V_{s30} Assessments: Understanding the underground

N. McConachie & L. Ingham
Cook Costello, Christchurch/Wellington, New Zealand.

ABSTRACT

Understanding the vulnerability of a construction site to seismic shaking is fundamental to robust building design in New Zealand. The recent release of the updated National Seismic Hazard Model reflects this, with an integral parameter in assessing a site's seismic hazard being the velocity of shear seismic waves within the uppermost subsurface at the site (Vs30), which can impact shaking. With uncertainty currently remaining regarding how the NSHM will be incorporated into updated building codes, we present methods and examples of how reliable shear wave velocity assessments can be determined across a range of different sites. Examples are given of how a balance of non-invasive geophysical techniques such as multi-channel analysis of surface waves (MASW) with invasive geotechnical investigations such as seismic CPTs can be used to give a comprehensive assessment of Vs30 across sites with varying characteristics and challenges.

The incorporation of non-invasive seismic techniques in site investigations allows for large areas to be assessed in a time-efficient manner, as well as enabling investigations to be undertaken in sections of difficult terrain and where invasive techniques are not economically viable. Meanwhile, targeted invasive investigations act as vital tie points and ground truthing for the seismic profiles measured. With an optimal balance of the complimentary techniques, a robust pseudo-3D map of Vs30 across any site can be developed in a time and cost-efficient manner, and with minimised environmental impact. Such an understanding of a site's vulnerability to shaking allows for buildings and infrastructure to be appropriately designed to minimise seismic risk.

1 INTRODUCTION

Shear-wave (Vs) time-averaged shear-wave velocity to 30 m depth (Vs30) has long been an important component when determining site classification in New Zealand. The introduction of the updated National Seismic Hazard Model (NSHM) proposes that Vs30 become a fundamental parameter to understand a site's seismic shaking vulnerability under earthquake conditions. With this, it is important for engineers to understand the various methods which can be used to determine Vs30, and which approach is best fit for different types of sites. We present comprehensive methodologies for acquiring and processing both invasive and non-invasive data to determine a site's Vs30, as well as how a combination of techniques can produce a comprehensive understanding of the underground.

2 METHODOLOGIES

A hierarchy for site classification methods is stated in the NZS1170.5:2004 (Standards NZ, 2016) which lists the measurement of shear-wave velocities, invasive and non-invasive, as the first and second most preferred methods out of the seven methods that are listed.

2.1 Invasive methods

Invasive or direct geophysical measurements of shear-wave travel times or shear-wave velocities are the preferred method for site classification, with the two most common techniques being Seismic Cone Penetration Tests (SCPT) and Down Hole (DH) shear-wave tests. These invasive methods directly measure the shear or secondary (S) waves (Fig.1), that propagate spherically from the energy source, within the subsurface. However, these methods may not be achievable on many sites due to spatial constraints where drilling is not possible, sites where subsurface conditions such as shallow aquifers and dense gravel layers do not allow for invasive investigations, or projects where a borehole(s) or many sCPTs are not financially nor physically viable.

2.2 Non-invasive methods

Obtaining shear-wave velocities through the inversion of non-invasive geophysical measurements, such as MASW, where the inversion is constrained by geotechnical information at or near the site, is outlined as the second most preferred method for site classification in the NZS1170.5:2004. Non-invasive methods for measuring Vs30 typically measure Rayleigh waves, which are dispersive hybrid compression/shear waves (Fig.1). This means that the different wavelengths of the wave components travel through the subsurface at different velocities, dependent on the properties of the materials they encounter (Aki and Richards, 2002). This non-invasive method provides a cost-effective and efficient means to gather a large amount of information across a site, reducing the reliance on invasive methods and providing the ability to investigate sites where invasive methods are not practical. There are, however, limitations to using non-invasive methods, such as spatial constraints of a site, as for MASW Vs30 measurements an array length of 60 – 90 m is preferred. The technique is thus unfeasible for smaller sites, as well as in areas that have significantly undulating terrain, where surface wave analysis becomes unreliable. The use of non-invasive geophysical measurements also adds an extra step of data processing, with an inversion of the measured data required to produce a final Vs profile. This step requires specialist software and the experience of a qualified geophysicist to ensure a robust and reliable final result.

3 DATA ACQUISITION

Both non-invasive and invasive acquisition of shear wave velocity data requires the same general equipment; a seismograph for data collection, an active seismic source generator, and receivers (geophones) to measure the wave input from the seismic source. The most common seismic sources used for Vs30 measurements in New Zealand are a sledgehammer strike and accelerated weight drop (AWD). Typically, a sledgehammer strike is sufficient to generate a strong seismic signal for Vs30 measurement, however, this is dependent on site characteristics.

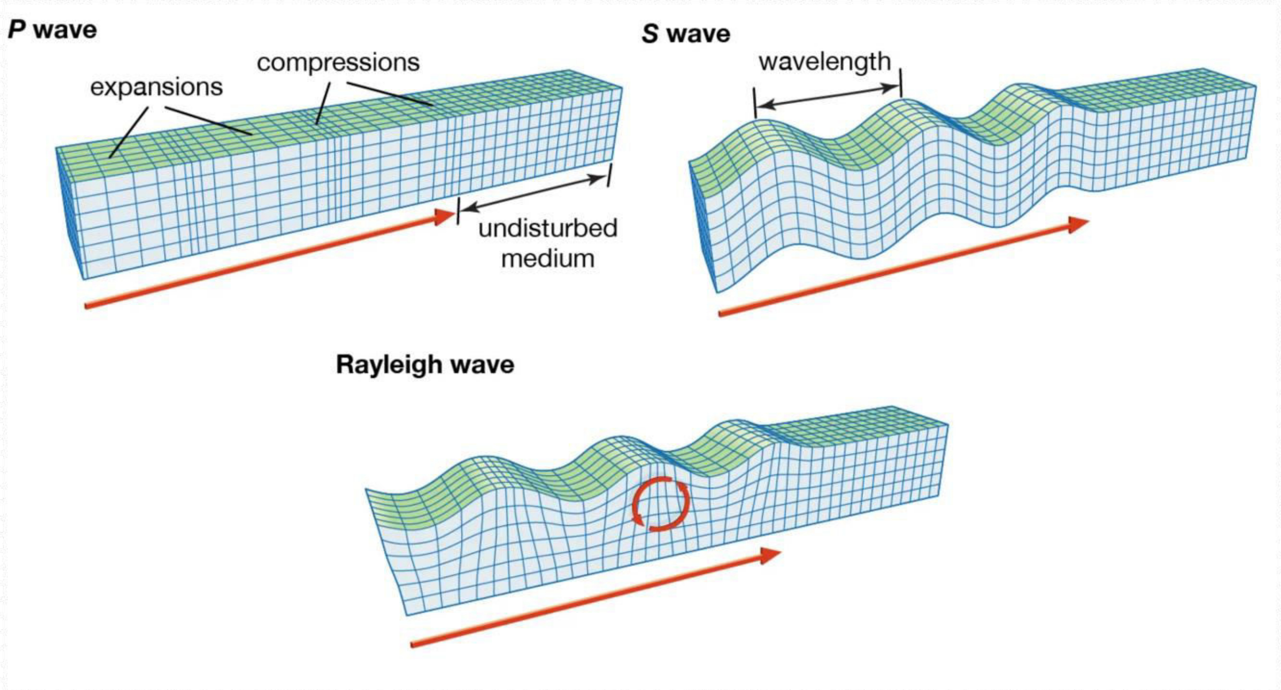

Figure 1: Particle displacements occurring with the passage of a harmonic plane P-wave (top left), S-wave (right), and Rayleigh wave (bottom). (Centre weather bureau – Seismological centre). (modified from Encyclopaedia Britannica "Applications of the seismograph").

3.1 Invasive methods

The two most used invasive methods used for determiningVs30 in New Zealand, sCPT and DH shear-wave testing, follow the same principles. These invasive methods require a receiver probe to be inserted into the ground or a borehole, which is inserted to set depth intervals (typically 0.5 m to 1 m increments), with the active seismic source located on the surface.

The data collection methods for both sCPT and DH are very similar and will, therefore, be discussed together, unless specific elements of either method need to be identified. The main difference between SCPT and DH tests is that the receivers are directly pushed into natural ground for SCPT tests, while the receivers for DH are inserted into a PVC pipe within a fully grouted borehole. In-situ seismic testing requires three main components (Wentz, 2019):

1. A source to generate seismic waves: The seismic source for these invasive methods typically involves a shear plank (for S-wave generation) and a metal plate (for P-wave generation), which are placed on the ground and struck with a sledgehammer. A trigger attached to the sledgehammer indicates to the seismograph to begin recording data once the plank is struck. The shear plank extends either side of the borehole and is struck by the sledgehammer at either end multiple times for each depth of investigation. Acquiring data from both ends of the plate generates opposing polarity S-waves (Fig. 2), while acquiring multiple shots at each site allows the stacking of data to develop a clear waveform. Both of these steps aide and simplify data interpretation. In addition, the metal plate is struck multiple times for each depth of investigation, with analysis of the resulting P-wave behaviour used to determine the depth at which the subsurface becomes saturated.
2. Probes with receivers (e.g., geophones or accelerometers) to measure the propagation of the seismic waves at specific depths: The seismic receivers or probes are inserted into the ground, either by direct push (SCPT) or lowered by hand/winch (DH). The probes usually comprise of one or two geophones, with two or more axes (horizontal and vertical), to measure the seismic waves at the set depth. Measurements are

usually taken at 0.5 m to 1 m depth intervals, depending on the desired resolution. The SCPT receiver is moved to each depth by a CPT machine into natural ground, while the DH receiver is coupled against the side of the PVC pipe, to ensure good signal strength. Coupling is achieved either by using a bladder, that is inflated for measurement and deflated to allow the probe to be lowered to the next depth, or by using a spring attached to the receiver with the probe pushed to each depth.

3. A data acquisition system (DAQ) or seismograph: This is used to collect, digitise and store the information from the receivers, with the collected waveforms shown on the screen.

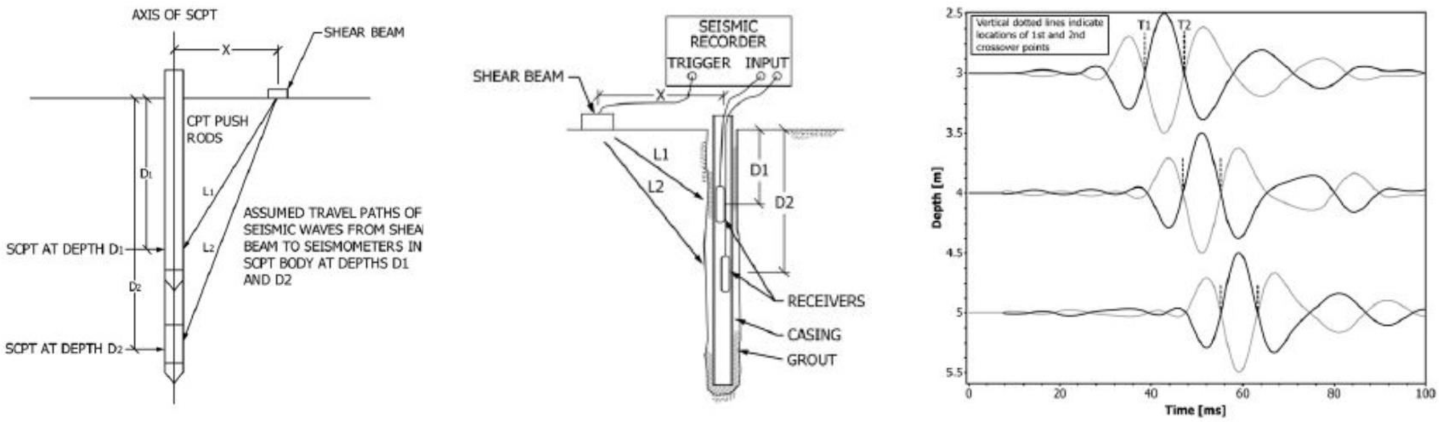

Figure 2: Diagram of SCPT data collection (left), diagram of DH Vs data collection (middle), and opposing polarity seismic waves at different depths (right) (modified from ASTM D7400 2017).

3.2 Non-invasive method

The most common non-invasive method used to measure Vs30 in New Zealand is MASW (as mentioned in Module 2, NZGS 2021). The setup for this method involves having an array of receivers on the ground surface with a source (usually a sledgehammer) generating the seismic wave energy.

MASW data collection can be split into two steps:

1. Setup: An array of geophones, typically 24, are laid out in a straight line along the ground surface. Contact with the ground is achieved by either inserting spike-tipped geophones into the ground or by connecting the geophones to a “land-streamer”. In the land-streamer method, geophones are mounted on small metal plates and connected to each other by webbing. The array of geophones can then be towed behind a vehicle, allowing for many different locations to be investigated in short time. The achievable depth of investigation is proportional to the length of the total array, along with site characteristics. A general rule of thumb is to have the array length at least equal to twice the desired investigation depth. Subsequently, an array length of 60–90 m is preferred when aiming to profile shear wave velocity down to 30 m depth bgl (Foti et al., 2017). The geophones are connected to a seismograph which collects and stores the seismic data.

2. Data acquisition: The seismic source for MASW data acquisition is typically a sledgehammer with an attached trigger which indicates to the seismograph to begin recording data when the sledgehammer strikes a metal plate. The location of the seismic source is called the shot point. Vs30 measurements require a minimum of one, and ideally three, different shot points offset from both ends of the array (e.g. offset shot points at 10, 15, and 20 m from both ends of the array). In practice, the number and distance of the shot points are dependent on spatial constraints. Measuring data from shot points at both ends of the MASW array accounts for the lateral variations in the subsurface, while obtaining measurements at

different offset distances allows for the capture of both low and high-frequency components of the seismic signal (i.e. near field and far field effects).

4 DATA PROCESSING

Quality data processing procedures are integral to obtaining meaningful and accurate geophysical results and interpretation.

4.1 Invasive methods

Three processing steps are required to convert raw invasive geophysical data to a 1D shear wave velocity profile:

1. Quality assurance: Raw data from all depths is sorted to determine if any files have low quality data that is unable to be picked. Issues encountered can include: noise from an external source that corrupts the acquired data, poor borehole grouting, or poor contact with the sides of the borehole (down-hole methods).
2. First break arrival picking: For each depth measurement two opposing polarity S-waves are produced. Once overlaid, the first arrival times of these waves are picked (right image in Fig 2). These arrival times are compiled and recorded for each corresponding depth.
3. Calculation of arrival times: The arrival times are entered into a spreadsheet, where the source offset distance and depth are used to calculate the slant ratio (L) that the wave must travel from the source to the probe. The shear-wave velocity is calculated using Equation 1 below:

$$Vs = \frac{L_2 - L_1}{t_2 - t_1} = \frac{\Delta L}{\Delta t} \quad (1)$$

where L is the travel path length shown in Figure 2, and t_1 and t_2 are the picked wave arrival times along L_1 and L_2, respectively (Wentz, 2019).

Following these three processing steps, it is possible to calculate the Vs30 using Equation 2 below.

$$Vs,d = \frac{\sum H_i}{\sum H_i/V_i} \quad (2)$$

where H is the thickness of a subsurface layer (i) and V_i the shear wave velocity of that same layer.

Following these processing steps, 1D shear-wave velocity profiles can be generated (right image in Fig3). Due to the nature of the survey, many data points are collected, thus a more detailed 1D profile can be generated than using non-invasive techniques.

4.2 Non-invasive methods

In order to generate a final shear wave velocity profile from raw seismic data, three main steps are required (Fig. 3):

1. Quality assurance: Seismic data from all shot locations are compiled and analysed to ensure shot points at opposing offsets have the same arrival times, that there are no bad data points, and that there is clear surface wave propagation.
2. Dispersion spectra analysis: For each shot location, the dispersion spectra are calculated from the raw seismic data through Fourier transform. At each shot point, the fundamental mode (the mode spanning the lowest frequency range) is identified and its dispersion curve is picked. Multiple modes of surface waves may be present in the data, which is why great care must be taken to correctly distinguish the fundamental mode from higher modes in order to avoid miscalculating the shear-wave velocity. It is

possible for “modal-mixing” to occur, where energy modes merge making it difficult for the processor to pick the fundamental mode. This stage requires the expertise of an experienced geophysicist.

3. Inversion of the dispersion curve into a layered earth Vs model: Processing software is used to match the observed dispersion curves with a theoretical dispersion curve, thus generating a 1D layered earth model with shear-wave velocities and depth (right image in Fig 3). At this step, data from intrusive investigations, for example, boreholes and CPT’s, can constrain the layered earth model with the accurate number of layers and thickness of those layers. Using the shear-wave velocities in the layered earth model, it is possible to calculate the Vs30 using Equation 2.

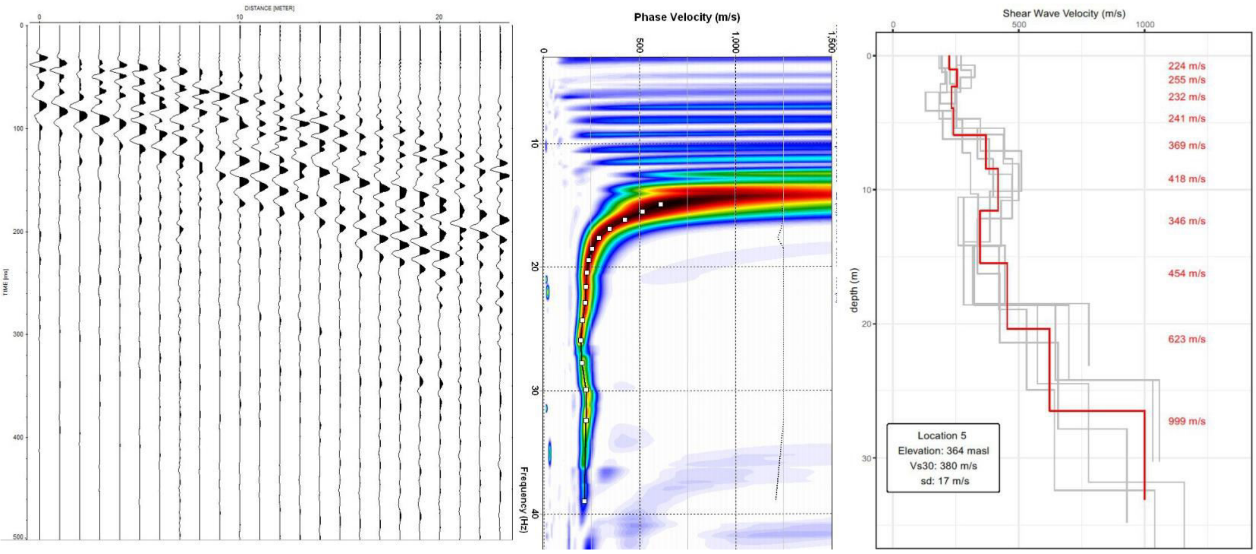

Figure 3: Example of MASW data. Left: seismic record as acquired in the field; Middle: dispersion spectrum with dispersion curve of fundamental mode picked; Right: A 10-layer Vs30 profile.

Where site conditions do not allow for an investigation to reach 30 m, Vs30 values can be estimated by using available empirical correlation methods, like those proposed by Boore (2004), Boore et al. (2011), and Wang & Wang (2015). The Vs30 estimate is then obtained by averaging the results from these five methods.

An advantage of using non-invasive geophysical techniques to obtain Vs30 measurements is that measurements can be obtained at a large number of locations within a short span of time. Acquiring Vs30 measurements across a large site allows for maps to then be produced with Vs interpolated between MASW profile locations. This gives a spatial visualisation of shear wave velocity variations across an entire site.

Figure 4, below, shows the spatial variations in Vs30 values across a site, exhibiting significantly higher values to the Northwest of the site, with the lowest shear-wave velocities to the Northeast of the site.

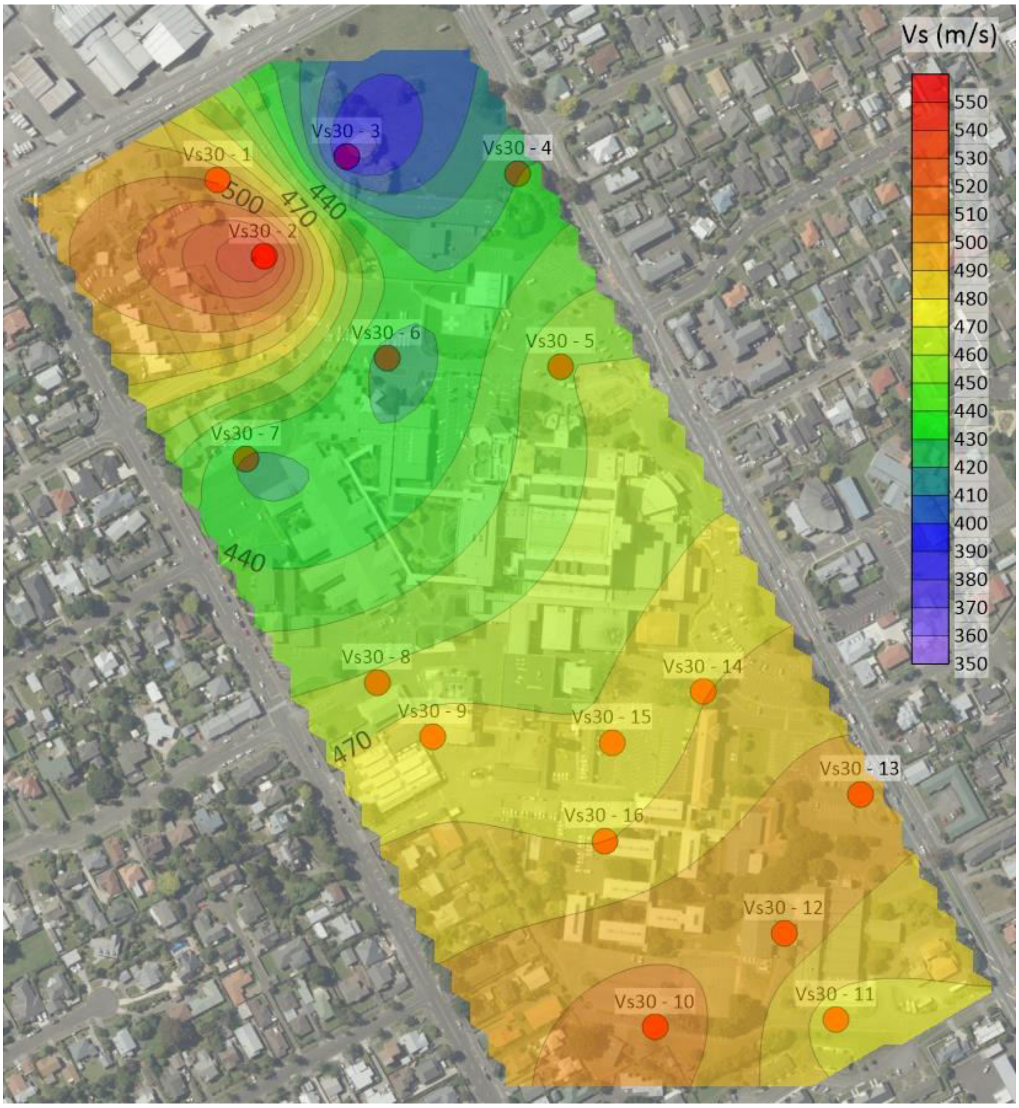

Figure 4: Example Vs30 contour map showing the variation in Vs30 values across a site.

5 INVASIVE AND NON-INVASIVE DATA CORRELATION

Correlating invasive and non-invasive data creates a superior understanding of the underground than what could be achieved by utilising only one of these methods. Invasive techniques can be expensive to undertake, resulting in less data acquired, while non-invasive testing alone requires an increased number of assumptions to be made in the inversion modelling stage. By undertaking a combination of invasive and non-invasive techniques a more complete picture of the subsurface can be generated. Invasive investigations such as SCPT, CPT, and boreholes, can provide vital tie points for non-invasive investigations. If invasive and non-invasive results correlate well when collected in the same location, it gives extra confidence that non-invasive will provide accurate results in areas with no invasive testing. As non-invasive methods are less expensive and more efficient to collect, undertaking additional investigations directly on top of the invasive investigations provides extra reassurance of data quality with little time penalty. Examples of how invasive and non-invasive techniques can be used for data correlation can be seen in Ingham et al. (2023). This paper discusses how data from boreholes, CPT, and MASW allowed for the mapping of the thickness and depth of geological layers across a Port site, including areas where invasive testing was not possible. From the general geological sequence observed in boreholes, together with the Vs step changes in the MASW inversion models, the Vs value ranges were identified for the four different lithologies across the site.

6 CONCLUSIONS

The recent release of the updated National Seismic Hazard Model incorporates Vs30 as an integral parameter in assessing a site's seismic hazard being the velocity of shear seismic waves within the uppermost subsurface at the site (Vs30). In this paper, we have presented comprehensive methods and examples of how reliable shear wave velocity assessments to 30 m can be determined across a range of different sites. Non-invasive and invasive shear-wave velocity methods have been discussed with their benefits, limitations, and their site-specific requirements. A balance of non-invasive and invasive seismic testing, along with invasive geotechnical testing has been shown to provide a comprehensive understanding of the subsurface. Such an understanding of a site's vulnerability to shaking allows for buildings and infrastructure to be appropriately designed to minimise seismic risk.

6.1 References

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