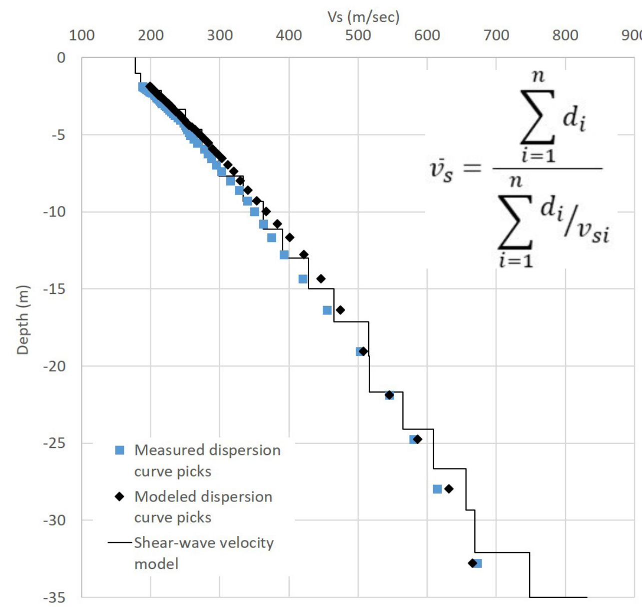
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion is of excellent quality and the fundamental mode can be easily picked. The microtremor analysis method (MAM) dispersion image is also of good quality from 10 to 25 Hz. However, it is used only as a check for consistency in the analysis because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the reverse MASW (offend geophone 48). The initial model has an RMSE of 10.9 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.2 percent. The final velocity model shows a steady increase in velocity with depth down to 30 m (100 ft). Our best Vs30 measurement is 380 m/s, which places the site on the low end of the C class. This Vs30 measurement and site class is the same as the predicted site class of C.



MASW dispersion image, with warmer colors indicating high coherence. The picked fundamental mode is shown as black circles, this is the measured dispersion curve .



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

WHITE PASS ELEMENTARY, JUNIOR—SENIOR HIGH SCHOOL

WHITE PASS SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

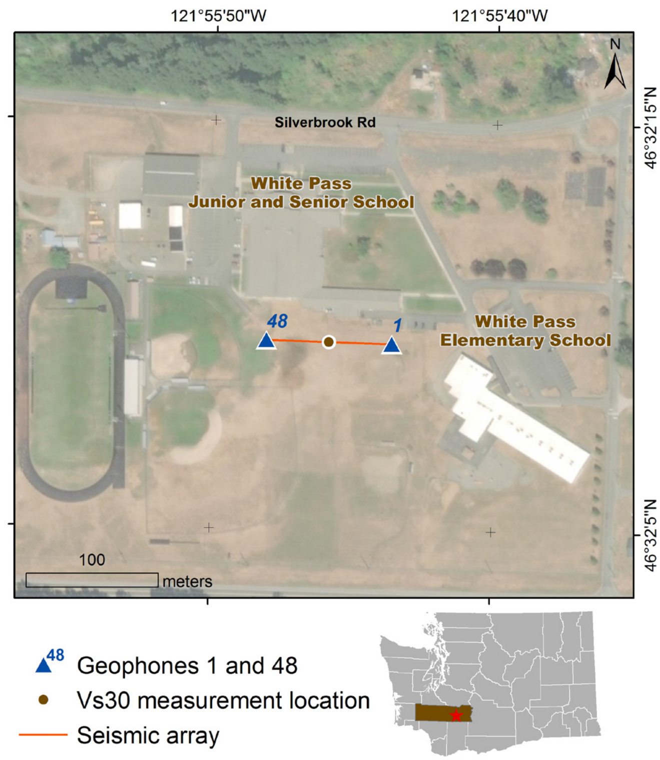
On August 13, 2018, a team from the Washington Geological Survey conducted a seismic survey at White Pass Schools. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS D



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on sand and gravel from glacial till and outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate hazard

Ground Shaking
Sever.

Lahar
In a mapped lahar hazard zone

Landslide
Hazard present

TECHNICAL OVERVIEW OF RESULTS

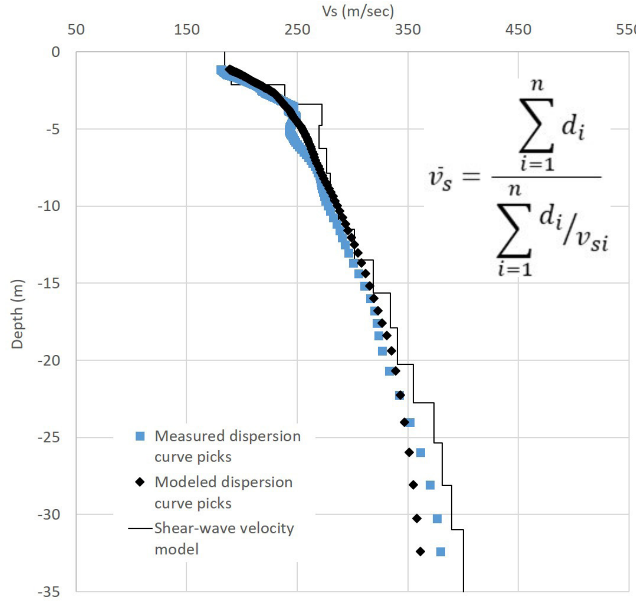
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 6.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.5 percent. The final velocity profile shows a rapid increase in velocity above about 4 m (13 ft) and a gradual increase in velocity below that. The best measurement for Vs30 is 304 m/s, which places the site in the site class D. The predicted site class is C or D, which correlates with the measured D site class.



$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}}$$

Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

WILSON CREEK ELEMENTARY AND HIGH SCHOOL

WILSON CREEK SCHOOL DISTRICT, GRANT COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

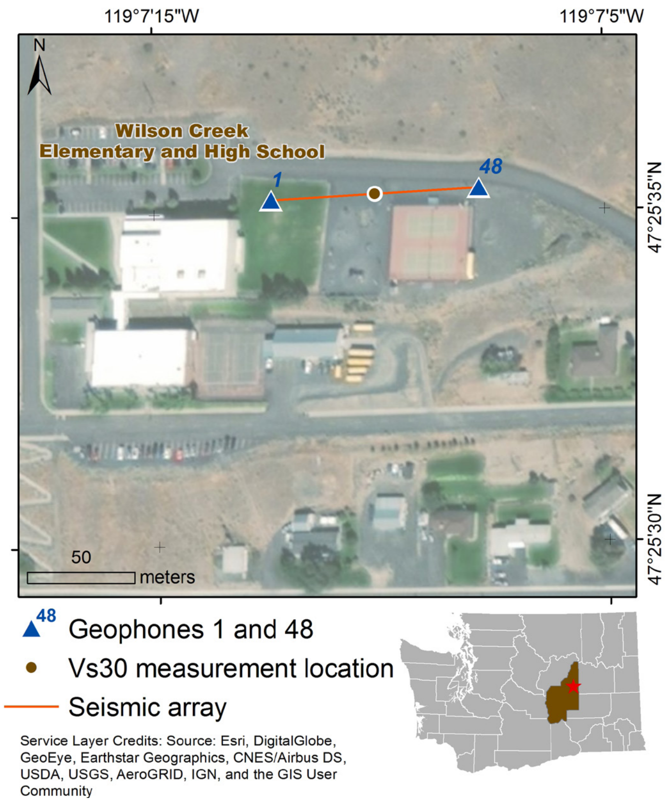
On July 31, 2018, a team from the Washington Geological Survey conducted a seismic survey at Wilson Creek Elementary and High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on deposits composed of pebbles, cobbles, and boulders in a sand and gravel matrix deposited by outburst floods.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low hazard

Ground Shaking
Strong

TECHNICAL OVERVIEW OF RESULTS

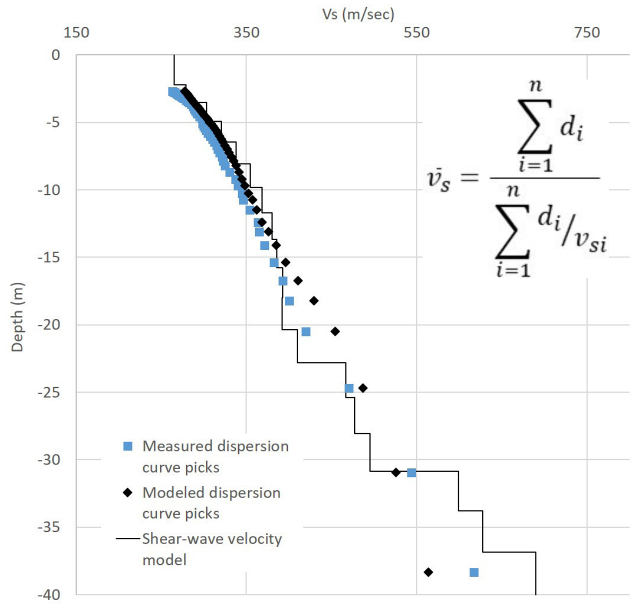
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image is of excellent quality and the fundamental mode can easily be picked. The microtremor analysis method (MAM) dispersion image is also of good quality but is used only as check for consistency in the analysis, because the MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves from the MASW forward direction (located off end geophone 1). The model has an RMSE of 8.5 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 3.9 percent. The velocity models shows a generally but not uniformily increase in velocity with depth. The best estimate for Vs30 is 374 m/s, which places the site on the low end of site class C. This site class is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.