Invasive Seismic Testing

A Summary of Methods and Good Practice

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Executive Summary

Shear (S) wave velocity (V_S) and primary constrained compression (P) wave velocity (V_P) are routinely used in geotechnical engineering for a variety of purposes ranging from assessing static foundation settlement to estimating earthquake ground motions. In particular, an accurate determination of V_S is required for robustly determining the site subsoil class when using the New Zealand seismic loadings standard, as well as assessment of site-specific seismic response.

In the aftermath of the 2010-2011 Canterbury and 2016 Kaikōura earthquakes, invasive seismic testing has become more commonly used in geotechnical earthquake engineering. However, several critical aspects of both data collection and data processing are not well understood by either the contractors collecting and processing the data or the geotechnical engineers using the data.

This report summarises the invasive seismic test methods typically used in New Zealand geotechnical engineering practice to measure V_S and V_P. It describes the test procedures and data processing that are generally accepted as 'good practice' – i.e., the procedures and processing that are necessary to obtain accurate and representative data that can be relied upon by geotechnical engineers for analysis and design. The report also describes the uncertainty inherent in the invasive seismic testing methods, including sources of uncertainty and how to quantify it. An example of an assessment of epistemic uncertainty using actual field data is provided, as are recommendations for what information should be included when reporting test results.

The information contained in this report is intended to provide the basis for development of a national technical guidance document for performing invasive seismic testing, processing the data and reporting the test results – perhaps as another module in the NZGS Geotechnical Earthquake Engineering Practice Guidelines.

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1 Introduction

This report describes various invasive seismic test methods for measuring shear (S) wave velocity (V_S) and primary constrained compression (P) wave velocity (V_P). Some of these are relatively frequently used in near-surface geotechnical site investigations in New Zealand, while others are less common but may become more widely used in the future. Specifically, the paper addresses aspects of the testing procedures and data processing/analysis that constitute good practice; primarily for the purpose of developing representative V_S and/or V_P profiles for a given site.

Seismic velocities V_S and V_P are directly linked to several important geotechnical properties including: small-strain shear modulus (G_0); small-strain constrained modulus (M_0); Young's modulus (E); and Poisson's ratio (υ). Therefore, they are routinely used in soil-foundation-structure-interaction (SFSI) analyses, and calculations of foundation settlement. They are also used in a variety of applications in geotechnical earthquake engineering. Accurate determination of V_S is required for seismic site classification (using New Zealand and other building codes), site-specific seismic response analysis and seismic hazard analysis. V_S can also be directly used in liquefaction triggering analysis (Kayen et al. 2013). V_P can be used to determine the depth at which the soil is fully saturated, as well as to help assess the effect of a partially saturated soil profile when assessing liquefaction hazard.

V_S and V_P can be measured in the laboratory using a resonant column device or bender elements. However, the ability to perform this type of testing commercially in New Zealand is relatively limited. In addition, while the in-situ void ratio and stress conditions can be replicated in a reconstituted laboratory test specimen, other factors such as soil fabric and cementation cannot (Wair et al. 2012). Laboratory testing also requires high-quality undisturbed samples, and obtaining and testing such samples is typically expensive, and often not practical for cohesionless soils. Additionally, laboratory tests only measure properties at discrete sample locations and these may not be representative of the variability of the soil profile or characteristics across a site.

Unlike laboratory testing, geophysical in-situ testing (i.e., in-situ seismic testing) does not require undisturbed sampling, maintains in-situ stresses during testing and measures the response of a larger volume of soil. Kramer (1996) and Mayne et al. (2001) discuss various geophysical methods for measuring the shear wave velocities of geomaterials which can be divided into two categories: invasive methods and non-invasive (i.e., surface) methods.

1.1 Purpose, scope and limitations

The purpose of this paper is to help both the contractors that collect and process seismic data, and geotechnical engineers that use (and sometimes process) the data, better understand the important aspects of the test methods and data processing, and the uncertainties associated with the testing. It is intended that the paper will form part of the basis for developing a formal technical guidance document for performing invasive seismic testing (perhaps a NZGS geotechnical earthquake engineering module or similar), as well as provide a common reference for contractors and engineers. It is envisaged that the guidance document will include input from a mix of experienced contractors, geo-professionals and university researchers.

Included in the paper are descriptions of the test methodologies, and international good practices for field testing methodology and processing seismic data. An important aspect of seismic testing for engineering analyses, which is often overlooked, is quantifying the uncertainties associated with both data collection and processing. Therefore, a section of the paper is devoted to a discussion of uncertainty and how it can be quantified.

Guidance on what information should be included in seismic testing reports is also presented.

This paper is intended to summarise the key aspects of invasive seismic testing and what constitutes current good practice. It does not address all testing methods, nor is it an endorsement of any particular testing methodology, equipment, trademark or processing method.

1.2 Shear wave velocity testing in New Zealand professional practice

The effects of local soil/site conditions are integral to estimating the level of ground shaking that could be expected to occur in a given earthquake. The effects of local soil/site conditions have been included in the New Zealand Building Code (NZBC) since at least 1992. New Zealand Standard (NZS) 4203:1992 incorporated the effects of local soil/site conditions through the use of a “site subsoil category.” One of the methods for determining the site subsoil category was through the use of the natural site period which implies the use of V_S, although the Code was silent on how to determine the natural site period.

Since 2004, the seismic loading standard (NZS 1170.5:2004) has included a quantitative procedure for incorporating the effects of local soil/site conditions based on V_S, though differently from the Canadian and U.S. approach wherein sites are classified in terms of the in-situ time-averaged V_S of the upper 30 m of material (i.e., “$V_{S,30}$”). The current NZBC (NZS

1170.5:2004 Amendment 1) explicitly incorporates the average V_S over the upper 30 m, and a minimum V_S in combination with a minimum unconfined compressive strength for assigning a "site subsoil class" of either "strong rock" or "rock." For "shallow" and "deep" soil sites, the site subsoil class can be determined from the site period which "…may be estimated from four times the shear-wave travel time from the surface to rock." For site subsoil classification of "very soft" soil sites, one of the criteria is more than a 10 m thickness of soil with a V_S of 150 m/s or less. The NZBC also states that the preferred method of site classification is through measurements of shear-wave travel times or shear-wave velocities.

The current NZBC does not discuss the test methodology to be used for measuring V_S. The choice of methodology is left to the discretion of the geo-professional. Key drivers of the decision are often the cost of testing and the geo-professional's familiarity with a particular test method.

Historically, the use of in-situ seismic testing appears to have played a relatively minor role in geotechnical site characterisation in New Zealand. While both invasive and non-invasive testing has been used in geotechnical investigations for larger projects such as dams, pipelines and mining facilities, it was less common for smaller, 'conventional' projects.

In the aftermath of the 2010-2011 Canterbury and 2016 Kaikōura earthquakes, increased awareness of liquefaction hazard, and the importance of seismic site response – by both geotechnical and structural engineers – has resulted in an increased demand for V_S profiling throughout New Zealand; particularly in main centres of Christchurch, Wellington and Auckland but also in smaller seismically active regions like Hawke's Bay and Bay of Plenty.

Following the 2010-2011 Canterbury earthquakes, one of the most common methods of in-situ V_S testing was multi-channel analysis of surface waves (MASW), and this is still used. The non-invasive procedure (i.e., energy source and receivers on the ground surface) and the ability to perform the test relatively rapidly and therefore relatively cheaply, undoubtedly contributed to the method's popularity. Less common was the use of invasive borehole testing (downhole - DH - or crosshole - CH) and seismic cone penetrometer testing (SCPT). However, the demand for SCPT (and seismic dilatometer test – SDMT) in particular has steadily increased, resulting in an increase in the capability to perform this type of testing.

As in-situ seismic testing to develop V_S profiles has become more common in New Zealand in the last few years, it has become apparent that there is a general lack of understanding around some of the key aspects of performing the testing, and processing/analysing the test data. The lack of understanding applies to both the contractors collecting the data, and the engineers using (and sometimes processing) the data and is related to both invasive and non-invasive test methods.

Specific issues include:

- incorrect test procedures;
- incorrect data processing/analysis – particularly for surface wave testing;
- lack of understanding of the limitations of the various test methods;
- limited understanding of the uncertainty associated with V_S testing and how to quantify it;
- no NZ guidelines or standards for conducting testing and reporting test results.

It should be emphasised that the above issues are not unique to seismic testing in New Zealand and are present to varying degrees in other locations including Europe, the U.S. and Canada (B. R. Cox and L. M. Wotherspoon, personal communication, October 2018).

1.3 Overview of seismic waves

There are four basic mechanical waveforms generated within a semi-infinite elastic halfspace. Shear or secondary (S) waves and primary or compression (P) waves are *body waves*, that is, they propagate spherically from the energy source within the medium and travel through it (i.e., through the earth). Rayleigh (R) waves and Love (L) waves are hybrid compression / shear waves that occur at the free boundary of the ground surface and layer interfaces. Figure 1-1 provides generalised illustrations of P-waves, S-waves and R-waves.

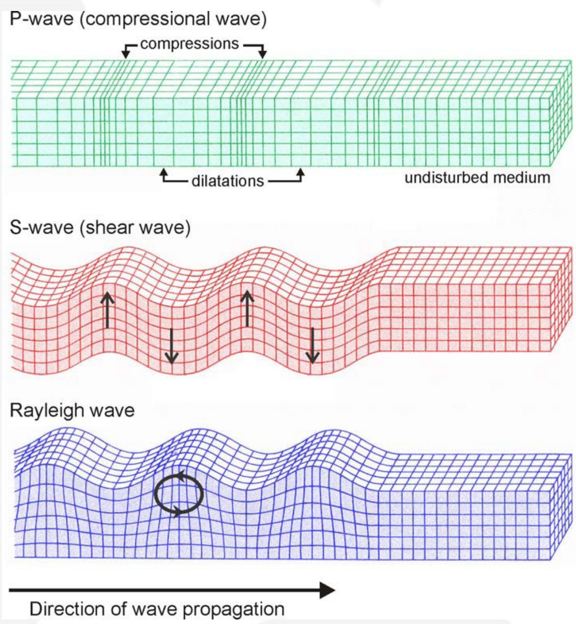

Figure 1-1: Particle Displacements with the Passage of P- Waves, S-Waves and Rayleigh Waves (National Highway Institute 2002).

The P-wave is the fastest travelling form of seismic wave and moves as an expanding spherical front emanating from the source with particle motion parallel to the direction of wave propagation. P-waves travel through fluids and solid; inherently causing volume change. In most soils, V_P is primarily controlled by the degree of saturation, and because the V_P of water is approximately 1500 m/s, a V_P through soil close to this value indicates a saturated or near-saturated soil condition (Allen et al. 1980).

The S-wave is the second fastest wave type and expands as a cylindrical front, with particle motion perpendicular to the direction of wave propagation. Hence, one can polarise the wave as vertical (up/down) or horizontal (side-to-side) in relation to the direction of propagation. S-waves do not result in a volume change of the soil. Because water cannot transmit shear forces, V_S is independent of the degree of soil saturation. V_S is largely controlled by effective stress, material density, and soil age and cementation effects (Richart et al. 1970). In general, V_S and cone penetration test (CPT) measured tip resistance (q_c) and standard penetration test (SPT) N-values should follow similar trends. However, there is no direct (i.e., one-to-one) correlation.

Typical values of V_S and V_P for various materials are shown in Figures 1-2 and 1-3. When testing saturated soils, P-waves are generally quite easy to separate from S-waves because they travel in the order of twice the speed or more of S-waves.

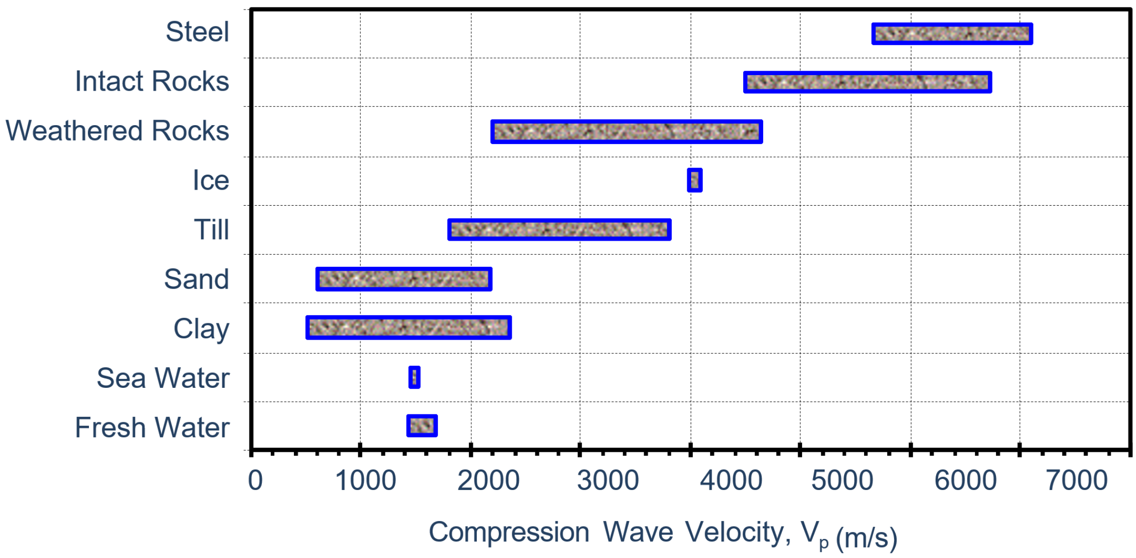

Figure 1-2: Typical P-Wave Velocities of Various Materials (National Highway Institute 2002)

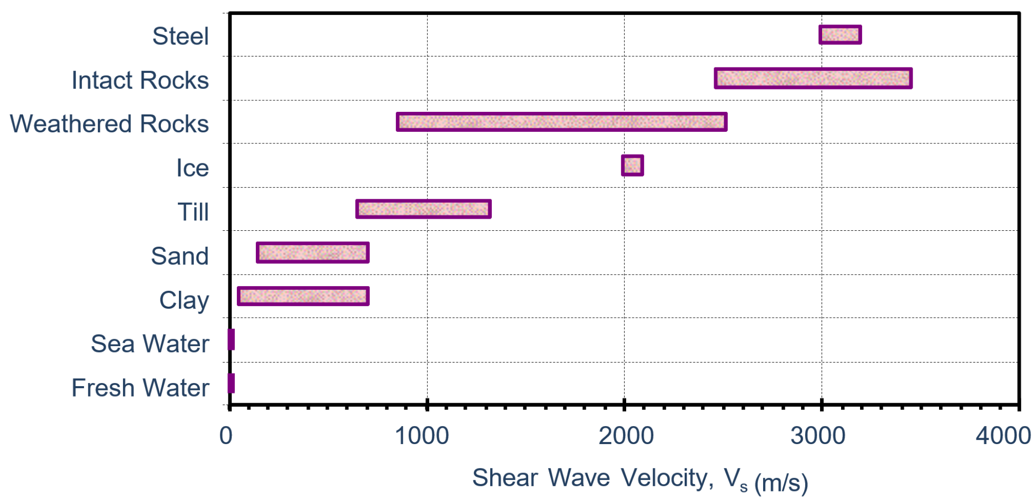

Figure 1-3: Typical S-Wave Velocities of Various Materials (National Highway Institute 2002)

R-waves have a near-surface retrograde elliptical particle motion and are sometimes referred to as 'ground roll'. They are produced by the interaction of P-waves and vertical S-waves with the ground surface. Love waves have a particle motion perpendicular to the direction of wave propagation and are produced by the interaction of horizontal S-waves with the ground surface. In non-homogeneous materials, both R- and L- waves are dispersive, meaning that different wavelengths can travel through the medium at different velocities, based on the velocity of the materials they encounter (Aki and Richards 2003).

Typical waveforms generated by seismic testing are shown in Figure 1-4.

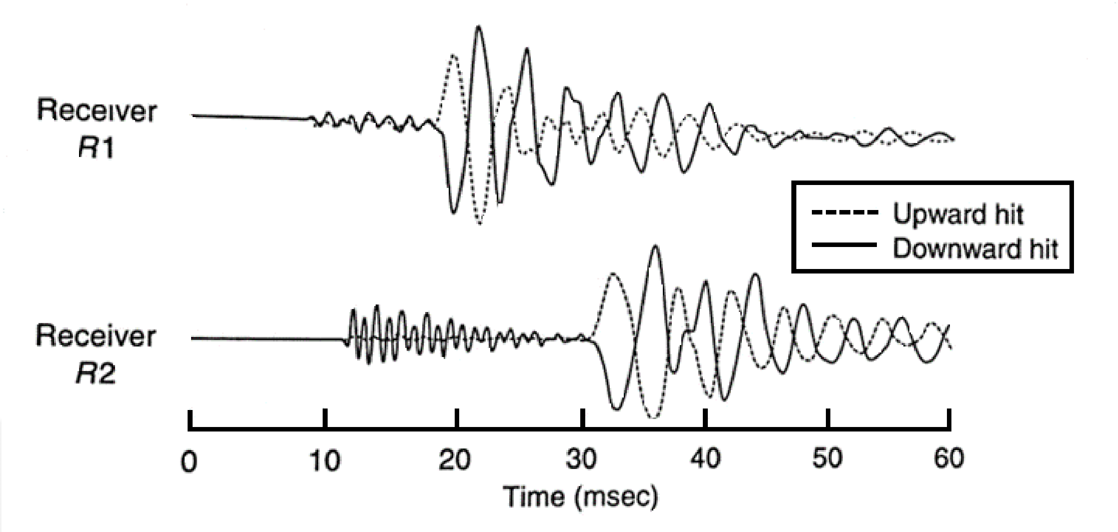

Figure 1-4: Typical Waveforms from Seismic Testing (Kramer 1996)

1.4 Overview of in-situ seismic testing methods

In-situ seismic testing requires three main components: (1) a source to generate seismic waves; (2) receivers with transducers (e.g., geophones or accelerometers) to measure the propagation of the seismic waves at specific locations; and, (3) a data acquisition system (DAQ) to acquire, digitise and store dynamic signals from the source and receiver(s). Non-invasive, surface-based test methods involve placement of the seismic energy source and receivers on the ground surface.

Non-invasive methods that are common in New Zealand geotechnical engineering practice include: multi-channel analysis of surface waves (MASW), spectral analysis of surface waves (SASW) and seismic refraction (SR).

Invasive seismic test methods (the focus of this document) are used to obtain localised measurements of V_S and V_P. Invasive testing requires the seismic energy source to be located either on the ground surface or within the ground, and the receiver(s) to be typically located within the ground. Invasive testing was first used for deep petroleum exploration but was adapted and further refined for use in geotechnical engineering investigations in the 1970s (Stokoe and Woods 1972, Woods 1978). Invasive methods were initially borehole-based wherein the source and/or receiver packages were lowered into the borehole; typically, at fixed depth intervals. Later, direct-push variants of the borehole test methods were developed wherein the instrumentation is installed in apparatus attached to the end of a steel probe which is pushed into the ground. Primary invasive in-situ seismic test methods include:

- downhole (DH);
- seismic CPT (SCPT) – direct push equivalent of DH;
- seismic dilatometer (SDMT) – direct push equivalent of DH;
- crosshole (CH);
- direct push crosshole (DPCH) – direct push equivalent of CH;
- P-S suspension logging.

Invasive test methods are generally considered to result in more reliable results (i.e., contain less uncertainty) than non-invasive methods because they are based on interpretation of local measurements of shear wave travel times, and theoretically provide a good resolution of velocity as a function of depth – albeit over a small area. However, there are uncertainties associated with both invasive and non-invasive test methods as discussed in Section 5 of this paper.

1.5 Use of CPT and SPT correlations to determine V_S

There are numerous published correlations for computing V_S from cone penetration test (CPT) tip resistance (q_c) and standard penetration test (SPT) N-values. V_S is a small-strain measurement (in the order of 10^{-3} % strain or less) while SPT and CPT are large-strain measurements (associated with soil failure). While correlations can be useful to check if the measured V_S profile is following the expected trend (i.e., V_S, q_c and N should generally rise and fall together), there is not a one-to-one relation between them. Also, there is significant scatter in the data used to develop the correlations. Therefore, correlations with CPT and SPT test values should only be used as a check or initial assessment of V_S (Cox 2018, GEESD V).

2 Downhole Seismic Testing

The principles and procedures associated with downhole (DH) seismic testing, whether using a borehole or direct push method (i.e., SCPT or SDMT), are similar. Therefore, the following discussion does not differentiate between borehole and direct push methods unless there is a need to clarify a particular aspect of a method.

2.1 Overview of method

Downhole seismic testing is conducted by generating seismic waves (S-waves or P-waves) at the ground surface and measuring the wave arrival times at a receiver lowered (borehole method) or pushed (direct push method) into the ground. The wave travel path is typically assumed as the straight-line/slant distance from the source to the receiver. However, this assumption is not always valid, and the actual wave travel path is unknown; particularly over the top several metres of the subsurface. The general equipment and procedures for conducting the downhole testing method are outlined in the ASTM test standard D7400 (2017).

As discussed previously, downhole seismic testing was historically performed in machine-drilled boreholes, and it is still commonly used for sites where drilling is required to recover samples and/or penetrate dense or hard materials. A schematic of a typical downhole borehole test setup is shown in Figure 2-1.

Drilling boreholes and installing fully grouted casing is a relatively time consuming and costly exercise, and unless drilling was required to recover soil samples or penetrate dense materials or rock, the cost of seismic testing using boreholes may not be justifiable for many projects. However, for sites with relatively soft soil conditions, it is possible to conduct downhole seismic testing in conjunction with CPT or DMT testing. This combined test is referred to as seismic cone penetrometer testing (SCPT – Robertson et al. 1986), or seismic dilatometer testing (SDMT – Marchetti 2014). A simplified schematic SCPT setup is shown in Figure 2-2. In addition to being less expensive than drilling, pushing the cone/receiver unit directly into the ground provides excellent coupling between the receiver and the ground, hence ensuring good transmission of seismic energy from the ground to the receiver.

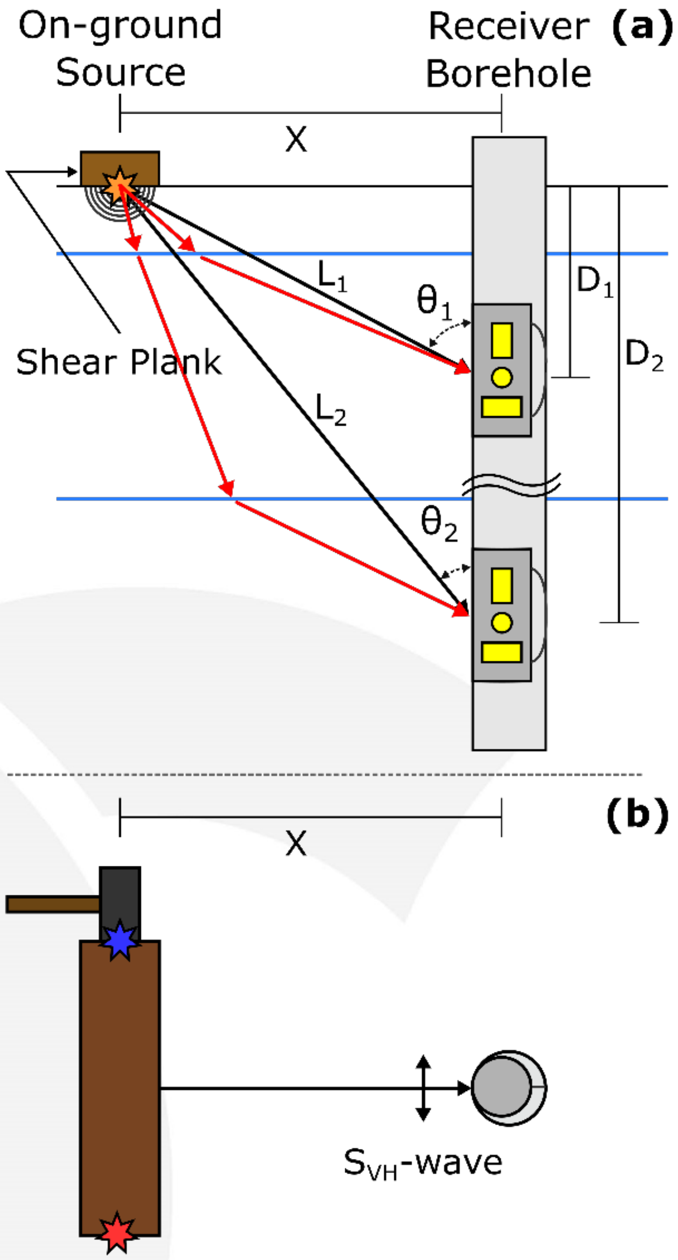

Figure 2-1: Schematic of downhole seismic test in cased borehole. X is the offset distance from the shear/traction plank (energy source) to the receiver(s). Lines L1 and L2 represent assumed straight-line travel path of seismic waves from the shear beam to the receivers at depths D1 and D2. θ1 and θ2 are the angles between the assumed travel paths and vertical. The blue lines represent soil layer interfaces. The red lines represent refracted travel path of seismic waves.

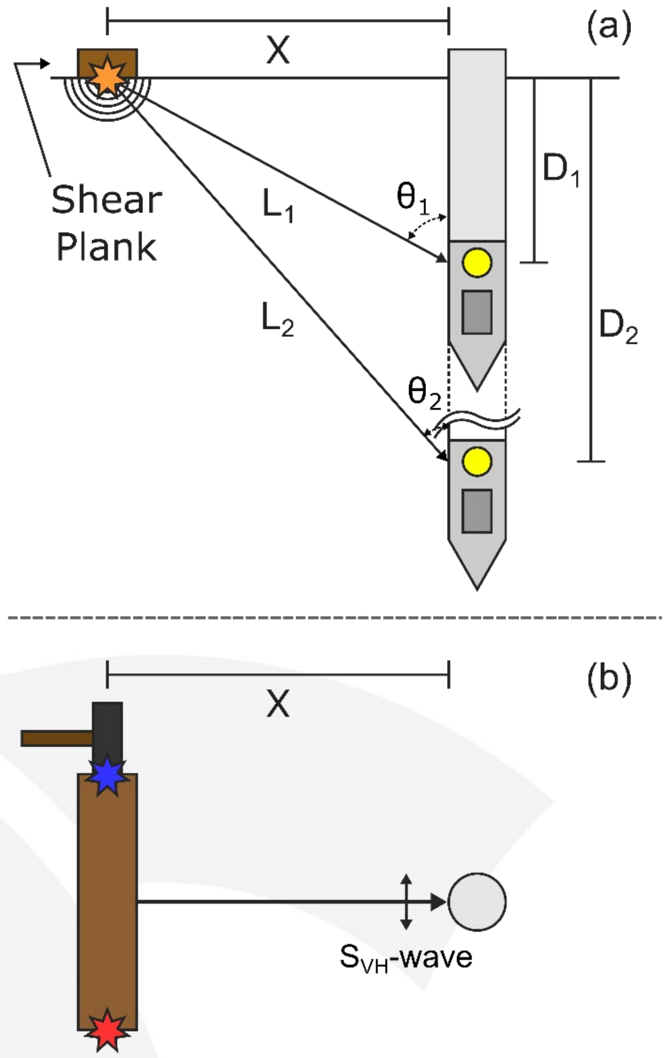

Figure 2-2: Schematic of a SCPT test (a) cross-sectional view and (b) plan view. The cone probe contains a single receiver package (Stolte and Cox 2019).

2.2 Test equipment

2.2.1 Seismic energy source

Seismic waves for downhole testing are generated by a source located at the ground surface. Vertically propagating (downward), horizontally polarised shear waves (S_{VH}-waves) are excited using a horizontal impact on a rigid shear/traction plank oriented perpendicular to the horizontal offset from the borehole/SCPT/SDMT sounding (Figure 2-1 and Figure 2-2). ASTM D7400-17 provides recommended dimensions and weights for shear/traction planks and hammers. A typical source for excitation of P-waves is a vertical impact on a metal plate that is firmly embedded into the ground surface.

The horizontal offset (X) from the energy source to the borehole or cone push rods is allowed to range from 1 to 4 m in ASTM D7400-17, with larger offsets (4 to 6 m) allowed "…to avoid response effects due to surface or near-surface features." Smaller offsets (< 1.5 m) are recommended when using the interval method to process the velocity data (Cox 2018, Hallal and Cox 2019), however very small offsets (< 0.75 m) can be problematic due to disturbance and/or interference from acoustic, rod or tube waves. If offsets larger than about 3 m are used, the effects of raypath refraction should be accounted for in the near surface (refer to Figure 2-1) as discussed in Section 2.4.2.

The magnitude of horizontal offset will also influence the choice of analysis technique used to develop profiles of V_P and V_S (refer to Section below).

2.2.2 Receiver

ASTM D7400-17 discusses minimum requirements for seismic receivers. For testing in a borehole, a downhole tool containing a receiver and mechanism for clamping the receiver to casing or borehole wall is used. It is typical for the receiver to comprise three transducers (e.g., geophones or accelerometers) mounted rigidly to the downhole tool; two oriented in orthogonal horizontal positions and one in a vertical position. The transducers are contained within a waterproof probe containing an outer mechanical clamping device which ensures that the tool can be tightly coupled with the borehole casing/wall. The better tools contain a compass to aide rotation/orientation of the transducers. Knowing (and maintaining) the orientation of the transducers during testing is important when interpreting waveforms and the polarisation of the waveforms.

Typically, SCPT testing is performed using a cone containing one sensor package consisting of 2 or 3 orthogonally-oriented transducers (single receiver). The diameter of the CPT probe at the location of the sensor package should be greater than the diameter of the probe below the sensor package to ensure good coupling between the instrument and the surrounding soil. Less common in practice is the use of a cone containing two seismic sensor packages vertically offset 0.5 to 1.0 m apart (dual receiver). A dual receiver cone allows simultaneous measurements of waves at two depths and hence true-interval velocities can be obtained (discussed in Section 2.4). Dual receiver seismic cones are less common because they are more expensive and require additional wiring and data acquisition channels – or the elimination of one of the existing channels such as hole inclination. Dual receivers are standard on SDMT probes but are less common in borehole testing.

For both borehole and SCPT/SDMT testing, one of the horizontal transducers should be oriented in the inline-horizontal direction – parallel to the shear plank and wave particle motion. This is illustrated by the yellow circular symbols inside of a SCPT probe in Figure 2-2 (a). The configuration is similar for a SDMT probe.

2.2.3 Data acquisition system

The data acquisition system (DAQ) is used to acquire, digitise and store dynamic signals from the source and receiver. It is often connected to a laptop computer to enable visual inspection of the data in real time as the testing is conducted, and for data storage. There are several variables to consider when selecting an appropriate DAQ (Cox et al. 2019). For high quality seismic testing, it is also necessary to invest in a high quality DAQ. For example, inexpensive analysers often have a high signal noise floor (i.e., the sum of all background noise and noise generated within the DAQ system) and/or low bit resolution which can 'swamp' the signal created by the surface source; particularly at greater depths. At a minimum, the requirements in ASTM D7400-17 for the recording system; including system accuracy and trigger accuracy should be met.

The number of channels should be sufficient to record the necessary data. The sampling frequency should be sufficient to allow adequate resolution of the wave travel times. The minimum record duration should be based on: (1) the maximum anticipated travel time of an S-wave travelling between the energy source; (2) the anticipated duration of the full wave train; and (3) other signals that may be important such as pre-trigger delays. Selection of a DAQ should also consider the range of expected signal amplitudes and whether amplification will be used prior to digitisation.

2.3 Test procedures

For testing using a machine-drilled borehole, the preparation of the hole should be done in general accordance with ASTM D7400-17. For SCPT and SDMT, the procedures outlined in an accepted test standard (e.g., ASTM D5778-12, ASTM D6635-15) should be used to conduct the non-seismic portion of the testing. The following discussion is not intended to cover every aspect of the test procedures, but to highlight some of the more important aspects of the procedures to help ensure collection of high-quality data.

It is recommended that the hole is cased with a PVC pipe or aluminium casing (centred in the hole) and firmly grouted in place. Lack of a casing may result in sloughing and/or collapse of the borehole and the loss of the downhole receiver tool. The Portland cement grout mixture used within the soil portion of the borehole should have density that is close to the average density of the soil (i.e., ~1.8-1.9 mg/m^3). The grout density can be adjusted by premixing the cement grout with bentonite. For casing in rock, conventional Portland cement grout should be used.

It is critical that the grout completely seals the annulus between the borehole casing and borehole wall. Inadequate grouting of the casing can result in poor coupling of S-waves. The ASTM procedure of anchoring the hole casing and pumping the grout up from the base of the borehole will remove mud and debris from the annulus and help ensure uniform filling of the annulus with minimum sidewall disturbance. The presence of large amplitude 'tube' waves and apparent oscillations of the downhole receiver during testing are indications of areas where poor bonding of the grout to the borehole casing has occurred (Hunter and Crow 2012).

A tube wave is a pressure pulse that propagates down (and up) the fluid column within the borehole casing. Tubes can appear similar to shear waves and can reverse polarity. As a general rule, they are less of a problem for shallower tests (<30 m), but they can be problematic at greater test depths. It is recommended to perform downhole testing in a dry borehole over at least the upper 10 m to avoid tube wave interference.

Prior to the start of testing, the receiver package should ideally be oriented so that the axis of one of the horizontal transducers is parallel to the shear plank as discussed in Section 2.2.2. In any case, it is critical to know both the orientation of the horizontal receivers, and the polarity of the shear waves. The initial polarity is the initial voltage departure (positive or negative) of the wave signal recorded by the DAQ for a given direction of strike on the shear plank – or any energy source. Hence, the polarity of the S-waves can be reversed by striking opposite ends of the shear plank. Reversing the polarity greatly aids and simplifies identification of the S-wave arrival time (discussed in Section 2.4).

Ideally, each end of the shear plank should be struck 3 to 10 times using firm consistent strikes, and the recorded waveform from each strike superimposed ('stacked') – more if necessary, to obtain a consistent waveform – to improve the signal-to-noise ratio. The resulting reversed polarity waveforms, when plotted together, should exhibit similar P-wave traces and diverge (i.e., 'butterfly') at the arrival of the S-wave to approximately mirror each other. An example of a butterflied waveform pair is shown in Figure 2-3.

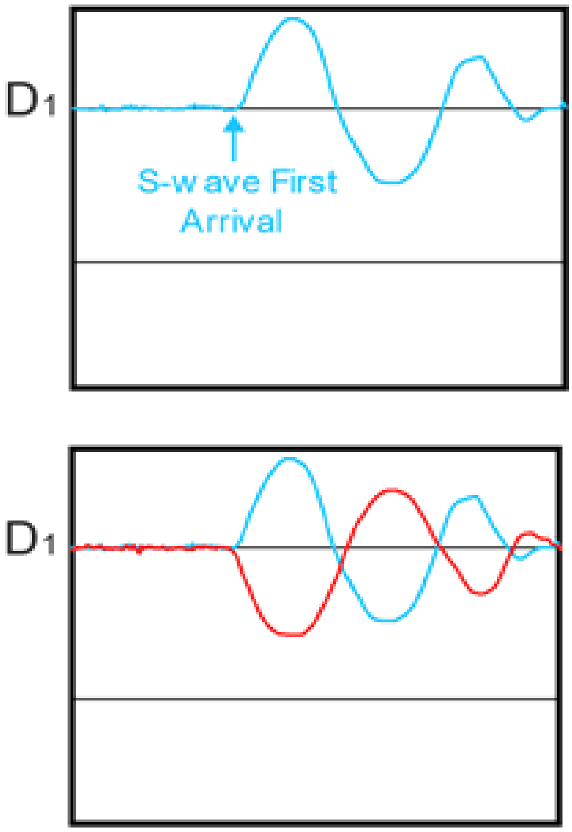

Figure 2-3: Example of butterflied SVH-waves at depth D1: (a) waveform from first shear plank strike – initial positive voltage departure. (b) A hammer strike on the opposite end of the shear plank results in an initial negative voltage departure – shown in red. (Cox 2018)

Once testing at one depth is complete, the receiver package is advanced to the next test depth and the test is repeated as described above. The minimum and maximum test intervals per ASTM D 4700-17 are 0.5 m and 1.5 m respectively; however, it is not uncommon for a larger depth increment to be used in deep (i.e. >30 m) boreholes. A test interval of 1 m is typical for SCPT and SDMT tests as that is the length of the push rod segments. Continue to advance the receiver package incrementally to all testing depths, repeating each test as described above.

If a single receiver package is used to record wave arrivals incrementally at two different depths using different energy source excitations, the test is referred to as a pseudo-interval measurement. When a dual receiver package is used to record a pair of wave arrivals simultaneously, the test is referred to as true-interval measurement. Seismic velocities computed from interval measurements are discussed in detail in Section 2.4.2.

True-interval measurement of seismic waves may be preferable because of trigger consistency between the pair of waveforms considered in the analysis.

With pseudo-measurement triggering can be inconsistent, resulting in timing errors. Such errors are difficult to identify and correct unless the trigger signal is recorded during testing, and this is not routinely done in practice.

The testing methodology for P-waves is similar to that for S-waves. The primary differences are: (1) the seismic energy source – compression waves must be generated using a vertical, downward impact on a metal strike plate as discussed in Section 2.2.1 and (2) P-waves are best measured using vertically oriented transducers in the receiver package. The offset distance, X, between the seismic energy source and the receivers is similar to that used for measuring S-waves. Similar to 'tube' waves travelling through borehole fluid as discussed above, P-waves often enter the steel push rods during SCPT and SDMT testing; arriving prior to, and hence obscuring the direct arrival of, P-waves through the soil. These indirect P-waves are generally referred to as 'rod noise' or 'rod' waves.

2.4 Data reduction and analysis

2.4.1 Picking seismic wave travel times

For developing V_S (or less frequently V_P) profiles, the first step in reducing the data is travel time evaluation of the seismic waves – either the direct travel time from the seismic energy source to the receiver, or the relative travel time between two measurement depths. Barring early rod or tube wave arrivals, P-waves always arrive at the receiver before S-waves. Therefore, the P-wave arrival is picked as the first departure from the noise floor (refer to Section 2.2.3), regardless of voltage polarity. The S_{VH}-wave (referred to as the S-wave hereafter) arrival is identified as the *first major departure* after the P-wave arrival *with the correct voltage polarity*. S-waves are typically associated with an abrupt increase in amplitude and change in frequency content.

If both ends of the shear plank are used to generate S-waves with opposite polarity, and the waveforms are plotted together (i.e., butterflied signals), the wave arrival may be picked at the point where a polarity is noted between the two waveforms (refer to Figure 2-4). Each pair of butterflied waveforms can be plotted with their associated measurement depth in a waterfall plot. An example of an S-wave waterfall plot is shown in Figure 2-5 with the average S-wave first arrival (FA) picks indicated by circular markers on the waveforms. FA picks are generally preferred because they are indicative of the initial arrival of the S-waves at the receiver. However, in practice, they can be difficult to identify and require subjective judgement.

Alternatively, later points in the waveform plots are picked such as the first peak/trough (PT) or the first crossover (CO) of the reversed waveform pairs, as shown in Figure 2-5. An advantage of picking first PT and CO times is that the process can be semi-automated by searching for local maxima/minima or minimum differences, respectively, between the amplitude of the two reversed waveforms.

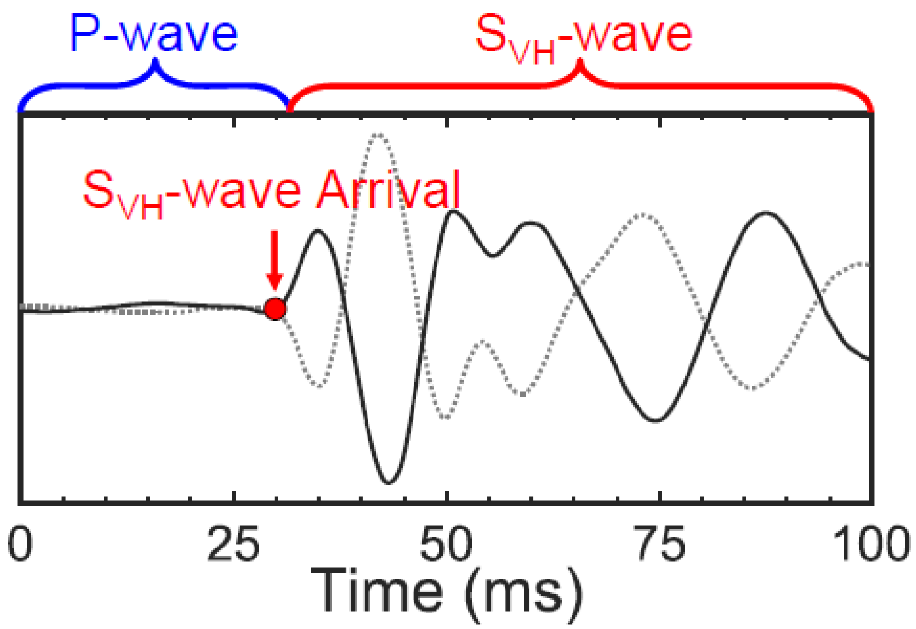

Figure 2-4: Example of first P-wave and S-wave arrivals. If both ends of the shear plank are used to generate S-waves, the first S-wave arrival can be picked at the point where a polarity reversal is observed in the two waveforms (from Cox 2018).

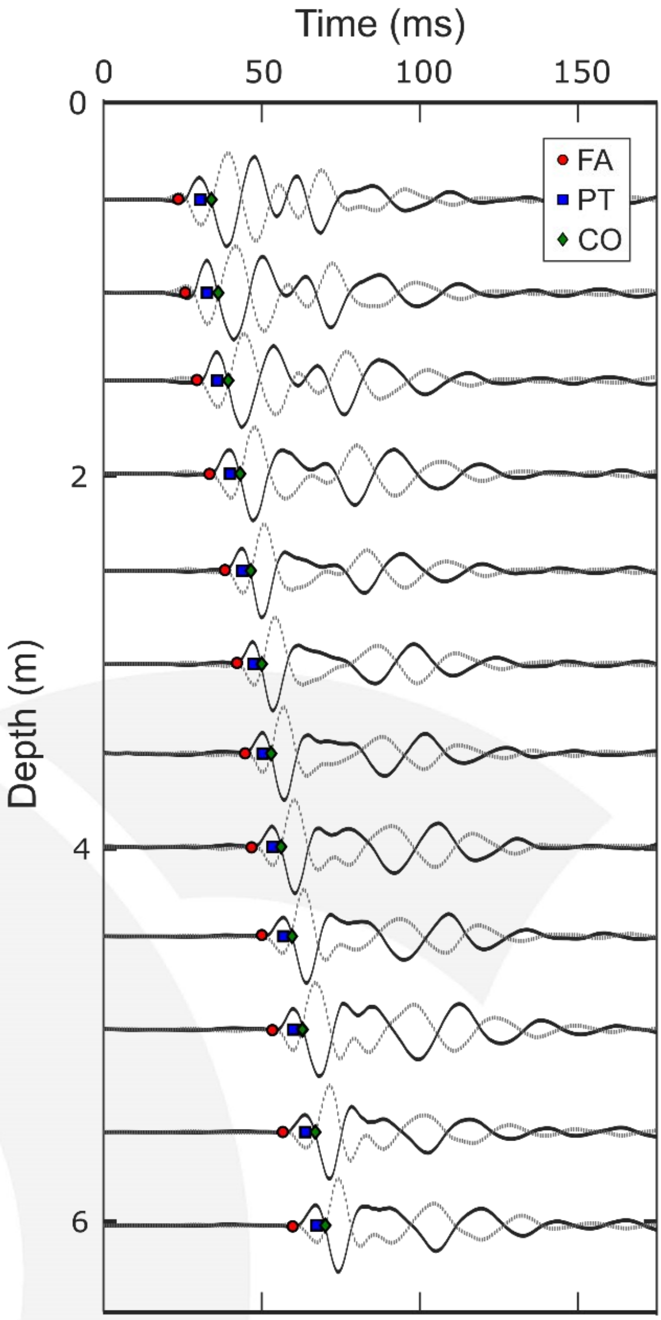

Figure 2-5: Waterfall plot of butterflied S_{VH}-waveform pairs illustrating three commonly-picked S-wave arrival times. Waveforms with initial positive voltage (upward) departures are shown as solid lines and those with initial negative voltage (downward) departures are shown as dashed lines (Stolte and Cox 2019).

When the interval wave travel time (Δt) between two measurement depths is needed for subsequent analyses, it can be obtained by taking the difference between the S-wave travel times obtained at each depth. This process is illustrated in Figure 2-6 (a) which shows two sets of reversed waveform pairs plotted together, along with their respective FA, PT and CO travel time picks. The waveforms were taken from measurement depths 5 m apart so that the Δt values can be easily seen. The Δt for each arrival picking method is shown both graphically and numerically in Figure 2-6 (a). Alternatively, Δt can be developed from the time delay (i.e., the product of the time lag and the sampling rate of the waveforms) associated with the peak response of the cross-correlation (CC) function between pairs of waveforms recorded at different measurement depths. Using the CC function to obtain Δt eliminates the subjectivity associated with manual arrival picks and uses the full waveform rather than discrete points (Baziw 1993). However, it is recommended to use only the CC function for the first wave period or one-and-a-half wave period, because using the entire waveform may introduce errors associated with wave splitting or other interference effects (Cox 2018). The cross-correlation function of the positive voltage polarity waveforms shown in Figure 2-6 (a) is shown in Figure 2-6 (b). There is little to no difference in the Δt values developed from the four picking methods used to obtain the shear wave travel times from the exact same waveforms for this example. It should be noted that this is not always the case.

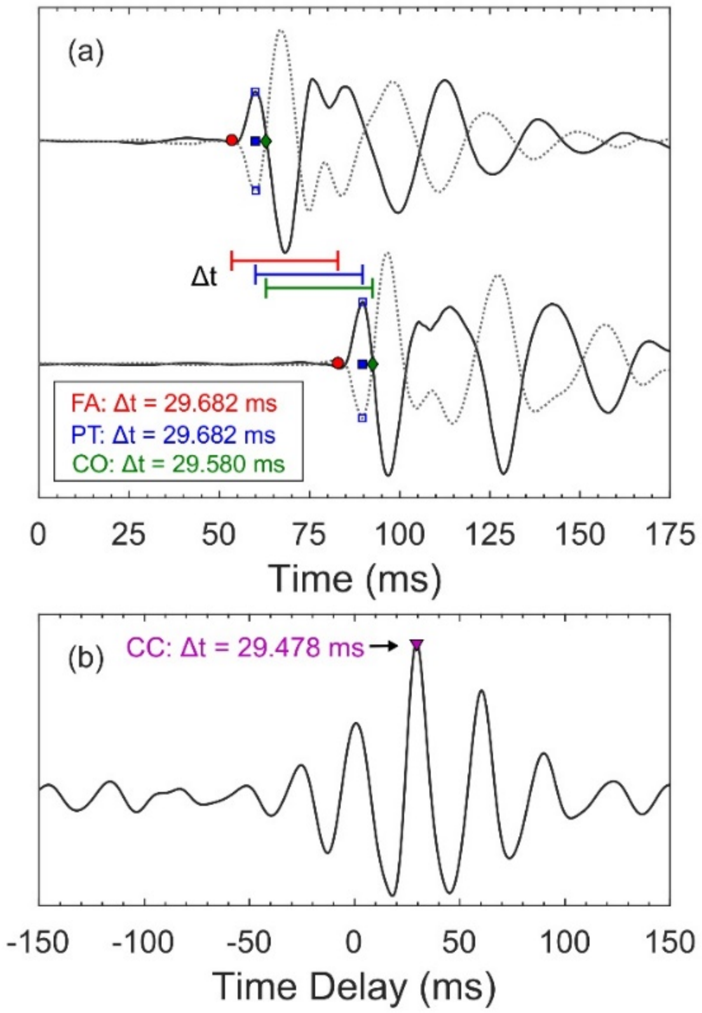

Figure 2-6: Example of interval travel time (Δt) evaluated from: (a) butterflied SVH-waveform pairs recorded at different depths, and (b) the cross-correlation function between the two positive voltage polarity waveforms shown in (a). (from Stolte and Cox 2019)

2.4.2 Velocity analysis

Four of the more common analysis methods used to develop profiles of V_P and V_S include: true-interval (TI); pseudo-interval (PI); corrected vertical travel time slope-based (SM) method (also referred to as the direct method); and raytracing (RT). The interval methods are described in ASTM D 7400-17 and are the most common methods used to reduce SCPT data (Stolte and Cox 2019), though they are also routinely used for reducing DH seismic data in general.

True- and pseudo-interval analysis

Both interval methods assume a direct (e.g., straight-line) travel path from the seismic energy source at the ground surface to the receiver based on the testing geometry (e.g., L_1 and L_2 as shown in Figure 2-1and Figure 2-2). The assumption of a straight-line travel path is not reasonable within the near-surface due to the potential for refraction of travel paths (refer to Figure 2-1). Refraction of travel paths may also occur across layer boundaries with significant stiffness contrasts. The assumption of a straight-line travel path becomes more reasonable as the test depth increases; particularly at depths where the travel path approaches vertical. Some experienced practitioners suggest disregarding the upper 3 to 5 m of a DH profile due to the potential effects of travel path refraction. As a rule of thumb, the depth at which the recorded shear wave velocities can be assumed to be reasonably unaffected by refraction (in the absence of high stiffness contrast layers) can be taken as 1.5 times the offset distance X (Cox 2018). For example, if the offset distance is 2 m, then the depth at which travel path refraction effects can be assumed to be small in homogeneous soil is 3 m.

The effects of refraction of the travel path can be assessed using Snell's law. ASTM D7400 requires that refraction be considered across layers with abrupt changes in density or elastic stiffness using Snell's law. However, in practice, it is not common for refracted ray paths to be considered when using either of the interval analysis methods. When wave refraction is not considered, many V_S profiles will not accurately represent the S-wave velocities within the upper several metres.

The interval velocity is computed for each successive pair of measurements using the following equation:

$$V_S = \frac{L_2 - L_1}{t_2 - t_1} = \frac{\Delta L}{\Delta t} \qquad \text{(Eq. 1)}$$

where L is the travel path length shown in Figure 2-1and Figure 2-2, and t_1 and t_2 are the are the picked wave arrival times along L_1 and L_2, respectively.

If a pair of seismic measurements are simultaneously recorded at two depths using a dual receiver package, the resulting velocity is considered a true-interval velocity. Alternatively, if pairs of seismic measurements are separately recorded at two depths using a single receiver package, the resulting velocity is considered a pseudo-interval velocity. As discussed in Sections 2.2.3 and 2.3, differences in energy source excitations and DAQ triggering may introduce timing errors into the evaluation of PI velocities. As a result, TI velocities are generally considered to be more accurate. To reduce timing errors when evaluating PI velocities, the trigger signal from the energy source excitation must be recorded. However, this is not routinely done in practice (Cox 2018). It is recommended that both TI- and PI-based velocity profiles be checked against velocities developed using the SM method (discussed below) to assess the stability of the interval velocities.

Corrected vertical travel time slope-based analysis

The corrected vertical travel time slope (SM) method is used to develop a shear wave velocity profile by examining linear trends in corrected vertical travel time (t_{FA}) with depth (Patel 1981, Kim et al. 2004, Redpath 2007, Boore and Thompson 2007). Boore and Thompson (2007) note that velocity profiles developed from this method are less prone to large and unrealistic fluctuations (i.e., jumps/reversals) in velocity as compared to the PI method due to the effects of inconsistent triggering and other small errors being averaged out by fitting a linear trend to multiple data points. Comprehensive analysis of field data by Stolte and Cox (2019) and an evaluation of hypothetical soil profiles by Hallal and Cox (2019) found that the SM method generally yields more reliable estimates of seismic velocities than the interval methods.

The correction converts the actual travel time along the slant path from the source to the receiver (due to the energy source being offset a distance X from the receiver hole) to the equivalent time required to travel vertically from the ground surface down to the receiver. The correction is accomplished using the assumed triangular geometry of the testing apparatus (refer to Figure 2-1) and the following equation:

$$t_{vert} = t_{FA} * \cos\theta = t_{FA} \frac{D}{\sqrt{D^2+X^2}} \qquad \text{(Eq. 2)}$$

where t_{FA} is the picked first arrival time, θ is the angle between the slant path and vertical, D is the measurement depth, and X is the horizontal source offset. If later points on the waveform (e.g., first peak/trough or first crossover point) are picked, they must be adjusted to an equivalent first arrival time using a representative 'time shift factor' (Δt_{FA}). Otherwise the travel time will be overcorrected, and the computed velocities will be too low.

The method of correcting for source offset when picking later waveform arrivals is as follows (modified from Redpath 2007):

$$t_{vert} = (t - \Delta t_{FA}) * \cos\theta = (t - \Delta t_{FA})\frac{D}{\sqrt{D^2+X^2}} \qquad \text{(Eq. 3)}$$

where t is the time to the first peak/trough (t_{PT}) or first crossover point (t_{CO}), and Δt_{FA} is the time difference between the time of the first arrival (t_{FA}) and t (refer to Figure 2-7).

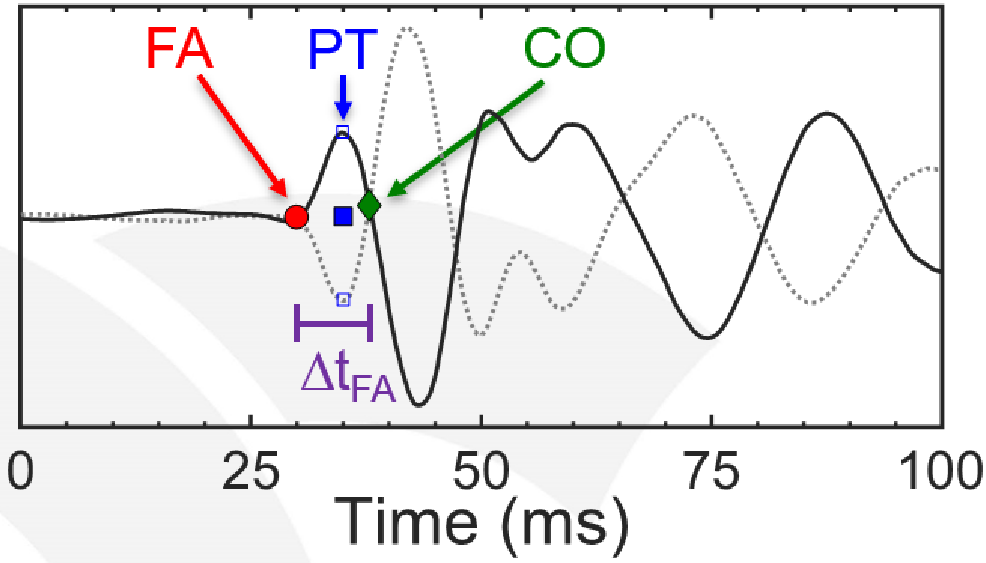

Figure 2-7: Illustration of 'time shift factor' (Δt_{FA}) computed as the time difference between the time of the first arrival (t_{FA}) and the time of the first crossover point (t_{CO})

It is noted that Δt_{FA} changes with depth due to changes in the frequency content of the measured S-waves. A representative 'average' value of Δt_{FA} can be used over a reasonable depth range to avoid having to compute it at every test depth.

The example SCPT dataset and supporting borehole data shown in Figure 2-8 illustrate the corrected vertical travel time slope-based method (SM). The average FA shear wave travel times at each measurement depth are taken directly from the waterfall plot in Figure 2-5. These are shown as hollow circles in the plot on the right side of Figure 2-8. They are corrected to vertical travel times (solid circular markers) using Equation 2.

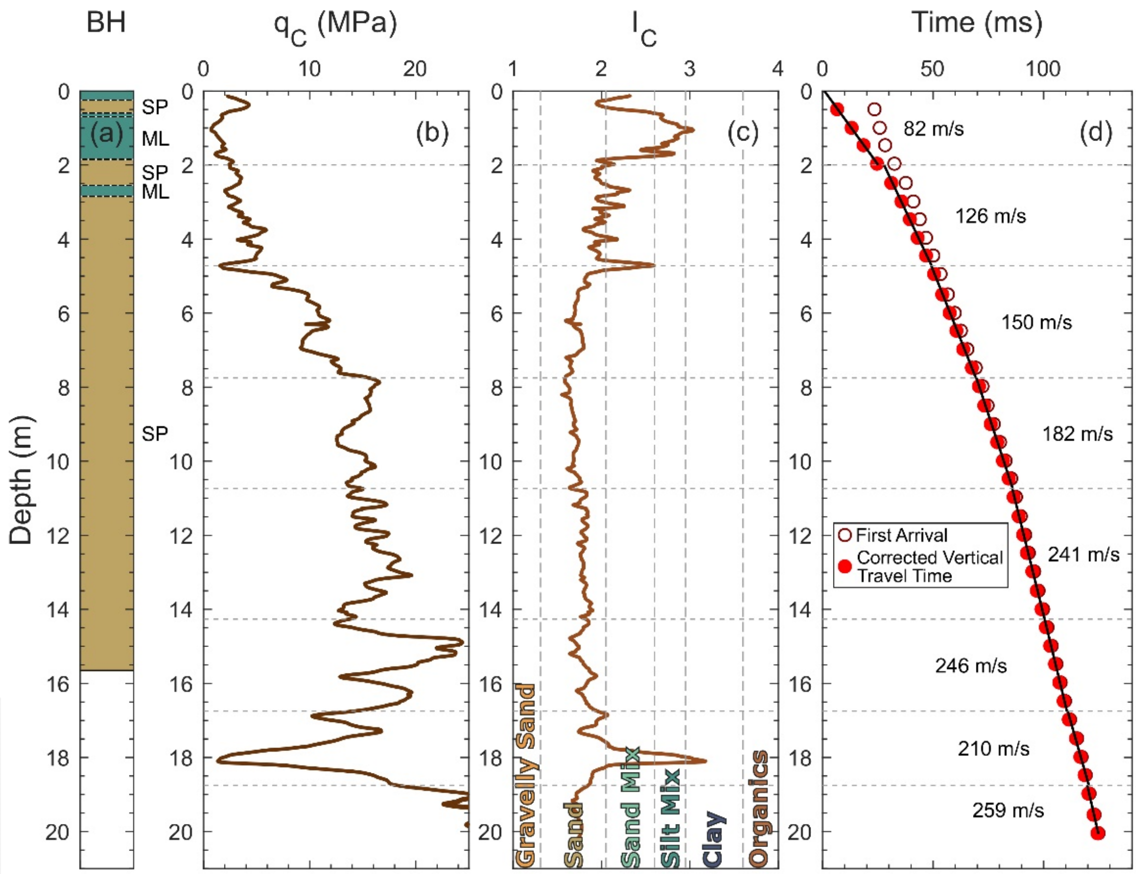

Figure 2-8: Example of slope-based VS evaluation using SCPT data (Stolte and Cox 2019).

The S-wave velocity profile is developed by fitting slopes to groups of data points based on either: (1) obvious breaks in the slope; or (2) using soil layer boundaries identified in supplementary geotechnical data such as CPT tip resistance (q_c) and normalised soil behaviour type index (I_C) and/or borehole logs. The use of supplementary data is required to help define layer boundaries when the changes in slope are subtle and difficult to discern. In the example shown in Figure 2-8, the q_c and I_c profiles were used to help select the layer boundaries. Once the layer boundaries are identified, linear trends are fitted to the corrected vertical travel time data for each individual layer using a least squares regression. Anomalous travel times can be given a lesser weighting or removed from the regression as appropriate. The slope of the fitted linear trend is the S-wave velocity of the corresponding layer.

Note that the resulting shear wave velocities in Figure 2-8 are rounded to the nearest metre per second – rounding to the nearest tenth, hundredth, etc. implies much greater accuracy than is appropriate for downhole testing. The velocities above and below the layer boundary at a depth of 14.25 m were computed as 241 and 246 m/s, respectively. These values are considered as the same value for practical purposes. However, the increase in cone tip resistance at this depth indicates an increase in density/stiffness. It should be noted that this level of accuracy applies to the output from all seismic velocity determination methods.

Raytracing velocity analysis

As discussed in Section 2.4.2 the assumption of a straight-line travel path between the energy source on the ground surface and the downhole receiver is not valid near the ground surface due to refraction. The raytracing (RT) method developed by Chander (1977) uses a raytracing algorithm to account for non-linear, refracted travel paths through an assumed horizontally layered velocity model by using Snell's law to determine refraction angles at layer interfaces. Baziw (2002) developed a forward modelling, downhole simplex method (FMDSM) to invert for the V_S profile by iterating layer velocities and comparing measured S-wave travel times to theoretical travel times calculated using Chander's raytracing algorithm. Typically, the FMDSM is implemented by assuming a horizontally layered profile with fixed layer interfaces either defined by a constant depth increment (e.g., one horizontal layer for every seismic measurement depth) or a-priori geotechnical data (e.g., CPT or borehole logs).

3 Crosshole Seismic Testing

Crosshole (CH) seismic testing is performed using two to three machine-drilled, cased boreholes. Crosshole testing requires more boreholes, more equipment, and more time to complete, hence it is considerably more expensive than downhole seismic testing; particularly when compared to direct push downhole methods (e.g., SCPT and SDMT). As a result, downhole testing is performed more frequently than crosshole testing. However, the results of properly performed and analysed crosshole testing are generally considered to be more representative than those obtained from downhole testing (Cox et al. 2019). The primary reasons for this are because the uncertainty associated with trigger timing errors are removed (when three boreholes are used), and the travel time measurement is relatively independent of the depth effects associated with downhole testing. Cox et al. (2019) discusses the technical advantages of crosshole testing relative to downhole testing in detail.

3.1 Overview of method

Crosshole seismic testing is performed by lowering a source for generating seismic waves (P-waves or S-waves) and one or two receivers incrementally down separate, in-line and cased boreholes spaced 1.5 to 5 m apart (Stokoe and Woods 1972, Sincennes 2012, Cox et al. 2019). The source and receiver(s) are located at a common measurement depth. The waves traveling along a predominately horizontal path arrive at the receiver borehole(s) and are recorded using properly oriented transducers (geophones or accelerometers). To evaluate the seismic wave velocity at each measurement depth, the assumed horizontal wave travel path is divided by the corresponding wave travel time. The true distance between the source and receiver boreholes at each measurement depth must be calculated from a borehole deviation survey. The P- and S-wave arrival times are manually picked from the seismic waveforms recorded at the receiver(s). The energy source and receiver(s) are typically moved up or down the borehole together in 0.5 to 3.0 m increments. The depth increments may be decreased near the ground surface, or in other zones of interest to improve the spatial capture of V_P and V_S.

The general equipment and procedures for conducting crosshole seismic testing are outlined in the ASTM test standard D4428/4428M-14. A schematic of a typical crosshole borehole test setup (two-receiver configuration) is shown in Figure 3-1. The ASTM test standard indicates a preference for a two-receiver setup but allows the use of a single receiver. The use of two receivers is preferable because it allows the measurement of three different travel times: (1) source-to-receiver one; (2) source-to-receiver two; and, (3) receiver one-to-receiver two.

Examining these three different travel times allows identification of refracted wave travel paths and/or inhomogeneity in material properties between the boreholes (Cox et al. 2019).

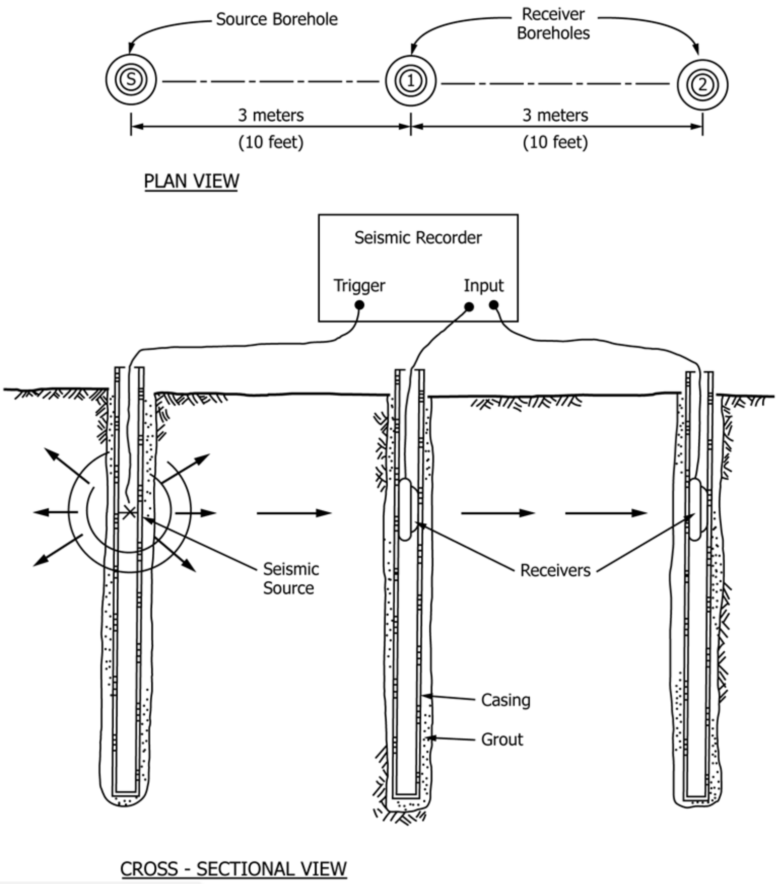

Figure 3-1: Schematic of crosshole seismic test in cased boreholes (ASTM D4428/D4428M-14). Two (source and receiver 1) or three (source, receiver 1, receiver 2) boreholes are required.

A recently developed variant of the crosshole testing – direct-push cross hole (DPCH) - utilises a pair of instrumented seismic cones pushed directly into the ground, eliminating the need for machine-drilled boreholes and installation of fully grouted casings. Seismic waves are propagated from one cone (the source) to the other (the receiver) in order to evaluate the V_P and V_S of the soils between the cones. The seismic energy is generated by either tapping on the top of the CPT push rod for the source cone, or by using a pushable, in-ground seismic source cone. Directly pushing the cones into the ground provides excellent coupling between the source/receiver(s) and the surrounding soil. It also allows the testing to be conducted at vertical intervals in the order of 0.2 to 0.5 m with little additional effort, thus providing greater resolution of the shear wave profile with depth. A schematic of a DPCH test setup is shown in Figure 3-2. Cox et al. (2019) provide detailed descriptions of the test method, procedures, and data processing and analysis.

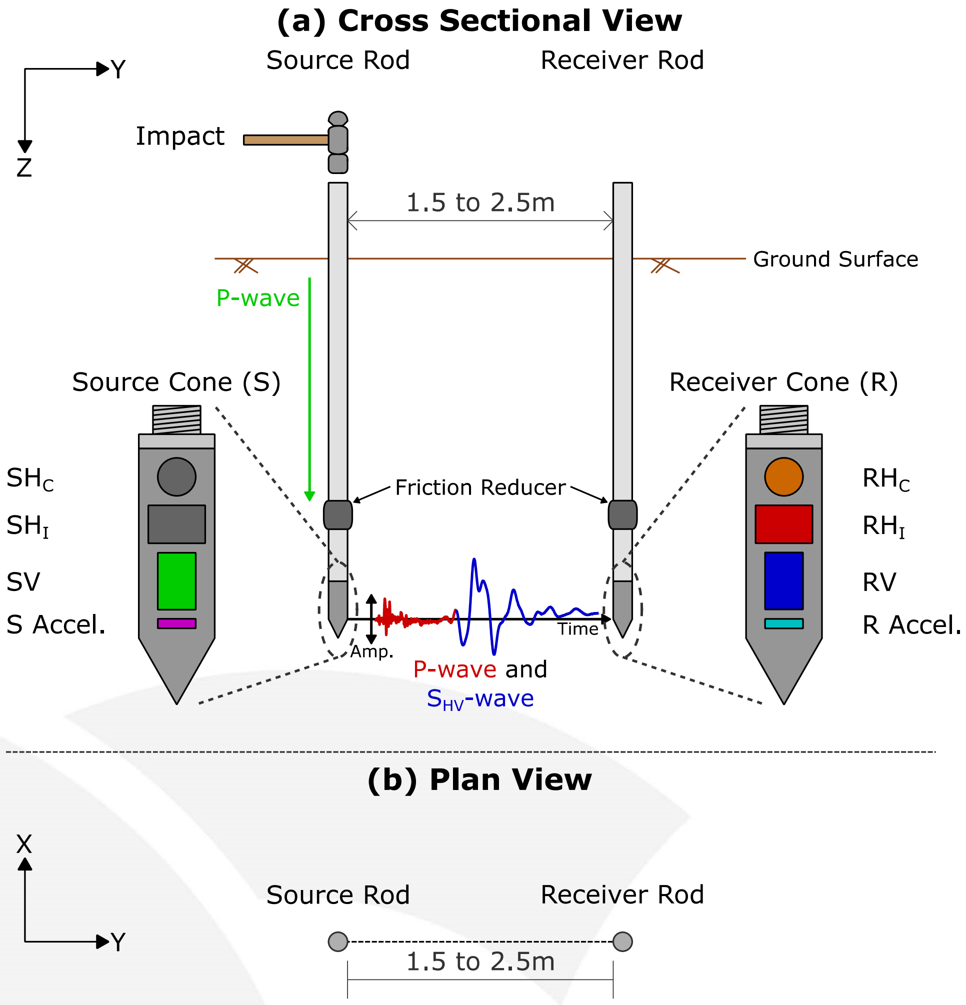

Figure 3-2: Schematic of direct-push crosshole (DPCH) test. (Cox et al. 2019).

The DPCH test method was first used on a regular basis by researchers at the University of Texas as part of in-situ liquefaction testing using in the early 2000s (Cox et al. 2009); primarily to investigate the degree of soil saturation, as inferred from V_P measurements. The use of DPCH testing increased significantly in the aftermath of the 2011-2012 Canterbury earthquakes, where it played a significant role in helping researchers assess the effectiveness of various shallow ground improvement methods (Stokoe et al. 2014, Wotherspoon et al. 2015, Stokoe et al. 2016, Wotherspoon et al. 2017, Hwang et al. 2017).

The principles and procedures associated with crosshole seismic testing, whether using boreholes or the direct push method, are similar. Therefore, the following discussion does not differentiate between the two variants except where there is a clear difference between particular aspects of the methods.

3.2 Test equipment

3.2.1 Thrust-providing machines (DPCH method)

Two machines capable of providing controlled downward thrust via hydraulic rams are required to advance and retrieve the instrumented cones for DPCH testing. A standard CPT rig is easily adaptable for this purpose. Small, track-mounted CPT rigs that use auger anchoring systems and can manoeuvre and position into the relatively tight spacing (< 2.5 m horizontally), have proven ideal for DPCH testing in relatively soft soils (< 15-20 MPa CPT tip resistance) down to 20-plus metres. Figure 3-3 is a photograph of two track-mounted CPT rigs advancing DPCH cones during a seismic test. Larger rigs can also be used.

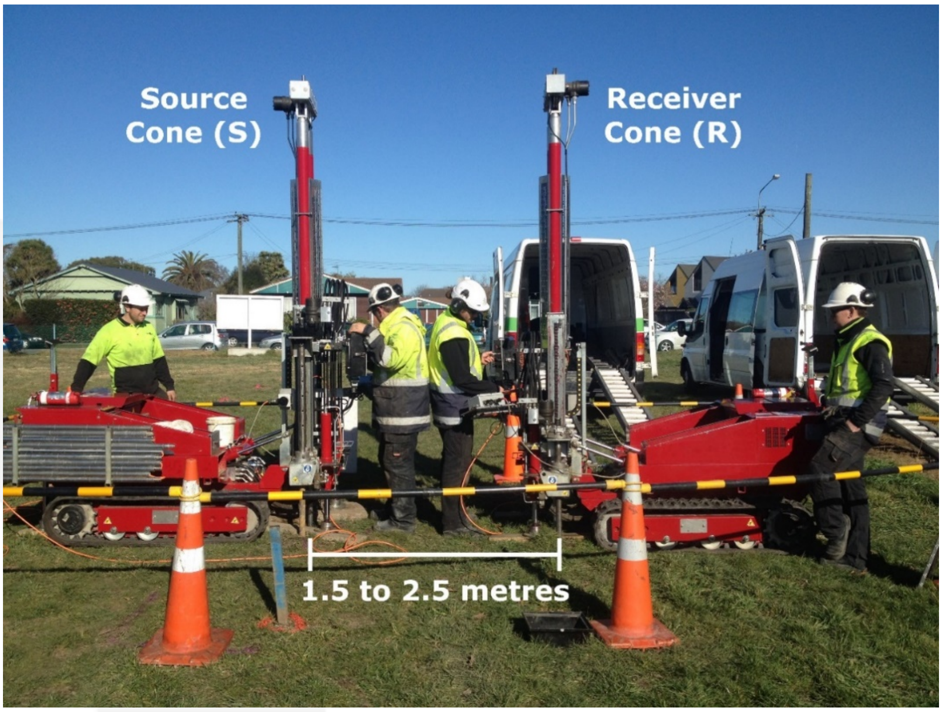

Figure 3-3: Photograph of two track-mounted CPT rigs advancing two DPCH cones during a seismic test (Cox et al. 2019).

The push rods used to advance the DPCH instrumented cones should comply with the test standard ASTM D5778-12. It is important to minimise firm coupling between the push rods and the surrounding soil. This is achieved by using friction reducers like those commonly used in CPT testing to decrease the frictional resistance along the cone push rods. As shown in Figure 3-2, a friction reducer is a short length of oversized-diameter (~25% larger) push rod located above the cone tip. As the cone is advanced into the ground, the friction reducer enlarges the hole in the soil created by the cone tip, so it is slightly larger than the diameter of the push rods. The resulting break in contact between the soil and push rods limits the transmission of waves along the rod-soil interface.

3.2.2 Seismic energy source

Seismic waves for crosshole borehole testing are typically generated by dropping a metal slide hammer on an anvil firmly locked in the source borehole at the test elevation to generate P-waves, horizontally propagating, vertically polarised shear waves (S_{HV}-waves), and/or horizontally propagating, horizontally polarized shear waves (S_{HH}-waves). A reversible polarity solenoid source can also be used to generate both P- and S-waves. A primary consideration when selecting the energy source is to make sure that the source should be rich in the type of energy required. For example, to produce good P-wave data, the energy source should impart adequate energy in compression or volume change (e.g., impulse sources such as hammers, air guns, explosives). For S-wave generation, the energy source should be capable of producing an S-wave train with an amplitude of at least twice that of the P-wave train, and ideally the source should be reversible. If a directional source is used (e.g. a horizontal solenoid), the source should be oriented correctly relative to the receiver as appropriate for generating the desired wave type. For example, if generating S_{HH}-waves, the source propagation should be oriented perpendicular to a line drawn between the source and receiver (i.e., cross-line direction). If generating P-waves, the source propagation should be oriented towards the receiver.

Seismic waves for DPCH testing are generated by vertically tapping the top of the source cone push rod to generate a P-wave which travels down the push rod to the source cone where the energy is transferred into the soil as radially propagating P- and S-waves. The horizontally propagating, horizontally polarised compression waves (P_H-waves) and horizontally propagating, vertically polarised shear waves (S_{HV}-waves) are of primary interest. Research has also been conducted to develop a specialised energy generating mechanism installed inside of the source cone (Cox et al. 2019).

3.2.3 Receivers

ASTM D4428/4428M-14 discusses requirements for seismic receivers (geophones or accelerometers) for crosshole borehole testing. It is typical for the receiver to comprise three transducers (e.g., geophones or accelerometers) mounted rigidly to a downhole tool that can be clamped to the hole casing; two oriented in orthogonal horizontal positions and one in a vertical position. It is important that all receivers used in the testing be of the same type and with matched characteristics. The receiver package setup is similar to that used for single receiver downhole seismic testing (refer to Section 2.2.2).

Although standard SCPT cones have been used for DPCH testing, purpose-built cones have proven to be preferable (Cox et al. 2019). Each DPCH cone must be capable of measuring several seismic waves radially propagating from the source cone with different polarities. Similar to crosshole borehole testing, it is preferable that the cones contain three orthogonally-oriented (vertical, horizontal in-line, and horizontal cross-line) transducers. Cone tilt during testing must also be measured and recorded so that the plan location and hence the spacing between the source and receiver can be accurately determined. Micro electrical mechanical systems (MEMS) accelerometers are preferred for measuring cone tilt because of their compact size, low power requirements, and ability to track tilt using gravity as a reference. Because DPCH testing requires incremental measurements every 20 to 50 cm, standard measurements of CPT tip resistance, sleeve friction, and pore water pressure are best obtained from a standard CPT sounding located nearby. Therefore, there is no advantage to including instrumentation for standard CPT readings in the DPCH cones. Cox et al. (2019) provide details for receivers used for DPCH testing.

3.2.4 Data acquisition system

Section 2.2.3, which summarises the principles and requirements for the data acquisition system (DAQ) for downhole seismic testing, also generally applies to crosshole testing so is not repeated here. Crosshole testing requires more channels/inputs than downhole/SCPT/SDMT testing because there are three (borehole) to five (DPCH) transducers in the source and each receiver. In addition, while the trigger signal is sometimes recorded in downhole/SCPT testing, it must be recorded in crosshole testing for source to single receiver measurements (i.e., S to R_1 and/or S to R_2).

At a minimum, the requirements specified in ASTM D4428/4428M-14 for the recording system, including system accuracy and trigger accuracy should be met for crosshole borehole testing. Refer to Cox et al. (2019) for a detailed description of the requirements for a DAQ to be used for DPCH testing – noting that many of these are also applicable to units used for crosshole testing in boreholes.

3.3 Test procedures

The following discussion is not intended to cover every aspect of the test procedures, but to highlight some of the more important aspects to help ensure collection of high-quality data.

Borehole testing is best conducted using three boreholes (i.e., S to R_1, S to R_2, and perhaps most importantly R_1 to R_2 measurements) located in a line and spaced between 1.5 and 5.0 m apart. DPCH testing typically uses a source cone and receiver cone (i.e., to R_1 measurement) located 1.5 to 2.5 m apart. Larger borehole/push rod spacing results in longer direct wave travel paths which in turn result in an increased potential for early arrival of refracted waves (refer to Section 2.4.2). A large spacing also results in a decreased signal-to-noise ratio. Borehole tests are typically conducted at vertical increments of 0.5 to 3 m while DPCH tests are done at vertical increments of 0.2 to 0.5 m.

In general, the preparation of the boreholes should be done in accordance with ASTM D4428/4428M-14, which is essentially the same as for boreholes to be used in downhole testing, and is described in Section 2.3. For borehole testing, a deviation survey (from vertical) must be completed for each borehole either before or immediately after the testing. ASTM D4428/4428M-14 requires the precise vertical alignment of each hole to be determined using a tilt measuring instrument with a sensitivity of 0.3 degrees. Knowing the vertical alignment allows computation of the horizontal position at the test elevation in the borehole, hence the horizontal distance between boreholes can be accurately determined for a given test elevation. In a DPCH test, the cone push rods are initially levelled with a carpenter's level, and tilt readings of the push rods are taken prior to the start of the first test, and again at each test depth.

Also prior to the start of testing, it is important to orient the horizontal receivers properly (i.e., the receivers should be oriented in the same direction). For borehole testing, a magnetometer can be used to orient one of the horizontal components to magnetic north. For DPCH testing, the cones are rotated to align the positive Y-components of the geophones and MEMS accelerometer in each cone with the positive Y direction of the local coordinate system (i.e., away from the source cone towards the receiver cone). This can typically be done using the markings on the cone casings.

For crosshole testing using two boreholes (e.g., S_1/R_1 configuration), calibration of the trigger is implicitly required by ASTM D4428/4428M-14 – Section 6.1.3.3 states: "When only two boreholes are used and velocities are determined by time interval S-R1, documentation of the trigger accuracy relative to the instant of seismic source generation must be provided."

Trigger calibration is also required for DPCH testing when using only a source and single receiver cone to correct for two factors: (1) the wave travel/compliance times inside of the cones; and (2) timing issues between the cones and the DAQ, including mechanical-to-electrical signal conversion and digitisation. The travel time of the P- and S-waves through the cone bodies for DPCH testing can be determined by performing a calibration before testing. The cones are tightly clamped together as illustrated in Figure 3-4. The hammer is used to tap on the source cone push rod and generate the seismic waves. Data acquisition is triggered by the source cone vertical geophone (SV). The P- and S-waves are measured by the receiver-geophones RHI and RV, respectively. The difference in arrival times of the seismic waves at the source and receiver cones is the trigger calibration time (t_{cal}).

As shown in Figure 3-4, the measured travel time (t) includes the actual wave travel time within the soil between the cones (i.e., the corrected travel time; t_{cor}) as well as the trigger calibration time. The calibration time must be subtracted from the measured travel times to determine the actual P- and S-wave travel times through the soil. Trigger calibration is beyond the scope of this paper, but the subject is discussed in detail in Cox et al. (2019).

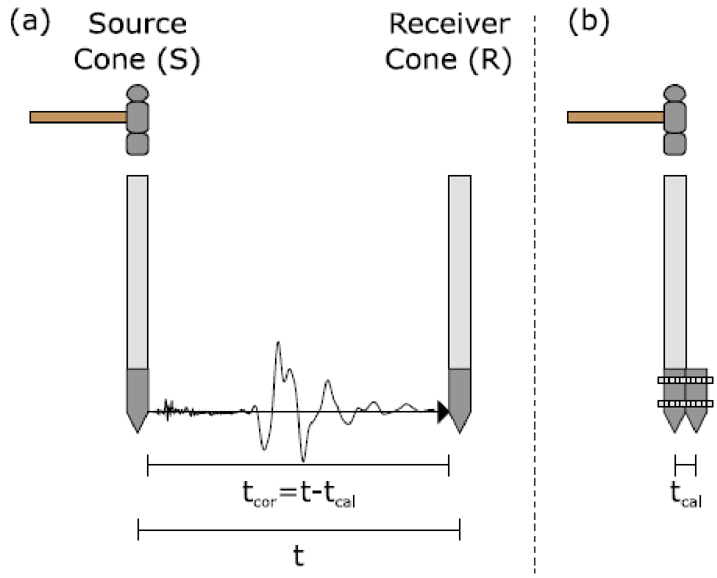

Figure 3-4: Overview of DPCH trigger calibration. (a) Generalised schematic of a DPCH measurement. The measured travel time (t) includes both the travel time through the soil (t_{cor}) and the travel time through the DPCH cone body to the internal geophones (t_{cal}). (b) Schematic of the trigger calibration. (from Cox et al. 2019)

After the source and receiver packages are advanced to the first testing depth, seismic waves are generated by exciting the seismic source. Similar to downhole testing, it is preferable to stack 3 to 10 source excitations to enhance the signal-to-noise ratio. P- and S-waves are often generated by the same source excitation, however, P-waves are best observed on in-line horizontal transducers and S_{VH}-waves are better observed on vertical transducers (refer to Figure 3-2). S_{HH}-waves are best captured by cross-line horizontal transducers, but this is not commonly done. In borehole testing, it is possible to generate reversed polarity shear waves to assist in picking S-wave arrivals. This can be done by reversing the source direction (e.g., pulling up on the sliding impact hammer) to generate reversed S_{HV}-waves.

After completion of the first test, the source and receiver(s) are advanced to the next test depth and repeat the test. This process is repeated for all testing depths. For borehole-based testing, a second borehole verticality survey should be conducted (at the same depth intervals used in the first survey) after completion of the last test.

3.4 Data reduction and analysis

Seismic wave (e.g., P- and and/or S-wave) velocities (V) from crosshole seismic testing are evaluated using the simple equation:

V = travel path distance / direct travel time (Eq. 4)

3.4.1 Evaluation of seismic wave direct travel time

Pre-processing of raw data and evaluation of wave travel times from crosshole seismic testing is non-trivial. The following discussion is intended to summarise the main steps required for proper evaluation travel times, and to highlight key aspects. A detailed description of wave travel time evaluation is given in Cox et al. (2019).

The travel time of a seismic wave between the source and receiver(s) is simply the difference between the arrival time of the wave at the receiver and the departure time of the same wave from the source. To determine the travel times of the direct S-waves at a given measurement depth, two points in time must be picked from the recorded waveforms: (1) the initiation of energy/arrival time at the source (i.e., the trigger time); and (2) the arrival time of the *direct* S-wave at the receiver. Similarly, the trigger time and the direct P-wave arrival must be picked to evaluate travel times of the direct P-waves. The trigger time and direct arrival times are picked from the stacked waveforms recorded at each measurement depth.

Before making arrival picks, pre-processing of the raw stacked waveforms may be necessary to clarify the waveforms and observe direct arrivals. The first step is to remove vertical offsets and low-frequency drift using linear detrending. There are a number of ways to do this in both the time and frequency domain as described in Cox et al. (2019). Filtering may be required to clarify wave arrivals at the receiver; however, the selection and application of filters requires considerable experience and judgement to avoid modifying the waveforms to the point that they are no longer representative.

The stacked waveforms from the entire test may be shown together in a waterfall plot by normalising the amplitude and vertically offsetting each waveform by its measurement depth (an example waterfall plot from a DPCH test is shown in Figure 3-5). Plotting the waveforms in this manner allows the analyst to identify changes in the direct wave arrival time, frequency content and amplitude with depth. It should be noted that normalisation removes any absolute trends in wave amplitude with depth, which may be indicative of changes in material type and material damping. The observable trends from surrounding waveforms on the waterfall plot, ideally combined with observations from other geotechnical data (e.g., CPT testing), will help with the identification of the direct arrivals on difficult waveforms.

Time zero as recorded during a test does not necessarily correspond to the true first arrival of the seismic wave at the source transducer (i.e., the trigger time, t_T). A pre-trigger delay is needed to pick the arrival of energy at the source, which is typically a few data points before the digitised zero time. Picking the true trigger time is necessary for obtaining the correct P-wave velocity. It is less important for obtaining the S-wave velocity.

To illustrate the importance of picking the correct trigger time at the source cone, consider the following example. A P-wave traveling 2000 m/s will travel 1.5 m in 0.75 ms. When sampling at 20 kHz, the travel time occurs over 15 samples. If the difference between the DAQ zero time and the true trigger time at the source is two samples, the V_P will be over-predicted by 13 percent. This magnitude of error can be significant when using the V_P to estimate geotechnical parameters such as void ratio and degree of saturation; particularly if compounded by other 'small' errors introduced during testing and data analysis.

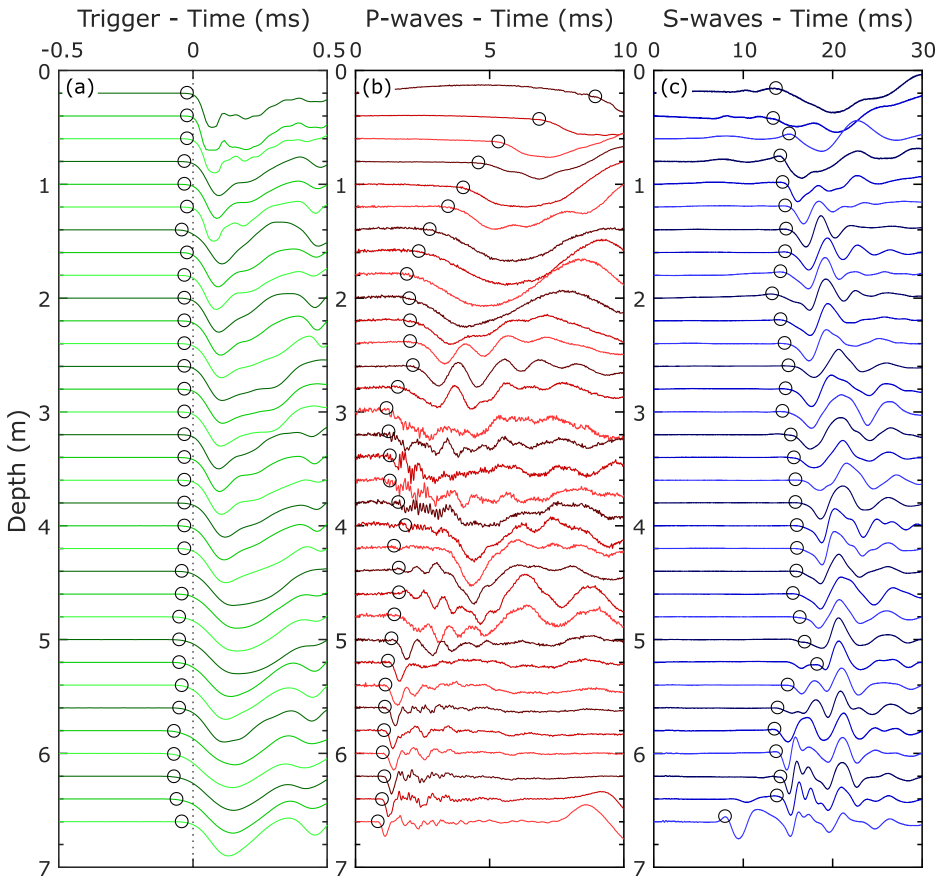

Figure 3-5: Example waterfall plots of: (a) the source trigger, (b) the P-wave, and (c) the S-wave waveforms recorded on the source cone vertical (SV), receiver cone horizontal in-line (RHI), and receiver cone vertical (RV) geophones respectively. The waveforms are normalised by absolute maximum magnitude and vertically offset by testing depth. The wave arrival picks are shown as black circles. (Cox et al. 2019)

Figure 3-5(a) shows a trigger plot for a DPCH test. As the length of the cone push rod and the soil/rod friction increases, the frequency content of the seismic energy arriving at the bottom of the rod changes. This in turn results in slight changes to the observed trigger time – in this example beginning at a depth of about 4.6 m.

The P-wave arrival time (t_{PA}) at the receiver is best observed using the horizontal in-line (RH_I) transducer. P-wave arrival times are picked as the first signal departure from the noise floor because they will always arrive first at the receiver. In unsaturated soil, the P-wave arrival is characterised by a low frequency and gradual departure. In saturated soil, P-wave arrival is characterised by a high frequency and abrupt departure. Enlarged waveform plots illustrating correctly picked P-wave arrivals are shown in Figure 3-6. The P-wave arrivals are much smaller than the later S-wave arrivals.

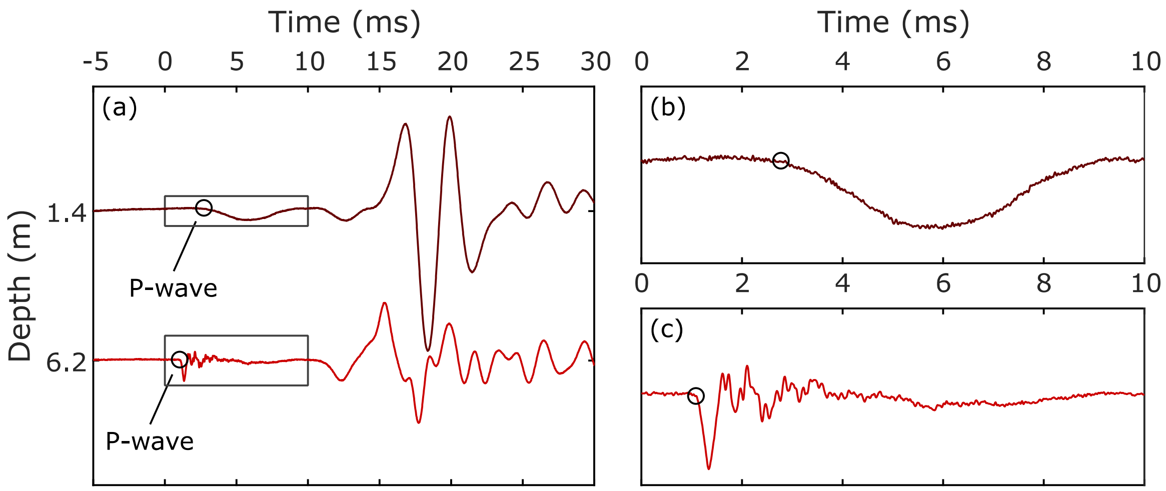

Figure 3-6: Example P-wave arrival picks indicated by black open circles on two sample waveforms recorded at the same site but at different depths on a horizontal in-line (RHI) geophone in the DPCH receiver cone. (a) The top waveform was recorded at a depth of 1.4 m in unsaturated soil, and the bottom waveform was recorded at a depth of 6.2 m in saturated soil. The zoomed-in portion of the wave forms are shown in (b) and (c). The higher amplitude arrivals later in the record (a) are S-waves. (Cox et al. 2019)

S-wave arrival time

The S-wave arrival time (t_{SA}) can often be seen with the P-wave arrivals on RH_I waveforms as shown in Figure 3-5. However, they are more reliably identified when recorded by a properly oriented transducer. A downward hammer tap on the top of the DPCH source rod or a vertical hammer drop onto the anvil in a borehole energy source will induce S_{HV}-waves with an initial downward particle motion. Therefore, t_{SA} is most precisely observed at the receiver on the vertical (RV) transducer.

As a rule of thumb, the arrival of S-waves is picked as the first *major amplitude departure*, after the P-wave arrival, *that has the correct polarity*. If a reversible source is used, the waveforms will butterfly (refer to Section 2.4.1) at the S-wave arrivals. It is critically important to know the voltage polarities for a given set of equipment when performing crosshole seismic testing.

Three S-waveforms from the example waterfall plot shown in Figure 3-5 are presented in Figure 3-7 – they were recorded at measurement depths of 6.2, 6.4, and 6.6 m at the receiver on a vertically oriented geophone. The testing was terminated at 6.6 m at the top of a dense gravel layer.

The transition from a softer material into the stiffer gravel layer is apparent in the waveforms shown in Figure 3-7. The top waveform measured at 6.2 m shows a clear downward S-wave arrival at about 14 ms. The bottom waveform from at 6.6 m shows a clear downward S-wave arrival at about 8 ms. (Note that the downward departure at 6.6 m is the direct S-wave arrival, not the preceding upward departure, because of the known downward particle motion of the S_{HV}-wave and the known negative voltage polarity of the RV geophone.) However, the waveform measured at 6.4 m shows two downward departures: a small amplitude arrival at about 10 ms followed by a larger amplitude arrival at about 14 ms. If the waveform at 6.4 m was considered alone, the analyst might be tempted to pick the smaller amplitude downward departure as the direct arrival of the S_{HV}-wave. However, when viewed together with the other waveforms in waterfall format, it is evident that the earlier arrival at 6.4 m is caused by a refracted wave off the stiff gravel layer beneath.

In general, refracted waves will have smaller amplitudes than direct waves and will not have a large reversal of polarity following their initial arrival. As can be seen in Figure 3-7 by the waveform at 6.4 m, the refracted wave has the correct downward polarity (e.g., negative/decreasing voltage). However, it is smaller than a later downward arrival and is not accompanied by a subsequent large upward departure.

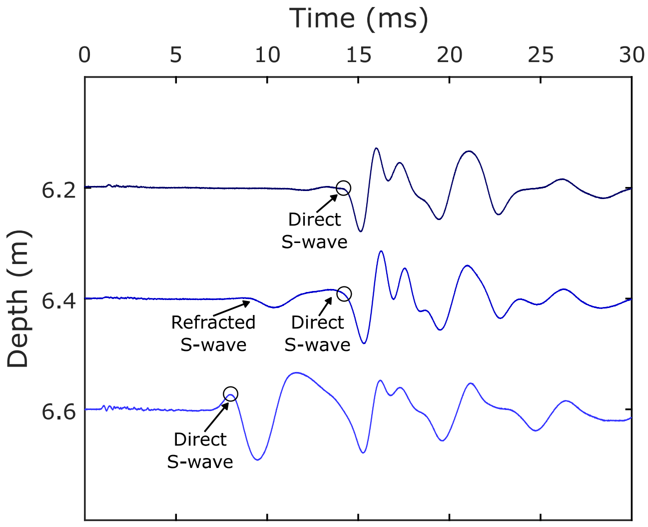

Figure 3-7: Example S-wave arrival picks indicated by black open circles on 3 sample waveforms recorded at the same site but different depths on a vertical (RV) geophone in the DPCH receiver cone. The waveforms at 6.2 and 6.6 m show clear direct S-wave arrivals (expected downward/negative polarity). The waveform at 6.4 m shows an early arrival from a refracted travel path off the stiffer gravel layer below. (Cox et al. 2019).

Computation of corrected travel times

Once the trigger time, and P- and S-wave travel times are picked, the actual travel time between source and receiver is calculated using the following equations (refer to Cox et al. 2019 for details):

Actual travel time of the direct P-wave is:

$$t_P = t_{PA} - t_T \quad \text{(Eq. 5)}$$

Actual travel time of the direct S-wave:

$$t_S = t_{SA} - t_T \quad \text{(Eq. 6)}$$

The direct P- and S-wave travel times must then be corrected using the triggering calibration values (t_{Pcal} and t_{Scal}, refer to Section 3.3) as follows:

$$t_{Pcor} = t_P - t_{Pcal} \quad \text{(Eq. 7)}$$

$$t_{Scor} = t_S - t_{Scal} \quad \text{(Eq. 8)}$$

The corrected travel times from equations 7 and 8 are used to calculate V_P and V_S once the travel path distance is determined.

3.4.2 Calculation of travel path distance

For crosshole seismic testing, the positions of the energy source and receiver(s), relative to each other in 3D space, must be known. Once the 3D positions are established, it is a trivial calculation to obtain the straight-line distance (L) between the source and receiver(s). For borehole-based testing, the results of the borehole deviation survey are used as described in ASTM D4428/4428M-14. The determination of the positions of the source and receiver cones in the DPCH method is described in Cox et al. (2019).

3.4.3 Evaluation of P- and S-wave velocities

The values of $V_{P,i}$ and $V_{S,i}$ at each depth increment (i) are determined from the corrected travel times and direct travel-path distances using the following equations:

$$V_{P,i} = L_i/t_{Pcor,i} \qquad \text{(Eq. 9)}$$

$$V_{S,i} = L_i/t_{Scor,i} \qquad \text{(Eq. 10)}$$

Where L_i is length of the direct travel path between the source and the receiver, defined using the deviation measurements that have been taken throughout the test. Refer to Cox et al. (2019) for details on how to calculate L_i.

The DPCH V_P and V_S profiles developed for a site in Christchurch (Cox et al. 2019) are shown in Figure 3-8, along with other geotechnical (borehole and CPT) data.

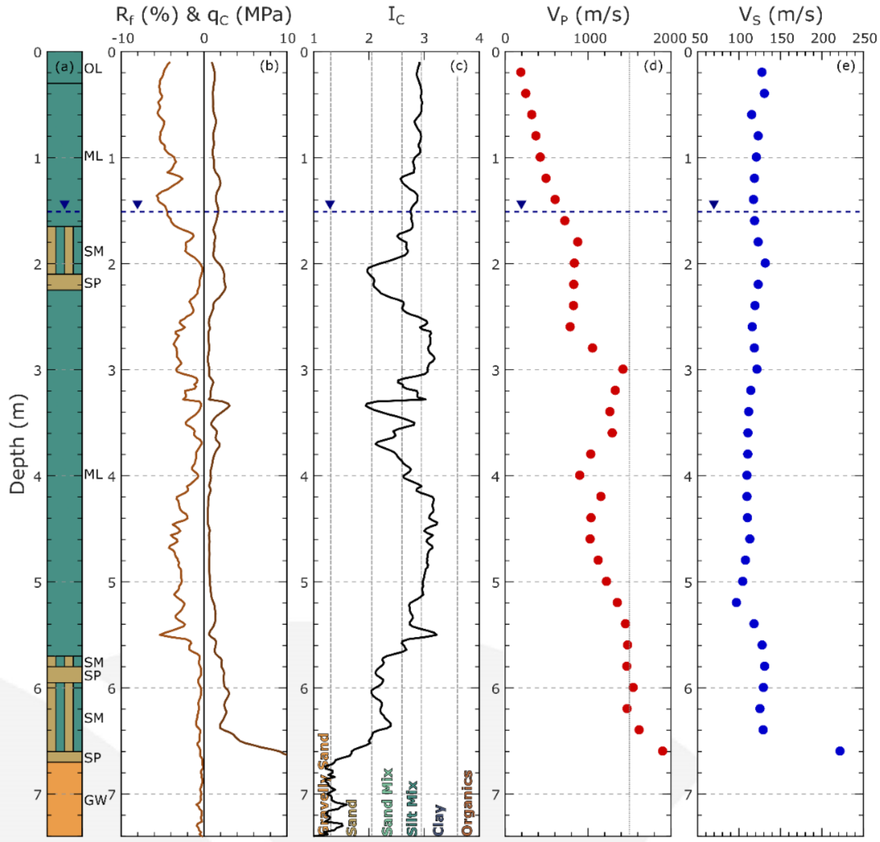

Figure 3-8: Comparison of V_P and V_S data with nearby subsurface data: (a) soil classification from borehole samples, (b) CPT friction ratio and tip resistance, (c) CPT normalised soil behaviour type index. Groundwater level based on piezometer readings is shown as a horizontal dashed line and inverted triangular symbols (Cox et al. 2019). Note that the soil is not fully saturated until a depth of about 5.4 m, hence the measured V_P of less than 1,500 m/s above this depth.

3.5 Limitations and challenges with crosshole testing

At sites with interlayered soil profiles containing stiff layers overlying very soft and thin layers (as indicated by CPT and/or borehole data), it can be difficult to resolve the proper V_S of the underlying soft, thin layers with crosshole testing. Depending on the thickness and the stiffness contrast of these soft materials, the waveforms can be complicated/contaminated by indirect wave arrivals, which may arrive faster than the waves traveling directly between the source and receiver(s). In this scenario, selecting the S-wave arrival as the first major departure with the correct polarity after the P-wave may result in shear wave velocities that are too high and nearly equivalent to those measured in the underlying and/or overlying stiff material.

Potential causes of the early arrivals include: (1) waves refracted along stiff layer boundaries – i.e., head waves; (2) waves converting modes (i.e., S_{HV}-waves converting to P-waves); and (3) for DPCH testing only – transmission of energy between the cone push rods through the overlying stiff material. As discussed previously, using friction reducers placed above the cones will reduce the coupling of the push rods with the surrounding soil and limit the indirect transmission of wave energy (refer to Figure 3-2). Cox et al. (2019) provide a comprehensive discussion of how to identify and address potential problems with non-direct wave paths and complicated wave paths in interlayered soils.

Correct trigger calibration, recording and processing of the source trigger times is not particularly difficult, however it does take some time and effort. If monitoring of trigger times is not done or done incorrectly, the resulting seismic wave velocities may not be representative of the actual conditions; particularly the P-wave velocity.

4 P-S Suspension Logging

4.1 Overview of method

P-S suspension logging was developed by researchers at the OYO Corporation in Japan in the 1970s as technique to measure V_P and V_S in deep, uncased boreholes (Nigbor and Imai 1994). It is also known as suspension logging or OYO P-S suspension logging. The method has been used successfully to depths of about 600 m. The suspension logging method directly determines the average velocity of a segment of the soil column surrounding a fluid-filled borehole by measuring the elapsed time between arrivals of a wave propagating upward through the soil column.

An energy source suspended in the borehole creates a pressure wave in the borehole fluid. At the borehole wall, the pressure wave is converted to P- and S-waves which travel radially from the borehole wall. At each receiver location, the P- and S-waves are converted back to pressure waves in the borehole fluid and detected by the geophones. The direct arrivals of the pressure wave in the borehole fluid is not detected by the receivers because the wavelength of the pressure wave is significantly greater than the width of the fluid column surrounding the test probe (i.e., m vs cm scale). A schematic of the P-S suspension logging system is shown in Figure 4-1. The source and receivers are raised and lowered as a unit in the borehole, producing relatively constant amplitude signals at all depths. The average seismic wave velocity of the interval between the two receivers is determined by inversion of the wave travel time between the receivers.

There is currently no ASTM test standard for P-S suspension logging. The general equipment and procedures for conducting the P-S suspension logging are described in various references (Ohya 1986, Kaneko and Kanemori 1990, Nigbor and Imai 1994, Diehl et al. 2006, Biringen and Davie 2010).

4.2 Test equipment

A typical P-S suspension logging system consists of a borehole source/receiver probe, a cable and winch to raise and lower the source/receiver probe, and control/recording instrument, as shown in Figure 4-1. The probe contains a source (S) and two biaxial geophones (R_1 and R_2), separated by flexible isolation sections, and is centred in the borehole by stiff nylon 'whiskers'. The source is joined to two biaxial receivers by a flexible isolation cylinder. The receivers are typically spaced approximately 1 m apart and are located above the source. The total length of the probe ranges from about 6 to 7 m. The probe receives control signals from, and sends the amplified receiver signals to, instrumentation at the ground surface via an armoured multi-conductor cable.

The cable is wound onto the drum of an electric winch and is used to support the probe. The cable travel is measured to provide probe depth data.

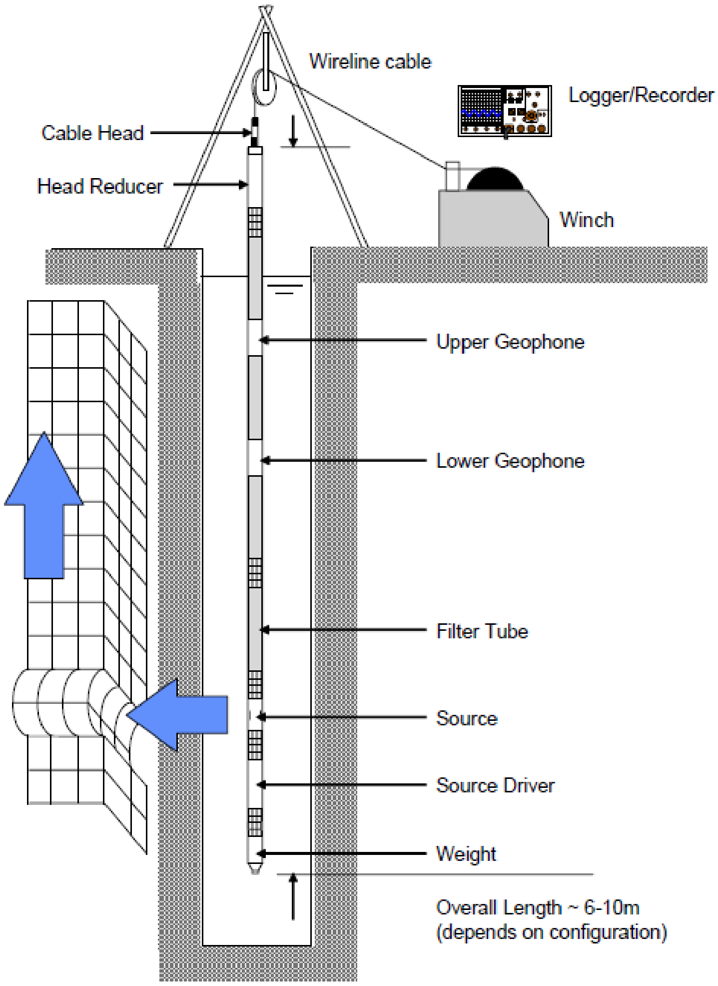

Figure 4-1: Schematic drawing of the P-S Suspension Logging System (Diehl et al. 2006).

4.2.1 Seismic energy source

Seismic waves for P-S suspension logging are generated by a combined reversible polarity solenoid. Because the probe containing the source and receivers is not coupled directly to the borehole walls, the source generates a horizontally propagating impulse pressure wave in borehole fluid surrounding the source. The length of the pulse can be adjusted to increase or decrease the amount of energy. The pressure wave is converted to P- and S_H-waves in the ground surrounding the borehole as it impinges the borehole wall. The P- and S_H- waves propagate through the ground surrounding the borehole. These waves in turn generate a pressure wave in the borehole fluid surrounding the receivers as the seismic waves pass their location.

The approximately 2.1 m of distance between the source and first (lower) receiver allows the faster P-wave to pass and damp significantly before the arrival of the slower S_H-wave. In denser/stiffer materials with higher wave velocities, the isolation cylinder is extended to facilitate greater separation of the P- and S_H-waves.

4.2.2 Receivers

The two receiver packages (R_1 and R_2) are typically located 1 m apart within the instrument probe, and above the source. It is typical for each receiver to include three transducers (e.g., geophones) – two oriented in orthogonal horizontal positions and one in a vertical position. During testing, one of the horizontal transducers in each receiver should be oriented in the inline-horizontal direction – parallel to the axis of the horizontal source.

4.2.3 Data acquisition system

Section 2.2.3, which summarises the principles and requirements for the data acquisition system (DAQ) for downhole seismic testing, also generally applies to P-S suspension logging so is not repeated here. From a review of the literature (Nigbor and Imai 1994, Diehl et al. 2006, Biringen and Davie 2010), it appears that the DAQ equipment used is often that supplied by OYO Corporation – the developer of the P-S suspension logging method.

4.3 Test procedures

P-S suspension logging is performed in a single machine-drilled borehole. It is preferable to use an uncased borehole drilled using the mud rotary method (Diehl et al. 2006). Uncased holes are preferred because the potential negative effects of casing and poor grout coupling on transmission of seismic waves is eliminated. Mud rotary drilling creates a relatively smooth borehole wall and bentonite drilling fluid helps to seal the borehole wall and prevent fluid loss. The best results are reportedly obtained using a borehole diameter of between 100 and 150 mm.

If a borehole casing must be used to maintain hole stability, the casing must be PVC in order to allow transmission of fluid pressure waves. The preparation of a cased hole should be done in general accordance with ASTM D4428/D4428M-14. As with other borehole seismic test methods, it is critical that the grout strength approximate that of the surrounding soil/rock and that there are no voids behind the casing. Large grout bulbs formed by filling cavities in the borehole wall should also be avoided in order to reduce uncertainty as a result of measuring wave travel times through the grout.

The suspension logging in uncased boreholes should be performed within a few hours of drilling when the borehole is stable, and the borehole fluid is well circulated and (presumably) leaking only slowly.

Both the orientation of the horizontal transducers, and the polarity of the shear waves, must be correctly established prior to the start of testing. The horizontal transducers should have the same polarity and orientation (parallel to the horizontal axis of the solenoid energy source). The probe depth recorders are set to zero and the test probe containing the source and receivers is typically lowered in the borehole, stopping at the selected test locations. A 0.5 m test interval is typical (Diehl et al. 2006). At each test location, the source is activated in one direction, then in the opposite direction to generate two S_H-wave records of reverse polarity. The source is activated a third time in the first direction to record the P-waves. The repeated source activation and recording facilitates picking of the P- and S-wave arrivals. The data from each transducer during each source activation is recorded as a separate channel. As with downhole and crosshole testing, it is preferable to stack multiple source excitations to enhance the signal-to-noise ratio.

At the completion of all testing, the test probe zero depth measurement at the ground surface/top of the borehole casing (zero reference point) should be verified prior to removing the probe from the borehole.

4.4 Data reduction and analysis

Figure 4-2 shows a sample set of R_1-R_2 horizontal and vertical seismic waveforms from a single depth. The arrival picks are shown as darker vertical lines, and the associated arrival times in milliseconds are shown numerically on the left vertical axis. Similar to downhole and crosshole seismic testing, the P-wave arrival is picked as the first departure from the noise floor, regardless of voltage polarity. The S_H-wave arrival is identified as *the first major departure* after the P-wave arrival *with the correct voltage polarity*. The difference in travel time between wave arrivals is used to calculate wave velocity over the receiver interval (typically 1 m). The box in the upper right corner of the plot shows the depth of the test and the calculated V_P and V_S values based on the vertical distance between the two receivers.

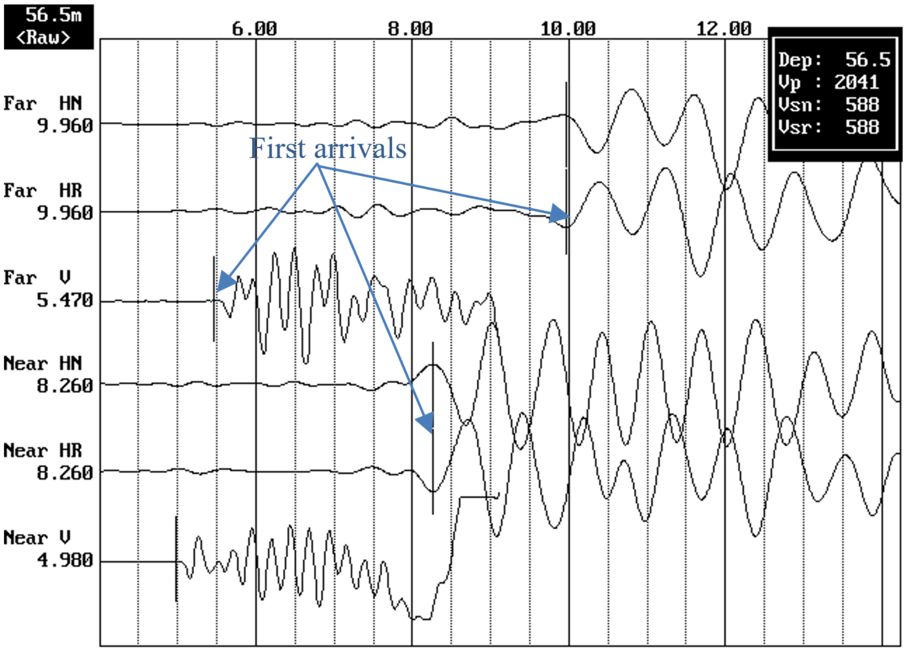

Figure 4-2: Example of seismic waveforms collected from a single depth using P-S Suspension Logging. The computed arrival times from each geophone are listed on the vertical axis. The bottom three channels show the normal and reversed horizontal (HN and HR), and vertical (V) waveforms and recorded at bottom (i.e., 'near' / R_1) receiver. The top 3 channels show the same set of waveforms recorded at the top (i.e., 'far' / R_2) receiver (Diehl et al. 2006).

The R_1-R_2 measurement of obtaining travel times is normally considered to be more accurate (relative to S-R_1) because the picks are made from the peak of the arrival waveform. The analyst picks the first arrivals, while software may be used to find the peaks. The travel time is then defined as peak-to-peak. The R_1-R_2 data also has higher resolution because the travel time is averaged over a much shorter distance than S-R_1. S-R_1 measurements are subject to a 'source delay' associated with the proprietary recording system (Diehl et al. 2006). This delay is verifiable, but it is also subject to change during testing if there is deterioration or damage to the energy source spring during testing. For this reason, the R_1-R_2 measurement should always be the primary measurement, and the S-R_1 only used as independent check (Diehl et al. 2006).

Nigbor and Imai (1994), provide further advice and explanation for picking and confirming waveform travel times. Figure 4-3 shows an example plot of depth-sequential waveform arrivals for normal S-waves recorded at the 'near' (R_1) receiver from P-S suspension logging in a single borehole.

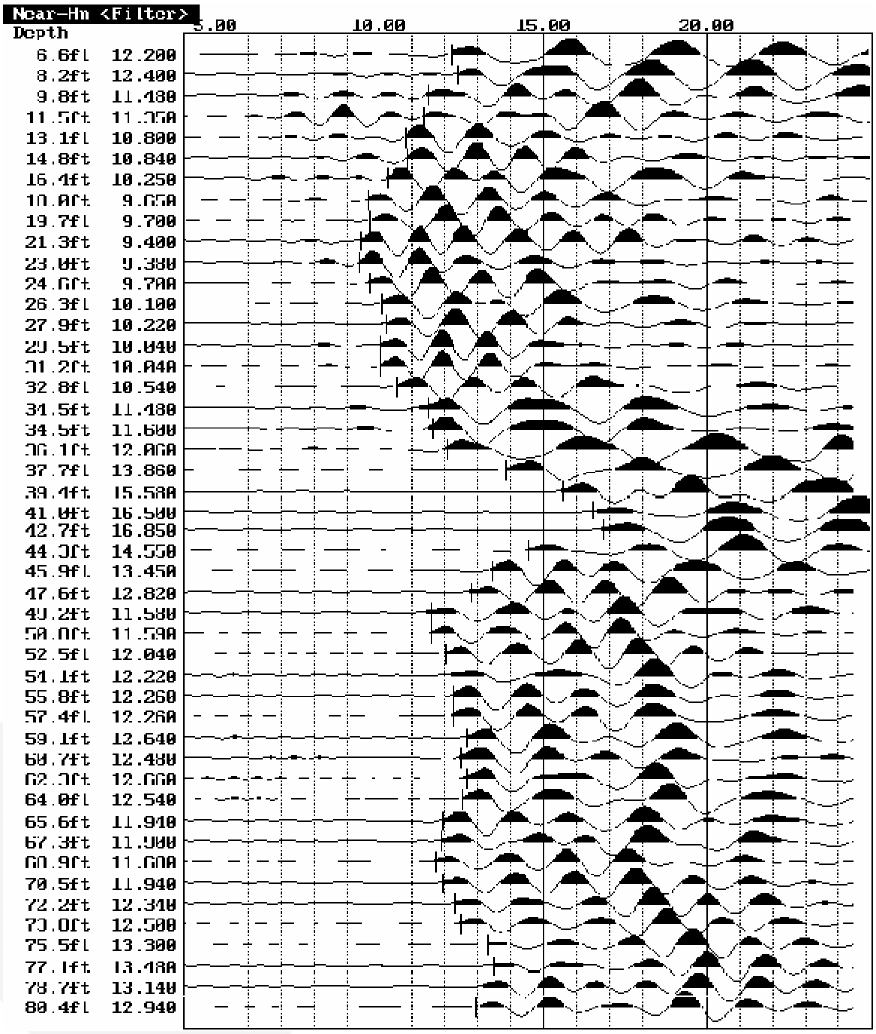

Figure 4-3: Example plot of depth sequential waveform arrivals for normal S-waves recorded at the 'near' (R_1) receiver from P-S suspension logging in a single borehole. The plotted arrival times indicate the presence of a soft layer at a depth of approximately 40 feet (Diehl et al. 2006).

The general principles for evaluation of seismic wave arrival times for downhole and crosshole testing (discussed in Sections 2 and 3) can also be applied to processing P-S suspension logging data, and may well be useful for helping the analyst interrogate and interpret the data beyond what the standard software processing allows.

4.5 Limitations and challenges with P-S suspension logging

Interpretation of clean suspension logging data is relatively straightforward, however poor data are often ambiguous. Ideally, the testing should be conducted in uncased boreholes in order to eliminate potential effects of the casing and grout on signal transmission and quality. Logging cased holes eliminates standby time but may result in lower quality data. For testing in soils, particularly softer soils and sands, drilling and maintaining a relatively undisturbed and stable hole will require a highly experienced drilling contractor. Disturbance or collapse of the borehole will result in poor quality data.

The test method cannot be used with steel casing as the pressure wave used to generate seismic waves will not penetrate the casing.

P-S suspension logging does not always provide good results in the near surface (< 5 m depth). This is because it is difficult to generate waveforms in the surrounding soil under low confining stress (Biringen and Davie 2010).

P-S suspension logging in cased holes in highly fractured rock above the groundwater level is particularly challenging (Diehl et al. 2006). Waves propagating up the borehole wall pass through the fracture planes resulting in attenuation and refraction, and processing/interpretation of the data in such cases is very difficult. Unfortunately, drilling in highly fractured rock is also usually difficult and requires casing to maintain fluid circulation and borehole stability. In such conditions, downhole testing may give better results. Sometimes it is necessary to combine methods to obtain the best results over the target depth profile.

Some researchers (Andrus et al. 2004, Aston and Boore 2005) have noted that the P-S suspension logging system only characterises materials very near to the borehole (e.g., within 1 m), hence characterising a smaller volume of material than the downhole and crosshole methods.

5 Uncertainty in invasive seismic testing

There are two types of seismic velocity uncertainty that need to be quantified for engineering analyses such as seismic site response (Electric Power Research Institute 2012): (1) aleatory uncertainty; and (2) epistemic uncertainty. In the context of seismic velocities, aleatory or random uncertainty results from the inherent variability of the subsurface layering and shear stiffness across a site. Aleatory uncertainty can be evaluated by considering the spatial variability of V_S profiles derived from invasive testing as they are essentially point measurements. Epistemic or knowledge uncertainty results from a lack of knowledge about a model or parameter. Therefore, even for a single test location, epistemic uncertainty exists due to factors such as data quality and the method(s) used for analysis (Stolte and Cox 2019).

Invasive test methods are often considered to be more reliable/less uncertain than non-invasive methods because the receivers are located within the materials being measured and the volume of material tested is smaller. However, a recent comprehensive study in Europe found that V_S profiles developed from surface wave testing exhibited variability that was similar to, and in some cases, less than that for velocity profiles derived from a combination of downhole, crosshole, and P-S suspension logging from multiple investigators (Garofalo et al. 2016). The results of the study highlight the fact that there is uncertainty associated with both invasive and non-invasive seismic testing. This is not a new finding – significant research has been devoted to quantifying uncertainty associated with non-invasive surface wave testing (Marosi and Hiltunen 2004, Foti et al. 2009, Griffiths et al. 2016, Teague and Cox 2016, Teague et al. 2018). Attention has also been directed at quantifying uncertainty associated with invasive (primarily downhole) seismic testing (Kim et al. 2004, Bang et al. 2014, Styler and Weemees 2017).

Nonetheless, it is rare in engineering practice for those conducting in situ seismic testing (invasive or non-invasive) to communicate the epistemic uncertainty in the test results to the end user (Stolte and Cox 2019; personal communication, L.M. Wotherspoon, October 2018). It is just as uncommon for the end user to request a quantification of uncertainty; for example, through the use of statistics or provision of multiple interpretations of the dataset. More common is for the provider to give a single V_S profile for a single test location. If uncertainty is accounted for by the engineer, the most common method is through the use of upper- and lower-bound V_S profiles which are developed by arbitrarily increasing/decreasing the reference profile by a constant, depth-independent factor; for example +/- 20% to 30% (Matasovic and Hashash 2012, Griffiths et al. 2016a). However, this methodology has been shown to yield variable and sometimes poor estimates of seismic site response (Griffiths et al. 2016b, Teague and Cox 2016). Therefore, methods for realistically quantifying epistemic uncertainty in V_S profiles derived from invasive seismic tests are needed.

Anecdotally, the lack of acknowledgement of uncertainty and hence failure to address it, by both providers and end users, appears to be largely driven by:

- a lack of understanding of the causes of epistemic uncertainty;
- a lack of understanding of how to quantify/constrain it;
- commercial desire to be as efficient as possible in collecting and processing the data;
- a lack of understanding of how the potential variability in a given V_S profile might affect the engineering analyses that incorporate it.

Following is a discussion on epistemic uncertainty in V_S profiles specifically relating to SCPT testing as this is the probably the most commonly used invasive seismic test method in New Zealand. However, the same principles can be applied to other invasive seismic test methods. While the focus of this section is on the uncertainties associated with data processing (i.e., determination of wave travel time) and the velocity analysis method used, there can also be considerable uncertainty associated with the quality of testing and the interpretation of arrival times. The uncertainties associated with testing quality can be addressed to a significant degree by following the practices described here.

Stolte and Cox (2019) examined the depth-dependent epistemic uncertainty in SCPT V_S profiles by considering the method used to obtain shear wave travel times and the method used to calculate the velocity. Specifically, four methods of obtaining S-wave travel times were investigated: (1) first arrivals (FA); (2) first peak/trough (PT); (3) first crossover (CO); and (4) cross correlation (CC). Using the travel times developed from these four methods, V_S profiles were developed using four analysis methods: (1) true-interval (TI); (2) pseudo-interval (PI); (3) corrected vertical travel time slope-based method (SM); and (4) a raytracing method (RT). These travel time and velocity analysis methods are described in Section 2.4.

Combinations of the four travel time processing techniques and the first three velocity interpretation methods were used to produce a total of eleven V_S profiles for 31 Christchurch SCPT datasets (note that the cross-correlation time delay is not compatible with the slope-based method). The profiles were developed using the commonly assumed straight-line, slanted travel path from the source to the receiver. Additionally, a raytracing algorithm was used by an independent and internationally experienced CPT contractor to develop an additional V_S profile for each SCPT dataset.

The results from two of the sites included in the Stolte and Cox (2019) study are shown in Figure 5-1through Figure 5-4. The first site (Avondale Playground) has a relatively homogeneous, predominantly sandy soil profile while the second site (St. Teresa's School) has a complex interlayered profile. It can be seen that the three V_S profiles obtained from the corrected vertical travel time slope-based (SM) method are relatively consistent irrespective of the method used to determine wave travel times (i.e., FA, PT or CO). The velocity differences are larger for both the pseudo-interval and true interval methods. Regardless of the velocity analysis method used, the V_S profiles based on PT and CO travel times are relatively consistent with each other, while the FA and CC travel times occasionally result in localised anomalous values.

The epistemic uncertainties associated with the V_S profiles are quantified in Figure 5-2(c) and Figure 5-4(c) in terms of the log-normal standard deviation of V_S for each depth (σ_{lnVs}). The coefficient of variation (COV) and log-normal standard deviation (σ_{ln}) are directly related to each other through the mean and standard deviation of a given dataset. When the COV is less than 0.3 (as is the case for the Avondale Playground site profile, and all but two relatively thin layers at the St. Teresa's School site profile), the COV and σ_{ln} are approximately equal. The σ_{lnVs} values at the Avonside Playground site are highest: (1) at shallow depths (i.e., depths less than 2 to 3 m), where the straight travel path assumption is not valid; and (2) in the 14 to 19 m depth range, where CPT q_C values indicate transitions from dense sands to a soft silt/clay layer and then back to dense sands. The lowest intra-analysis method σ_{lnVs} (single analysis method for the range of travel time picking methods) is associated with the SM method, which is to be expected given the consistency and stability of the SM V_S profiles with depth (refer to Figure 5-1(c)). The σ_{lnVs} associated with the PI and TI methods is generally higher. This reflects the increased uncertainty in interval V_S profiles, arising from both the fluctuating shear-wave velocity depth-to-depth, and slight differences in interval travel times (i.e., FA, PT, CO, and CC) due to timing errors, changing frequency content, etc.

Similar to the Avonside Playground site, the lowest σ_{lnVs} values at the St. Teresa's School site are also associated with the SM method, while the highest σ_{lnVs} values are associated with the TI method. The large spikes/fluctuations in σ_{lnVs} are typically caused by a single outlier velocity associated with either a FA or CC travel time. At the St. Teresa's site, the σ_{lnVs} values associated with all eleven SCPT V_S profiles are generally higher than those at the Avondale Playground site. This is expected due to: (1) the difficulty in resolving the boundaries between thin layers with seismic measurements taken once every half metre; and (2) the large fluctuations in stiffness of these layers, as reflected in the q_c profile. The σ_{lnVs} values exceed 0.4, indicating a high level of epistemic uncertainty, within two depth ranges: (1) in the top 1.5 m where the TI V_S profiles indicate a much softer surface layer than the other methods; and (2) from 17 to 17.5 m, where there is a strong impedance contrast at the boundary between the dense gravel layer and overlying very soft silt, and the V_S is not well constrained between the various methods.

It is important to note that the interanalysis method σ_{lnVs} values do not consider all possible sources of epistemic uncertainty in V_S. For example, there is also epistemic uncertainty associated with the testing method selected to collect seismic measurements and develop V_S profiles.

To illustrate this point, a single V_S profile for each site obtained via DPCH testing (this method is described in Section 3) is shown in Figure 5-2(b) and Figure 5-4(b) in comparison to the SCPT V_S. While the V_S profiles from both test methods generally agree below a depth of about 2 to 3 m, the SCPT V_S ranges from 50 to 100 m/s lower. If the DPCH V_S profiles were included in the σ_{lnVs} calculations for each site, the uncertainty values in the near-surface would be considerably higher. The results of the DPCH testing are considered to be more accurate in the near-surface, primarily due to the difficulty in determining the actual travel path of the SCPT V_S waves in the top few metres of the profile (a challenge with downhole methods in general).

The V_S profiles shown in Figure 5-1 and Figure 5-3 were developed using widely-accepted data processing methods. Hence, any one of these profiles could have been provided by a SCPT contractor. While it is not always necessary to develop a suite of V_S profiles at each test location for routine projects, it is important to realise that there is always epistemic uncertainty associated with the development of V_S profiles, and this uncertainty should be acknowledged openly and communicated to the end-user. For an end user who has a reasonable knowledge of the principles and procedures associated with downhole seismic testing, it should a relatively straightforward exercise to process shear wave arrival times and evaluate velocities using two or more methods in order to quantify uncertainty as described here.

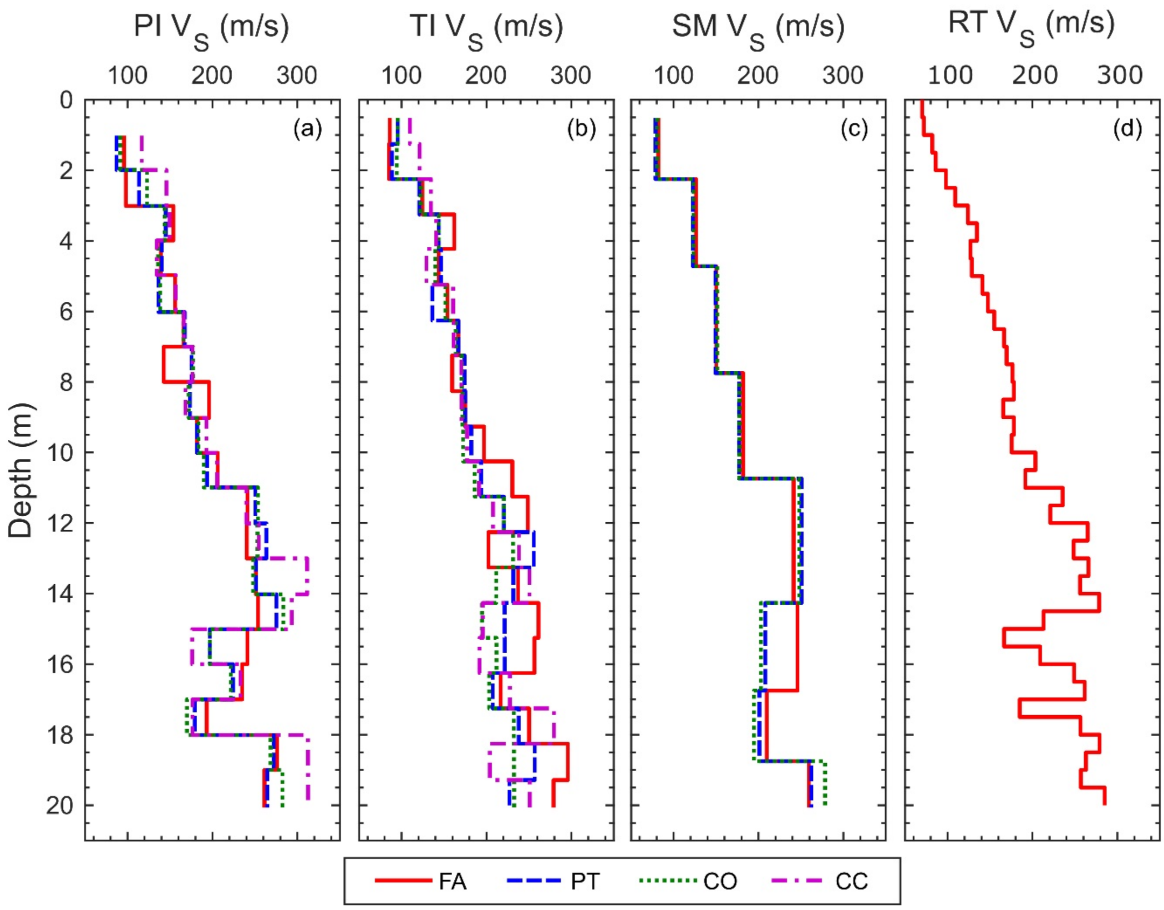

Figure 5-1: Comparison of SCPT VS profiles developed for the Avondale Playground site (Stolte and Cox 2019).

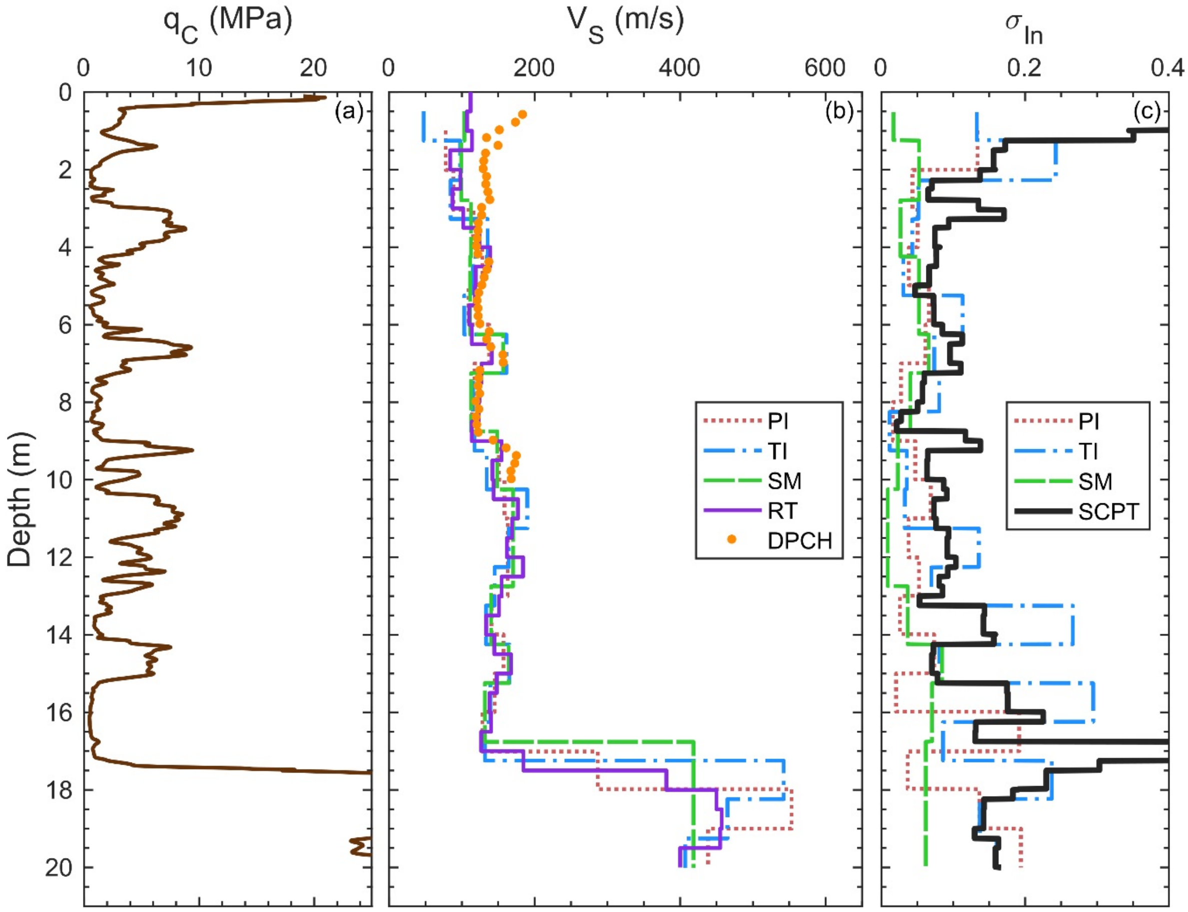

Figure 5-2: Summary of SCPT profiles for the Avondale Playground site: (a) Raw cone tip resistance (q_c), (b) Comparison of shear wave velocity profiles, and (c) The log-normal standard deviation of Vs (σ_{lnVs}) within each SCPT V_S analysis method and between all SCPT methods. (Stolte and Cox 2019).

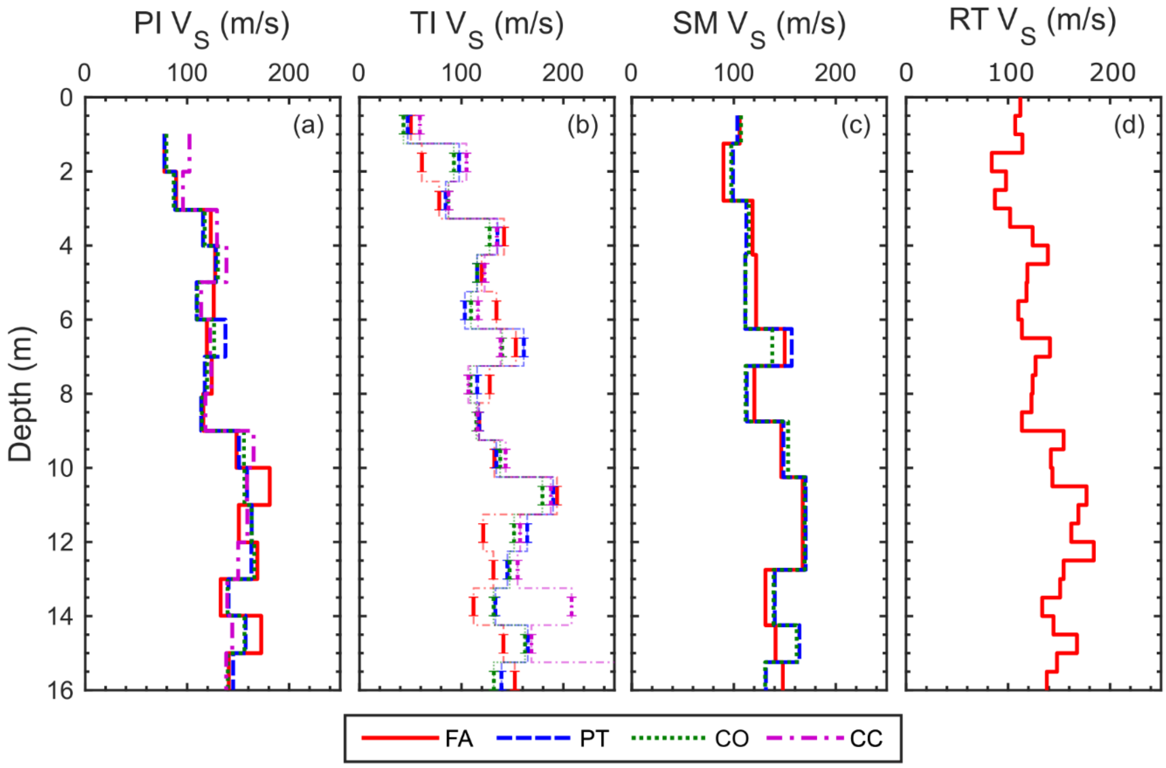

Figure 5-3: Comparison of SCPT VS profiles developed for the St. Teresa's School site (Stolte and Cox 2019).

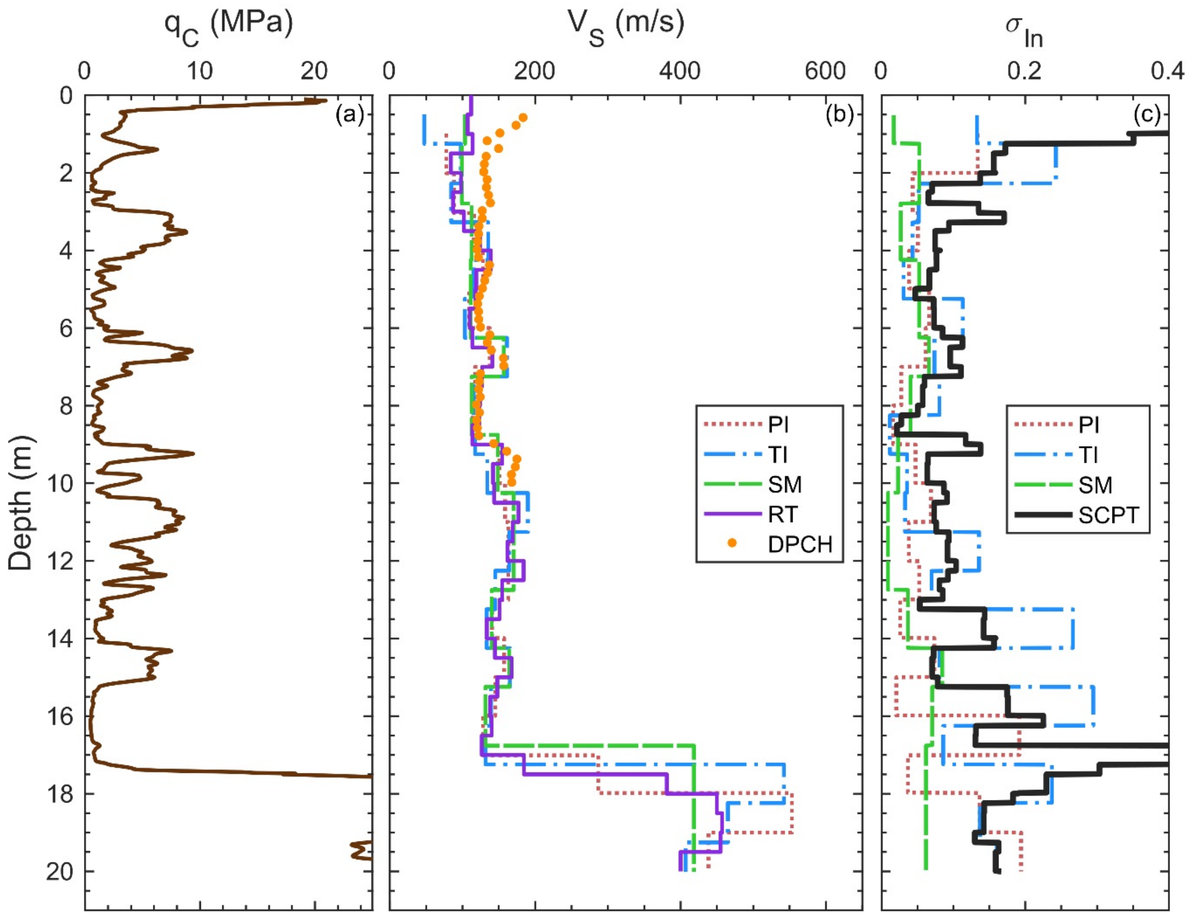

Figure 5-4: Summary of SCPT profiles for the St. Teresa's School site: (a) Raw cone tip resistance (q_C), (b) Comparison of shear wave velocity profiles, and (c) The log-normal standard deviation of V_s (σ_{lnVs}) within each SCPT V_S analysis method and between all SCPT methods. (Stolte and Cox 2019).

6 Recommendations for reporting invasive seismic testing results

Most seismic testing reports contain routine information such as a summary of test method and procedures, a description of test equipment, the test locations and a summary of results – often presented as velocity profiles. While this information is necessary, the following should also be included in testing reports so that the end user can independently assess the test results and, if desired, investigate epistemic uncertainty:

- The source-receiver offset distance used (downhole test methods including SCPT and SDMT);
- Tabulated distances between source and receiver holes as a function of depth (crosshole testing including DPCH);
- Were multiple hits (i.e., source excitations) stacked? If so, how many?
- Were the waveforms filtered, either prior to digitization by the DAQ (e.g., an analog filter was used) or during processing (e.g., using a digital filter in the analysis software)?
- Were the waveforms linearly detrended (effectively high-pass filtering)?
- Were the waveforms normalized before plotting?
- Were the waveforms amplified, either electrically before digitization or digitally in the post-processing?
- A clear explanation of the methods used to determine wave arrival times (i.e., FA, PT, CO, CC);
- The velocity analysis method used;
    - Downhole testing (PI, TI, SM, RT);
    - Crosshole testing and P-S suspension logging (S-R_1, S-R_2, R_1-R_2, RT);
- The expected waveform voltage polarities for S-waves (downhole, crosshole, PS-suspension logging);
- Waveform travel times presented on waterfall-style plots with travel time picks clearly shown;
- Tabulated wave travel times and velocity values with test depths;
- Where CPT and/or borehole logs are available close enough to be representative of the subsurface conditions at the seismic testing location, a plot of each velocity profile relative to the CPT or borehole log. There should also be a statement regarding whether this data has been used to help interpret the seismic results.

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Invasive Seismic Testing

A Summary of Methods and Good Practice

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