In Situ Shear-Wave Velocity Measurements at the Delaney Park Downhole Array, Anchorage, Alaska

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ABSTRACT

Many studies are ongoing within Alaska's most populous city to understand better its unique seismogenic setting as well as its seismic hazard and risk. With its relative proximity to the Aleutian megathrust subduction zone and other earthquake sources, Anchorage has been subjected to regular earthquakes, including the 1964 Great Alaska earthquake. In 2004, a downhole array was installed near downtown Anchorage within the Bootlegger Cove Formation, which was responsible for much of the ground failure during the 1964 earthquake. This study provides new information regarding the downhole array and the dynamic soil properties found at the array site. Shear- and compression-wave velocities were measured at the site. Evaluation of the transfer function of the new velocity model is compared with the measured response at the site. In addition, several comparisons are performed utilizing nearby historic cone penetration test (CPT) and standard penetration test (SPT) data measured during installation of the deepest accelerometer at the site. A significant improvement in the theoretical modeling of the site is achieved utilizing the new shear-wave velocity profile.

INTRODUCTION

Anchorage, home to approximately half of Alaska's population, is located within a highly seismogenic zone. This zone is composed of the Pacific plate underthrusting the North American plate at a rate of greater than 50 mm/yr. Anchorage is situated in a region of complex geology that consists of a sedimentary basin abutting metamorphic bedrock exposed in the Chugach Mountains, located on the eastern side of the city. One of the most important features affecting the ground response in Anchorage is the Bootlegger Cove Formation, consisting of glacial and glaciofluvial deposits of interbedded clay, silt, and sand (Schmoll and Dobrovolny, 1972). Significant ground loss and slope failures within this formation resulted in the northern portion of the city during the 1964 M_w 9.2 Great Alaska earthquake. Significant effort by seismologists and engineers has been placed in understanding the anticipated ground response resulting from the next major earthquake because of the population density and unique seismic setting of the Anchorage area.

BACKGROUND

A downhole array, with three-component accelerometers placed at seven depths from the surface to 61 m below ground (Fig. 1) is located in Delaney Park, part of downtown Anchorage, Alaska, and has been recording strong ground motions since 2004 (Fig. 2, upper left inset). The site is located on level ground approximately 800 m south and 800 m east of the 1964 Great Alaska earthquake 4th Avenue and K Street ground failures, respectively. Recorded ground motions at the borehole array have been analyzed as part of a systematic approach to develop a ground-motion model and to measure the impedance characteristics of the soil column located at the borehole array. The soil column at the array site is similar to the soils encountered north of the array, where significant damage resulted from the 1964 Great Alaska earthquake. The general subsurface conditions consist of alluvium over glacial outwash and the Bootlegger Cove Formation (a stratified sequence of clastic sediments). Very dense glacial till lies below the Bootlegger Cove Formation and because of its high shear (S)-wave velocity ($V_S > 760$ m/s) acts as a seismic site class B/C boundary (Dutta *et al.*, 2009).

During the installation of the downhole array 7.5 cm casing was installed into boreholes, but very little is published about the exact makeup and engineering properties of the soils at the site. Several efforts have been made to characterize the thicknesses of the soil layers and their key engineering properties such as shear-wave velocity, shear modulus and damping, and unit weight (Thornley *et al.*, 2013, 2014a,b). As shown in Figure 1, an assumed shear-wave velocity profile, measured for a geotechnical study at a building approximately 250 m northwest, was suggested for the site prior to this study, as there was no shear-wave velocity data collected at the downhole array. Comparisons between the instrument recordings and modeled ground motions did not show a good fit when evaluating the transfer functions of modeled earthquake ground motions between instruments, when compared with the suggested profile. Several models were developed and refined to modify the

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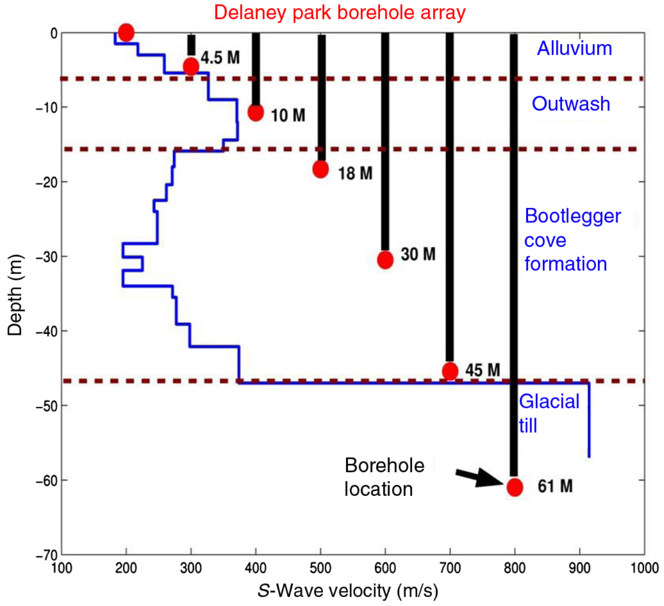


▲ **Figure 1.** Delaney Park borehole array sensor layout and generalized geology with the previously assumed shear-wave velocity profile. The color version of this figure is available only in the electronic edition.

estimated shear-wave velocity profile to better model measured ground motions between instruments at the array site. However, the results of the models suggested that collecting *in situ* measurements at the downhole array site would be necessary to gain additional improvements.

FIELD STUDY

To capture *in situ* measurements at the downhole array site, the deepest accelerometer (61 m below ground surface) was removed from the casing and shear-wave velocity profiling was performed. Upon removal of the accelerometer, the groundwater level was measured within the casing. Its depth is estimated to be approximately 21 m below ground surface.

VERTICAL SEISMIC PROFILING OF THE CASING

Vertical seismic profiling is a single borehole geophysical method. Seismic energy is generated at the ground surface by an active seismic source and recorded by a geophone located at known depth below ground surface. The time required for energy to reach the geophone along a path of known distance, between the source and receiver, provides a measurement of average seismic-wave velocity of the medium between the source and receiver. Data obtained from different geophone depths are used to calculate a detailed seismic-wave velocity profile of the subsurface in the immediate vicinity of the accelerometer casing.

The seismic source used for this study was a wooden beam, 3.7 m in length, laid horizontally on the ground in close vicinity to the casing. The beam was coupled to the ground by parking a vehicle on the beam. A 7.3-kg sledge hammer was used to strike alternate ends of the beam to induce polarized shear waves. A three-component borehole geophone was lowered in the casing and clamped against the casing.

For data acquisition, the team utilized a Geostuff BG2 3-axis (triaxial) borehole geophone, a Geometrics Geode multichannel seismograph with an accelerometer electronic trigger, a field laptop computer, and Geometrics Seismodule software. Data were processed using Geometrics SeisImager software.

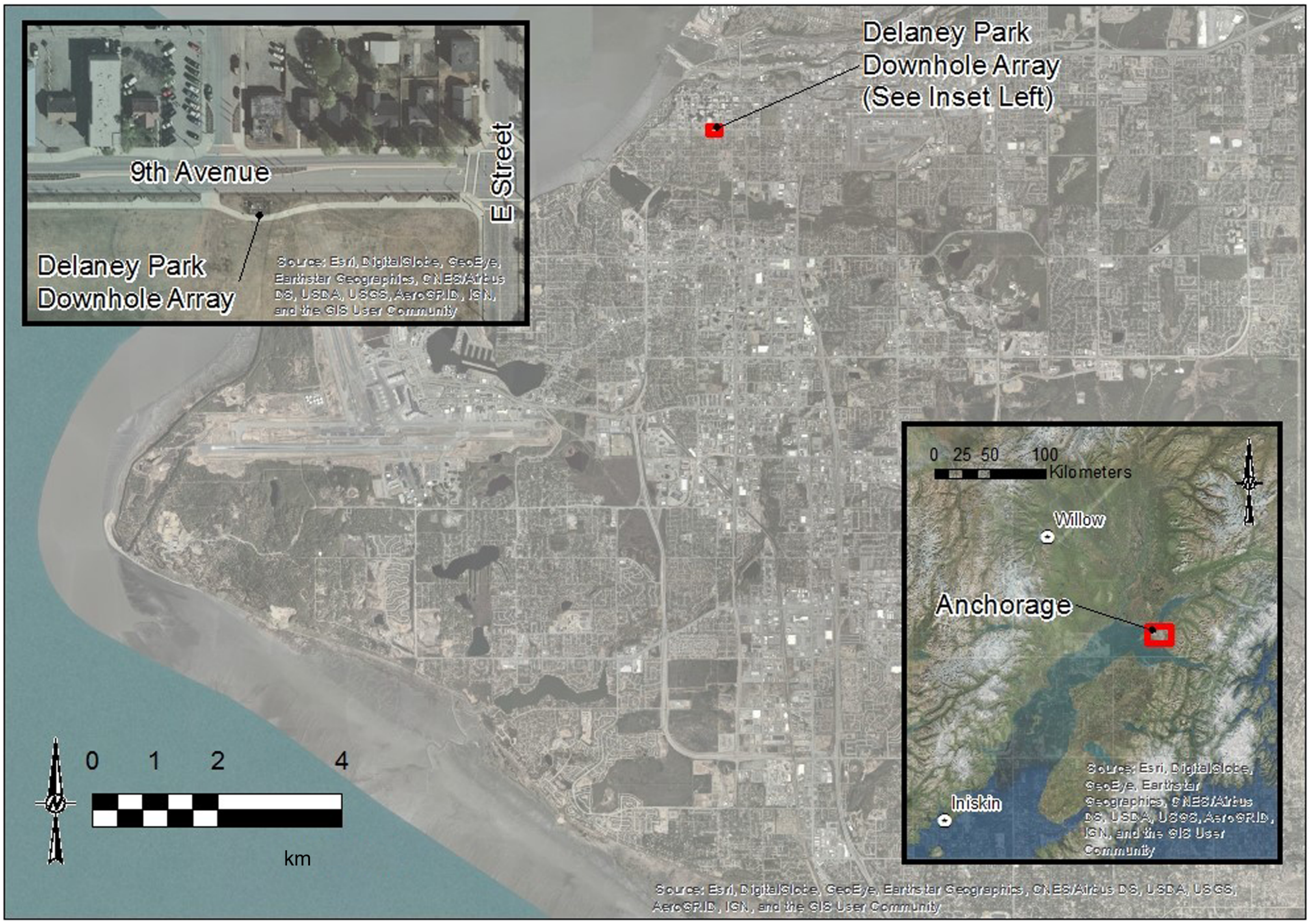
The borehole geophone was suspended downhole at a maximum depth of 59.7 m. For each depth where data were recorded, three seismic records were acquired separately (two shear waves of opposing polarity and a compressional wave). Each record was composed of multiple stacks to minimize the influence of background seismic noise. Data collection commenced at a depth of 59.7 m, continued at 0.91 m intervals, and ended at 0.3 m below the ground surface.

The recorded data were subsequently analyzed by splitting the three recorded components (vertical, longitudinal, and transverse) into depth wavetrains. *P*- and *S*-wave first arrivals were then picked and were best fit to a model to derive layer thicknesses and compression and shear-wave velocities at the site.

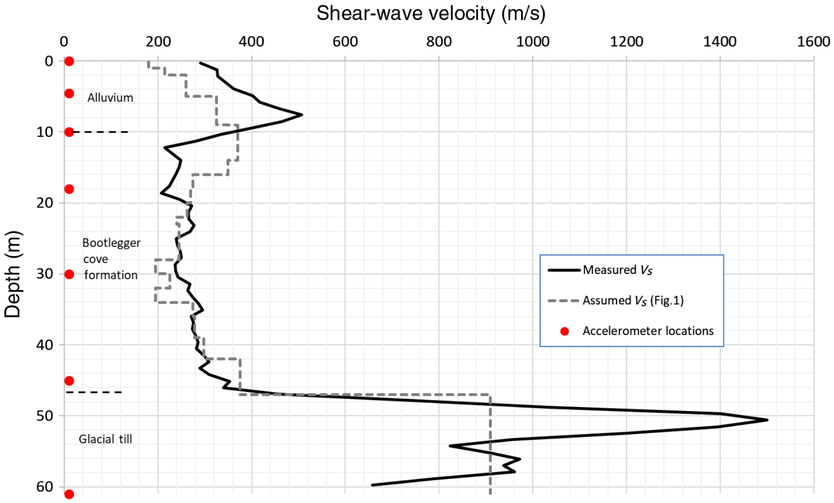
SUMMARY OF RESULTS

The *P*- and *S*-wave velocity profiles (V_P and V_S, respectively) are presented in Figures 3 and 4, respectively. Because of the density of the measurements and relative scatter from one measurement to another, a five-point moving average has been applied to the data. In general, the shapes of the velocity profiles are similar. It is observed that the measured *P*-wave velocities do not seem to have been affected by the water in the casing at approximately 21 m.

To evaluate the V_S profile further, Figure 3 presents the V_S profile, including the depths of the accelerometer sensors at the array site. The previous shear-wave velocity profile that was assumed for the downhole array site has been included in Figure 3 to illustrate the changes between the measured and assumed profiles. When comparing the generalized geology of Figure 1 and site-specific measurements of Figure 3, there are some notable observations that can be made. The higher velocity alluvium and outwash materials estimated in the profile of Figure 1 appear to be thinner at this site and the lower velocity structure of the Bootlegger Cove Formation appears to begin closer to the 10 m accelerometer. The lowest velocity portion of the subsurface appears to be at a depth of 12–18 m, while velocity does not substantially increase until the interface with the underlying glacial till material at approximately 47 m. The linear increase in velocity near the surface is a feature that peaks at a much higher velocity than that measured at the nearby site and is higher than would be anticipated for typical alluvial sands and gravels. The glacial till material



▲ **Figure 2.** Location of the Delaney Park downhole array. (Upper left inset) The location of the array site adjacent to Delaney Park in downtown Anchorage; (lower right inset) the relative locations of the two earthquake events used in this study. The color version of this figure is available only in the electronic edition.

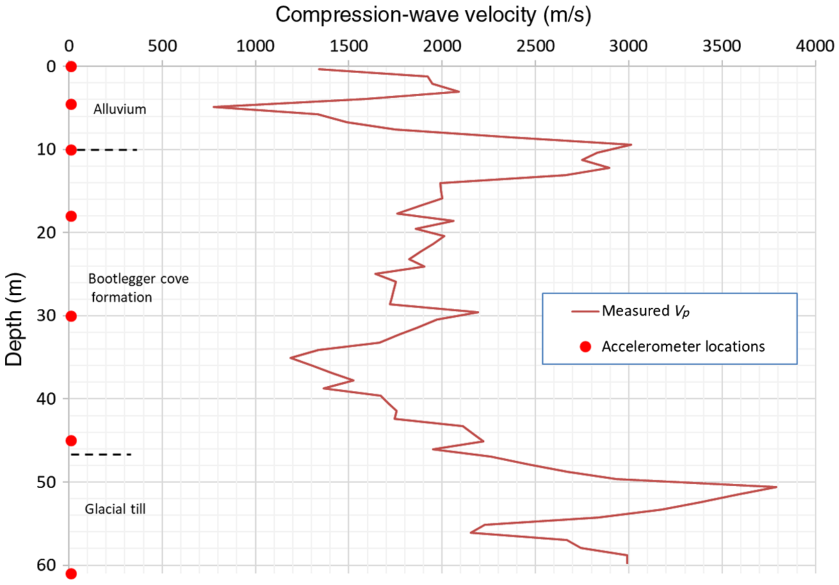


▲ **Figure 3.** Measured five-point moving-average shear-wave velocity profile. The color version of this figure is available only in the electronic edition.

was observed to have high-velocity values, which is in line with other studies within Anchorage.

TRANSFER FUNCTION EVALUATION

An evaluation of the transfer functions of the measured DPDA ground motions compared to the theoretical transfer function using the measured shear-wave velocity profile was performed using the program Strata v.0.5.9 (Kottke *et al.*, 2013; Strata, 2017, see Data and Resources). The theoretical transfer functions were compared with the measured transfer function for two recently recorded earthquake ground motions. The earthquake ground motions selected were the 24 January 2016 **M** 7.1 Iniskin earthquake and the 25 September 2014 **M** 6.2 Willow earthquake, located roughly 260 km south and 130 km north of the DPDA site,



▲ **Figure 4.** Measured five-point moving-average compression-wave velocity profile. The color version of this figure is available only in the electronic edition.

respectively (see Fig. 2, lower right inset; Data and Resources). The instrument at the bottom of the array (D6) and the instrument at the surface (D0) were used to calculate the measured transfer function. The same depths within the theoretical Strata model were used to calculate the theoretical transfer function. Figure 5 presents the average horizontal-component results for several transfer functions. The theoretical transfer functions for both the assumed and measured shear-wave velocity profiles are presented for instruments at each depth using the deepest instrument for comparison. The surface theoretical transfer functions are compared with the measured transfer function at the surface instrument. The theoretical transfer function from the measured shear-wave velocity profile shows a promising match to the measured transfer function. Although the amplitude is slightly higher than the measured transfer function, the peaks generally match well.

Nonlinear behavior was not evaluated in this effort. The shear-strain index (I_γ; Idriss, 2011) was below 0.3% for both ground motions and is estimated to have little influence of the 1D site-response analysis methods used in this study (Kim *et al.*, 2016). This is likely due to the great distance of the ground motions from the site, as detailed in Table 1.

COMPARISON OF RESULTS TO THOSE FOR NEARBY SITES

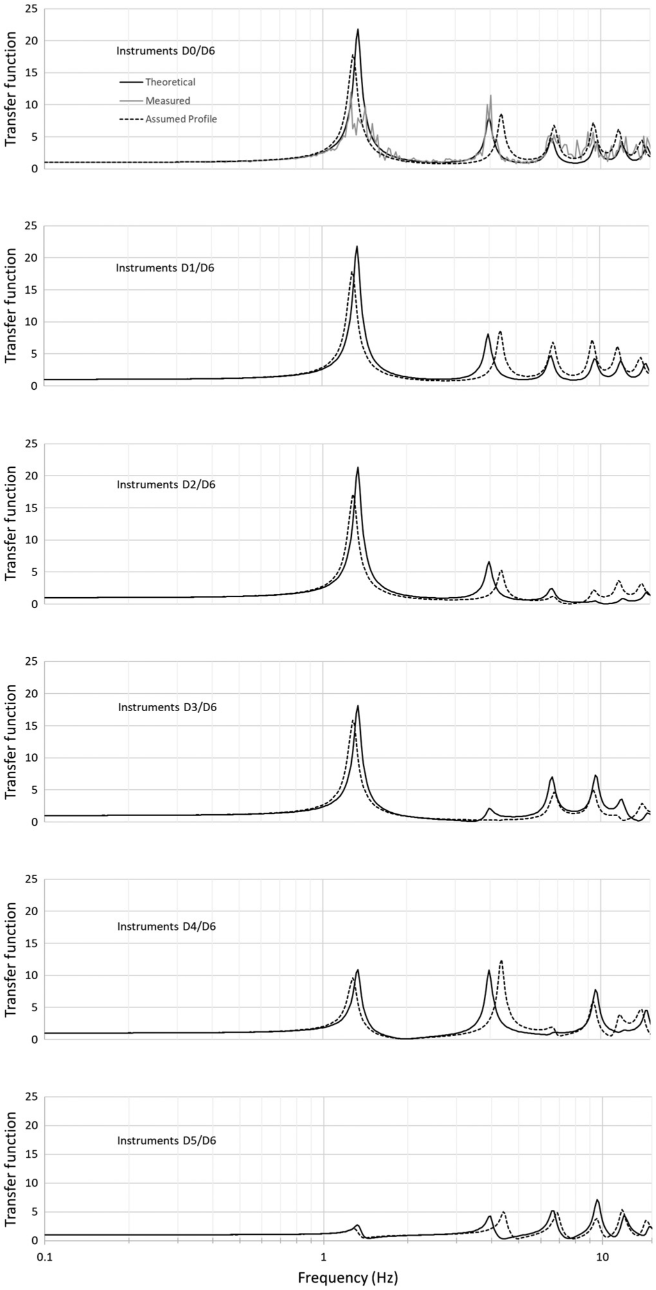
A literature review was performed to compare the findings from this study to other nearby data. Very few buildings in downtown Anchorage have available V_S data. However, in the 1980s the State of Alaska Department of Natural Resources performed cone penetration testing (CPT) along Delaney Park (Updike and Ulery, 1986). Cone Penetrometer Sounding PS-C-08 was advanced in 1982 and is located approximately 45 m southwest of the downhole array. Measurements of the friction resistance and cone tip resistance were recorded on 0.3 m intervals to the depth of approximately 47 m, with refusal on the underlying glacial till. Using the results of that study, several correlations were applied to empirically calculate the V_S profile. Several different correlations were applied, based on the guidance of Wair *et al.* (2012). In addition, the data, processed using software by GeoLogismiki (2014, see Data and Resources) which uses the correlation by Robertson (2009), were evaluated. Because the evaluation of the CPT data was strictly for comparison to the measured data at the downhole array, the Robertson (2009) correlation was used to compare the results of the study.

Figure 6 presents several V_S profiles, including the five-point moving-average values measured at the downhole array and the calculated V_S profile utilizing the CPT data presented by Updike and Ulery (1986) using V_S correlations by Robertson (2009). In general, the profiles are in good agreement. The measured V_S profile appears to estimate higher values in the upper 10 m with relatively good agreement between profiles down to the glacial till at approximately 45–47 m below existing ground.

Recently, a borehole log was found, which had been collected during the drilling and installation of the instrumentation (D. Cole, personal comm., 2017). Using geotechnical drilling and logging methods, the soil lithology was recorded, and relative density relations were collected by driving a sampler and recording blow counts, also referred to as the standard penetration test (SPT). As part of this study, the blow counts were corrected and a correlation to V_S was calculated using methods presented in Wair *et al.* (2012). The basic equation for all soils was used without modification of the blow counts, other than geotechnical corrections. The results of the SPT correlation of V_S at the site are also presented in Figure 6.

RELEVANT ENGINEERING PROPERTIES

Using the small strain velocity data collected at the site, several other properties have been calculated, including the shear modulus values with depth. The equation $G = \rho V_S^2$, in which G is the shear modulus and ρ is the mass density (which typically ranges from 19 to 21.5 $\mathrm{kN/m^3}$), was used to estimate the shear modulus from measured V_S data. The Idriss (1990) shear modulus reduction and damping curves were utilized for the previously discussed transfer function analysis. To further evaluate the shear modulus estimate, we utilized the CPT data previously discussed and the correlation by Robertson (2009). The transformation can be done but is not presented here to save space. As with the velocity profiles discussed above, the fit is relatively good, especially considering the period of collection for the CPT data (Updike and Ulery, 1986) and the potential



▲ **Figure 5.** Comparison of theoretical transfer functions of the assumed and measured shear-wave velocity profiles using two recent earthquakes.

variabilities. From these relationships, one can develop average values that can be used in the evaluation of estimating site response at the Anchorage downhole array.

CONCLUSIONS

The results of the downhole velocity profiling measurements provided a significant improvement on the understanding of the dynamic properties of the soils at the Delaney Park downhole array site. Although V_S velocity profiles near the site have been used in the past to model site response, it has proved difficult to match modeled results using these profiles to actual recorded earthquake ground motions, as shown in the transfer functions for a recent earthquake. The comparisons of the velocity profiling results to other nearby data, including CPT and SPT measurements, give further confidence that the V_S profile is representative of the *in situ* velocities down to 60 m at the site. These new data should allow for improved modeling of site response at the downhole array site.

DATA AND RESOURCES

The following data were utilized in this study: the earthquake ground motion data can be obtained from the Center for Engineering Strong Motion Data at www.strongmotioncenter.org (last accessed April 2018) and the standard penetration test (SPT) blow count data were provided by D. Cole (personal comm., 2017). The other relevant information can be found at GeoLogismiki Geotechnical Software CPeT-IT v.2.0 (2014, geologismiki.gr, last accessed December 2017) and Strata Equivalent Linear Site Response Software v.0.5.9 (2017, github.com/arkottke/strata, last accessed January 2018).

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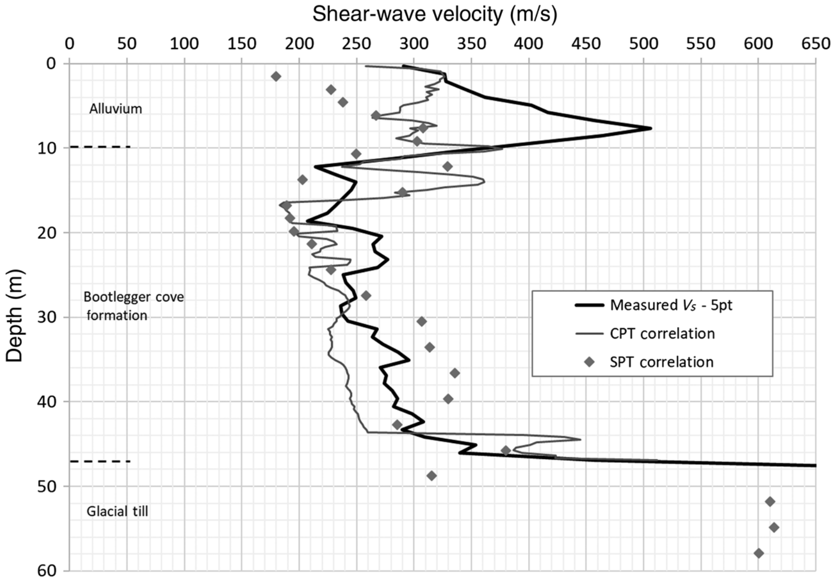
Table 1
Earthquake Event Details

Event	Latitude (°N)	Longitude (°W)	Depth (km)	Hypocentral Distance (km)	Azimuth (°)	Moment Magnitude (M)	PGA (*g*)	PGV (cm/s)
Iniskin	59.620	153.339	125.6	261	310	7.1	0.071	11.66
Willow	61.945	151.816	108.9	130	230	6.2	0.073	5.81

PGA, peak ground acceleration; PGV, peak ground velocity.



▲ **Figure 6.** Comparison of measured shear-wave velocity and estimated shear-wave velocity through cone penetration test (CPT) and standard penetration test (SPT).

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