Assessing shear wave velocity profile uncertainty using multiple sCPT interpretation and processing methods

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ABSTRACT

This paper quantifies the influence of seismic Cone Penetration Test (sCPT) interpretation and processing methods on shear wave velocity (V_S) profile uncertainty using data from 20 sites in Christchurch, New Zealand. The near-surface soil profiles varied across the sites, both in terms of the soils that were present and the profile layering characteristics, reflecting the depositional environment that is influenced by alluvial and coastal processes. The same experimental setup was used at each site, consisting of a dual receiver sCPT cone and a hammer source method at a consistent horizontal offset distance. Three commonly used shear wave arrival time picking methods and the cross-correlation method were used to define arrival times and time intervals between testing depths for each site. The pseudo-interval, true-interval and slope-based processing methods were used with these arrival times and time intervals to develop 11 V_S profiles for each site. Alongside this, a ray tracing inversion method provided an additional V_S profile at each site. The uncertainty in the V_S profiles that were developed at each site are presented, highlighting the variability resulting from different processing and picking methods. Results across sites are combined to provide a representation of the uncertainty across all methods and the differences in the uncertainty across the various processing methods.

Keywords: seismic cone penetration testing, shear wave velocity, uncertainty quantification.

1. Introduction

The shear wave velocity (V_S) of a soil deposit and the V_S profile at a site play an important role in many aspects of civil engineering projects. Material properties important for foundation design and settlement analyses, such as small strain moduli, can be estimated using V_S measurements. Seismic site response analyses require V_S profiles to underpin material properties for each layer. A number of different in-situ and lab-based methods are used to define V_S.

A summary of some of the in-situ invasive methods that can be used to obtain or estimate V_S profile are summarised in Figure 1. Invasive methods involve the advancement of a probe (cone penetration test (CPT), dilatometer test (DMT) or testing at intervals within a borehole (standard penetration test (SPT)). Seismic measurements are not taken as part of these methods, so V_S profiles can only be developed through the use of empirical correlations. Correlations are not discussed further here, but these often have significant uncertainties associated with their use. Invasive seismic methods also use probes to advance seismic sensors (seismic CPT (sCPT), seismic DMT (sDMT), direct-push crosshole (DPCH)) or lower seismic sensors down a borehole(s) (downhole methods (DH), crosshole methods (XH)). Sources of seismic energy are located at the ground surface (e.g., sCPT, sDMT, DH) or at various depths below ground (e.g., DPCH, XH).

Both sets of methods require a robust field methodology to ensure quality of data, with more effort and expertise required to acquire invasive seismic data. Invasive seismic methods require data interpretation to translate the data collected in the field into information that can be used to develop V_S profiles. Some invasive methods also require the additional step of inversion, involving the use of modelling and additional interpretation. These details will be discussed further in subsequent sections of this paper.

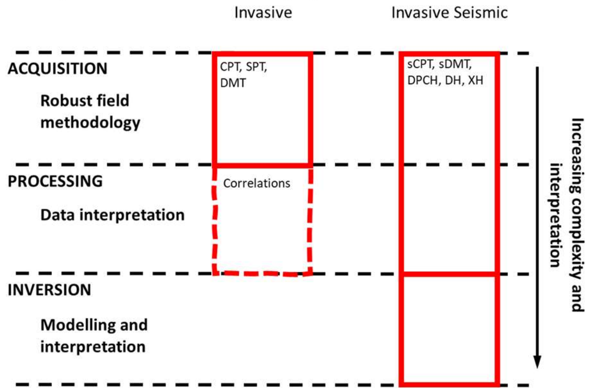

Figure 1. Summary of the key steps involved in the application of invasive and invasive seismic site investigation methods. Correlations used with invasive methods follow a different path to the development of Vs profiles using invasive seismic methods, hence the use of dashed lines. There is a solid red line between the processing and inversion steps for invasive seismic methods as most approaches do not have an inversion step.

V_S measurements are influenced by aleatory variability and epistemic uncertainty. Aleatory variability is a result of the natural spatial variability of soil properties, both in the vertical and horizontal directions. This has been explored in several studies but is not discussed further herein. This study focusses on epistemic uncertainty, which is a result of data and processing method uncertainty. This uncertainty can be influenced by the acquisition, processing and inversion steps outlined in Figure 1.

Few studies have explored the epistemic uncertainty of V_S profiles developed from invasive site investigation methods. These studies have focussed on different aspects of the interpretation of data from these methods, including wave propagation assumptions (Kim et al. 2004), measurement errors (Bang et al. 2014, Styler & Weemees 2016) and interpretation methods (Kim et al. 2004, Bang et al. 2014). Stolte & Cox (2020) used multiple travel time methods and velocity interpretation methods to quantify the depth-dependent epistemic uncertainty in V_S from sCPT data. This paper is an extension and expansion of this research and follows the same analysis approach.

This paper presents a quantification of the influence of sCPT data interpretation and processing on V_S profile uncertainty. The details of the experimental dataset from Christchurch, New Zealand and the field-testing setup and methodology will be first presented. The picking and analysis methods are then discussed. The results for individual sites are presented and then combined to assess the variability across different methods and processing approaches. Key insights and then summarised.

2. Field Investigation Dataset and Method

The sCPT data used in this study was obtained from 20 sites across the city of Christchurch, New Zealand. The sites were located in areas that were underlain by both Springston Formation alluvial sand and silt deposits, and the sand, silt and peat deposits of the Christchurch Formation. Locations were in an area of roughly 10 km by 12 km, with the water table within few metres of the ground surface. Some of these sites had evidence of liquefaction manifestation following some of the events during the 2010 – 2011 Canterbury Earthquake Sequence.

The sCPT soundings were collected at each site using a Pagani track-mounted CPT rig. The CPT cone collected tip resistance, sleeve friction and pore pressure (u_2 location) measurements, while behind the cone a dual receiver sCPT system was used with a vertical offset of 0.5 m between sensor packages. Seismic measurements were collected at 1 m intervals, with the dual receiver cone therefore collecting waveforms at 0.5 m intervals. The source plank at the ground surface was typically offset by 1.7 m from the CPT rods and a sledgehammer source used.

At each measurement depth reversed signals were collected by hitting on each end of the source plank, with these opposite polarity waveforms creating mirror images and a 'butterfly' pattern at each depth. The first source impact at each depth was used to seat the source plank, with the waveform discarded. Two to four impacts were then used and stacked to improve the signal to noise ratio. The opposite end of the source plank was then hit, with the first impact against discarded, followed by two to four source impacts.

3. Analysis Method

V_S profiles can be developed using several different approaches. In this paper different combinations of travel time methods and velocity interpretation methods were used to develop multiple V_S profiles at each site.

The travel time methods were:

- First arrivals (FA)
- First peaks and/or troughs (PT)
- First crossover points (CO)
- Cross-correlation (CC)

The three velocity interpretation methods were:

- Pseudo-interval method (PI)
- True-interval method (TI)
- Corrected vertical travel time slope-based method (SM)

The travel time methods can be used to define the total travel time from source to receiver or the relative travel time between two receiver locations (interval velocity Δt). This involves identifying the shear wave arrival with the correct polarity relative to the source impact orientation. The FA pick is the initial arrival of the shear wave, which can sometime be difficult to identify. The PT is the first peak after the FA for one source direction and the first trough for the other source direction. The CO is the first point after the FA where both waveforms cross each other. When the interval travel time is required, differences in the picked arrivals at subsequent depths for a particular method are used. An example of this is shown in Figure 2a. The CC approach makes use of the peak response of the cross-correlation function between pairs of waveforms from subsequent measurement depths to define the interval travel time, as shown in Figure 2b.

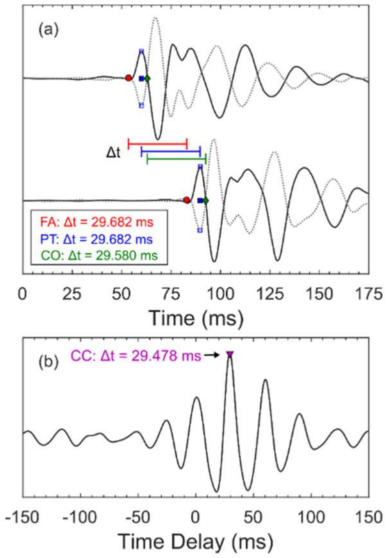

Figure 2. a) example of arrival times and interval times from different travel time methods; b) example of the cross-correlation approach and identification of the interval time based on the peak of the function (after Stolte & Cox 2020).

The PI and TI methods are the most common approaches used to define V_S profiles, with the method described in the downhole testing ASTM Standard D7400-17 (ASTM 2017). These methods use the interval velocity between measurement pairs and the difference in wave travel path from source to each receiver location (ΔL). These methods typically assume a straight-line travel path from source to receiver at each test depth, although the ASTM standard suggests that refracted travel paths are considered at shallow depths. The TI method uses waveforms from a dual receiver cone each test depth, with these recorded simultaneously from a single source impact. If a single receiver cone is used, waveforms need to be recorded using different source impacts at two different depths and the PI method is used. Both use the same calculation approach; however, the use of separate source impacts can introduce timing errors in the data acquisition. Both methods are applied here, as the collection of data using a TI setup still allows for PI analyses using the TI data collected from two different measurement depths. The shear wave velocity for the depth range between each measurement pair is calculated using:

$$V_S = \frac{\Delta L}{\Delta t} \tag{1}$$

The SM identifies linear trends in the relationship between corrected vertical travel time and depth to develop a V_S profile (Patel 1981, Kim et al. 2004, Redpath 2007). If FA travel time were used, they were corrected to a vertical travel time (t_{vert}) based on the assumed straight-line travel path from source to receiver at each test depth using:

$$t_{vert} = t_{FA}\frac{D}{\sqrt{D^2+X^2}} \tag{2}$$

where t_{FA} is the FA time, D is the measurement depth and X is the horizontal source offset. If PT or CO were used in this analysis, they were adjusted to an equivalent FA time (following the approach from Redpath 2007). Profiles were developed by fitting linear trends to depth ranges that were separated by changes in slope and CPT test data that identified layer boundaries. A least squares regression was used to fit a slope to these depth ranges, with the slope of the line equal to the V_S of the layer.

The FA, PT and CO methods were used with all the interpretation methods to create nine V_S profiles. The CC method could not be used with the SM interpretation method as individual travel times at each depth are not produced. Using the CC method with the PI and TI interpretation methods developed two more V_S profiles, resulting in a total of 11 V_S profiles for each site.

Alongside these approaches, another V_S profile was developed independently at each site using FA travel times and the forward modelling downhole simplex (FMDS) method (Baziw 2002). This method accounts for refracted travel paths from source to receiver, instead of the straight-line assumption used in the other methods, based on the ray tracing algorithm developed by Chandler (1977). This method is referred to as RT in this paper.

At each site, the V_S profiles are developed across the methods described. Assuming a log-normal distribution of V_S, the epistemic uncertainties associated with the V_S profiles are represented using the log-normal standard deviation of V_S (σ_{lnV_S}). V_S has been shown to be log-normally distribution here and in other studies (e.g. Stolte & Cox 2020). σ_{lnV_S} as a function of depth was calculated for the V_S profiles from each velocity interpretation method separately and for all V_S profiles combined. Results from across all the sites are then combined and compared.

4. Results

An example of the V_S profiles developed at a site are presented in Figures 3 and 4 from Site 1. The V_S profiles for the different velocity interpretation methods presented in the first three panels of Figure 3 highlight the potential variation in the V_S profiles as result of the different travel time methods. There is good agreement between the V_S profiles developed using the PI method above a depth of 10 m. However, below a depth of 10 m there is clear fluctuation in the V_S values, swinging back and forward in a manner that does not reflect the soil conditions at this site. The outlier profile is the one based on the FA picks, which may be a result of the difficulties that are inherent in the picking of the first arrival on a waveform and the typical reduction in signal-to-noise ratio with depth for these methods.

The variation in the V_S profiles for the TI method is more consistent with depth, with an increase in the variability of the V_S profiles at depths below approximately 12 m. Below this depth the profiles still vary by up to 100 m/s around values of 200 – 250 m/s, clearly not a small difference but smaller than the variability of the PI method for this site. The RT V_S profile is presented in Figure 3d, based on independent FA picks and using a profile with 0.5 m thick layers in the FMDS analysis. There is a slight fluctuation in the V_S for each layer above 10 m depth. Like the PI method, there was increased V_S fluctuation in the layers below 10 m depth. Compared to the other velocity interpretation methods, there is a clear difference in the trends observed for the SM approach. The SM V_S profiles are very similar across the three travel time methods, and sit almost on top of each other for the majority of the profile.

Figure 4a presents the V_S profiles for Site 1 using each velocity interpretation method and the FA picks (acknowledging that the RT method may have used different FA picks). These profiles all follow a similar general trend with depth, identifying the gradual increase in V_S with depth down to 10 m, before stabilising with some evidence of a softer layer between 14 and 17 m. Even with the same general trend, at some depths the differences in V_S are greater than 100 m/s, representing a 30% difference in the profiles. The agreement is good for depths less than 10 m for this site, with variations in V_S less than about 50 m/s. The SM and RT profiles show fairly good agreement, albeit with less fluctuation in the SM V_S profile.

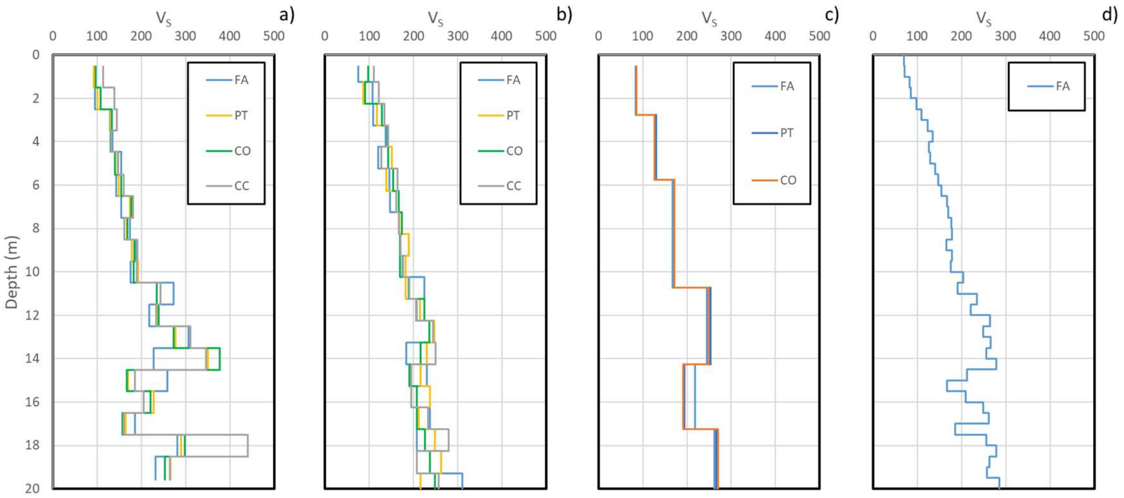

Figure 3. V_S profiles developed for Site 1 based on different travel time methods: a) PI method; b) TI method; c) SM method; d) RT method.

Figure 4b presents the σ_{lnV_S} for the profiles developed using each individual velocity interpretation method, and the σ_{lnV_S} for all the profiles. SM has the lowest σ_{lnV_S} of all the velocity interpretation methods, with only a slight fluctuation deeper in the profile (i.e., 14 to 17 metres). Apart from this depth range, σ_{lnV_S} is less than 0.02 throughout the rest of the profile, again highlighting the good level of agreement of profiles developed using this approach using different travel time methods. The PI and TI methods both have larger σ_{lnV_S} values in comparison. These are higher in the top few metres, with values between 0.1-0.2, potentially due to difficulties in picking arrivals and issues related to wave path assumptions. The $\sigma_{ln\ s}$ reduces between 3-10 m depth, with values fluctuating around 0.05, aligning with the tighter range of Vs profiles at these depths, as shown in Figure 4a. Below this depth, σ_{lnV_S} increases, shifting the general trend up to a value of about 0.1, with some larger spikes throughout. These increased values may be due to issues with signal-to-noise ratio and the changing of the characteristics of the waveforms with depth. The PI and TI methods don't have consistent trends, with one method having greater $\sigma_{ln\ s}$ at some depths, and less at other depths. Looking at all the profiles combined, the trend of $\sigma_{ln\ s}$ with depth is like that observed for the PI and TI. Given the consistent σ_{lnV_S} values with depth for the SM approach, this is not surprising. Overall, $\sigma_{ln\ s}$ varies between approximately 0.05 and 0.2 throughout the soil profile.

Figure 5a presents the σ_{lnV_S} from the 20 individual sites based on the SM approach and Figure 5b presents the data from the PI approach. In both figures the median σ_{lnV_S} across all the sites is shown by the bold black line. Across the individual sites similar general trends to those observed in Site 1 were observed. The SM approach had a smaller σ_{lnV_S} value than the PI approach in general, with only a few depths where the PI value dipped below the SM value. Typically the SM values remained relatively consistent with depth, apart for relatively small depth ranges where there was a increase in $\sigma_{ln\ s}$. Similar to site 1, this difference was often because the profile based on the FA picks were different to those from the other two travel time methods (PT and CO). Most of the profiles are closely bunched, suggesting similar variability in the profiles from one site to the next, with most sitting below a σ_{lnV_S} value of 0.03. There was more variation in $\sigma_{ln\ s}$ from one site to the next for the PI method, with most of the values sitting below a value of 0.1. There were several spikes that increased beyond this value, with some exceeded 0.3. These spikes are typically due a V_S from one travel time method being clearly different to those from other methods. This was often associated with the FA method, due to picking difficulties, or the CC method that is applied to the entire waveforms and is not just focussed on capturing the arrival time of the initial S-wave. Although the soil profiles had a range of characteristics, there are some consistent trends with depth across all sites. The reasons for this are covered in the discussion related to Site 1, and clearly there is much less variability in the 4-10 m depth range. Although not shown here, similar σ_{lnV_S} trends for both the PI and TI methods were observed across the sites.

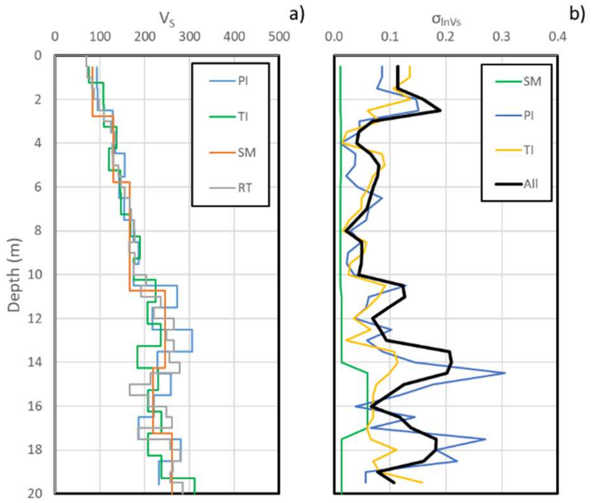

Figure 4. a) Comparison of all V_S profiles for Site 1 using the FA picks; b) $\sigma_{ln\ s}$ for each velocity interpretation method and across all methods.

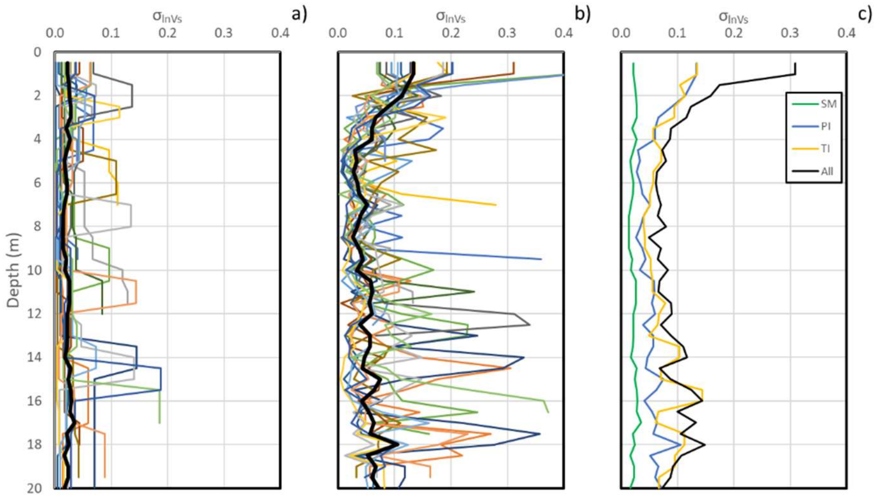

Figure 5. a) Variation of σ_{lnV_S} with depth: a) SM for all sites; b) PI for all sites; c) comparison of the median σ_{lnV_S} for each velocity interpretation method and for all methods combined.

The median of the σ_{lnV_S} values across all sites is summarised in Figure 5c for each velocity interpretation method along with the median for all methods combined. The SM method is very consistent with depth, with values between 0.015 and 0.035. As described by Stolte & Cox (2020) the stability of the SM V_S profiles based on different travel time methods is due to averaging out of errors associated with picking uncertainty by fitting the slopes to more than two datapoints. The PI and TI methods both have larger σ_{lnV_S}throughout the entire depth range and similar general trends with depth, with the TI having larger values in general. These differences do not reflect the accuracy or effectiveness of the different approaches however, with the TI approach eliminating some of the epistemic uncertainty associated with the sCPT methodology related to data acquisition system timing. At shallow depths σ_{lnV_S} is equal to 0.13 for both methods, before quickly decreasing with depth and stabilising below 3 m depth. From 3-12 m depth these values vary between 0.03 and 0.08. There is a slight increase below 12 m for the PI method, and larger increase up to approximately 0.015 for the TI method.

Focussing on the σ_{lnV_S} for all the methods combined, the trends with depth match those for the PI and TI method, again due to the larger uncertainties that these methods produce. Apart from the very top of the profile, σ_{lnV_S} remains below 0.15 for the entire depth range of the profiles considered. The epistemic uncertainty here was often less than the epistemic uncertainty identified in research that explored inter-analyst uncertainty based on the same initial dataset at select sites (Boore & Asten 2008, Garafolo et al. 2016). These results are less than the V_S profile uncertainty defined by several studies (EPRI 2012, Matasovic & Hashash 2012, Stewart et al. 2014). For example, one of the simplest approaches used in site response analysis has been to assume a variation of plus or minus 20-30% from a reference V_S profile (Matasovic & Hashash 2012). This level of variability is aligned with the values at the near surface in Figure 5c but is much larger than the variability evident below a depth of 2 m for this dataset. It is important to note that these studies intended to capture both the epistemic uncertainty and aleatory variability, with the second source of uncertainty not represented in the results presented herein. The quantitative estimates of the epistemic uncertainty can be combined with aleatory variability estimates to better inform overarching uncertainty estimates.

5. Conclusions

This paper has provided quantifiable estimates of the epistemic uncertainty in the V_S profiles from sCPT testing at 20 sites in Christchurch, New Zealand. The influence of the use of multiple travel time methods and velocity interpretation methods on the V_S profiles developed at a single site were presented and the uncertainty quantified. The observed trends in uncertainty in V_S with depth were then combined across all sites to highlight systematic trends. The SM approach had the smallest σ_{lnV_S} value of each of the velocity interpretation methods and did not vary significantly with depth. The interval-based velocity interpretation methods had larger values at shallower depths, which then reduced and stabilised down to a depth of 15 m, before showing some increase with depth. The σ_{lnV_S} values for the SM method were typically less than half the values for the PI and TI methods. Across all methods, the σ_{lnV_S} value typically varied between 0.05 and 0.15 below depths of 3 m. These levels of uncertainty are less than those observed in other studies, and need to be combined with aleatory variability estimates to capture all sources of V_S profile uncertainty. More research is needed to explore the epistemic uncertainty in other locations and depositional environments and provide more constraint on reasonable uncertainty estimates to use in geotechnical engineering applications.

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