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The use of SCPT and HVSR for site period and subsoil class estimation

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ABSTRACT

NZS 1170.5:2004 provides a subsoil classification system of classes A to E, which are determined by specific criteria of soil or rock characteristics. The fundamental site period, T, is a key parameter in the classification system and is particularly useful in deciding between soil classes C and D, where the boundary is T = 0.6 s. The site period can be estimated from a shear wave velocity profile, such as that obtained from a downhole seismic test. The seismic cone penetration test (SCPT) provides a rapid means of obtaining shear wave velocity without having to drill a borehole. In addition, to the downhole seismic (S) part of the test, the CPT component can also provide an independent estimate of V_s by way of empirical correlations. Alternatively, the site period can be estimated directly using the horizontal to vertical spectral ratio (HVSR) method.

This paper describes how SCPT and HVSR techniques can be used separately or in combination to estimate site period and subsoil class for soil sites where rock is within 50 m of the ground surface, or to a far greater depth in the case of HVSR alone. Methods for interpolating SCPT data and extrapolating beyond the depth of the tests are also discussed. The methods are illustrated by a case example from a site in Mangere, Auckland in Puketoka Formation soils.

1 INTRODUCTION

The New Zealand earthquake loadings standard (NZS 1170.5:2004) provides a subsoil classification system, which categorises sites into five classes, A to E. Classes A and B represent rock sites and are relatively easy to identify, whereas determining the soil classes, C to E, can be more difficult. In simple terms, Class E is defined as sites where there is 10 m or more of soil with shear wave velocity, V_s, of less than 150 m/s. If not

Class E, then Classes C and D are distinguished by the fundamental site period, T; Class C if $T < 0.6$ s and Class D, if $T > 0.6$ s. There are other alternative criteria that relate to borehole information.

NZS 1170.5 specifies a hierarchy of methods for site subsoil classification, as follows:

1. From the site period based on four times the travel time of shear waves from the underlying rock to the ground surface

2=. From borelogs, including measurement of geotechnical properties (undrained shear strength, s_u or SPT N)

2=. From site period determined from Nakamura ratios (HVSR)

2=. From site period determined from recorded earthquake motions

3. From boreholes with descriptors but no geotechnical measurements

4. From surface geology

The hierarchy would suggest the intent of the Standard is that some form of determination of site period is the preference. Although, classification from borelogs with geotechnical properties is ranked second equal in the hierarchy, such borehole information does not measure Vs or site period directly. In boreholes, the geotechnical properties that are mentioned in NZS 1170.5 (s_u and SPT N values) are typically determined by handheld shear vane or SPT tests taken between drill runs (usually 1.5m). These tests, particularly SPT, have a high degree of uncertainty associated with them (Mayne 2000) and the large depth interval between tests provides sparse, non-continuous information with depth. Furthermore, correlations between s_u or SPT N with shear wave velocity are generally based on empirical correlations which are difficult to verify on a site-specific basis without comparison to direct in situ measurement of V_s. In comparison, CPT provides data in a near continuous fashion and correlations from CPT to V_s can be site-specifically verified if done in conjunction with downhole seismic testing (i.e. SCPT).

In the authors’ opinion the hierarchy of testing, in alignment with the believed intent of NZS 1170.5, would more aptly be:

1. Site period determined from in situ shear wave velocity testing (e.g. SCPT)
2. Site period determined from HVSR
3. Site period determined from CPT correlations to V_s (using verified correlations)

Boreholes, either with or without s_u and SPT N information, would sit well below these three methods in the hierarchy. Larkin and van Houtte (2014) found that applying borehole information to Table 3.2 of NZS 1170.5, which helps identify class C sites, provides inconsistences and may result in the unconservative selection of subsoil class. Consequently, Larkin and van Houtte (2014) recommended that Table 3.2 be either amended or removed from future iterations of the Standard. This illustrates the unreliability of determining subsoil class from borehole information.

The in situ testing of shear wave velocity, the first of the three methods listed above, can be achieved by a variety of means, such as direct push downhole seismic, MASW, cross-hole seismic, borehole downhole seismic or downhole p-s suspension logging. Many of these methods require either a borehole to be drilled and/or significant post processing. Direct push downhole seismic, such as SCPT, is rapid and cost-effective in comparison to the other methods and does not require a borehole. A SCPT combines the downhole seismic component with a conventional CPT, which allows an independent correlation to V_s to be made.

Consequently, SCPT provides two independent estimates of V_s, which can be used to determine site period. By adding the HVSR method, a further independent estimate of site period can be obtained.

It is the use of these methods (SCPT and HVSR) for estimating site period that is the topic of this paper.

2 HVSR

The horizontal to vertical spectral ratio method (HVSR), or Nakamura method, is a method to estimate the fundamental site period from ambient vibrations of the ground, recorded passively at the ground surface. The method is described by Nakamura (1989). A more detailed analysis of the method is given in a European study named, SESAME (Acerra, et al. 2004).

The method has been shown experimentally to provide a peak frequency that closely approximates the fundamental frequency of a site where there is a significant impedance contrast between the rock and the overlying soil. The exact geophysical mechanism behind the method is still disputed, with several contesting theories, the leading two based on Rayleigh wave propagation and the total wavefield. All theories work on the basis that there is a disparity between the horizontal particle motion and the vertical particle motion at the fundamental site frequency, such that the ratio of the horizontal to vertical approaches infinity. This can be defined by mathematical analysis of the recorded ground motion.

To calculate the H/V ratio signals are first recorded at single stations on site, using a three-component seismometer, comprising two horizonal sensors (North-South and East-West) and one vertical sensor (up-down). The signals from each of the three sensors are initially processed in parallel by splitting each component into matching time windows, usually of thirty seconds or one minute. This allows windows with unusable signals to be removed. The recorded signals in each window are split into their component frequencies using a Fourier transform algorithm. The results are smoothed using the method by Konno & Ohmachi (1998). The two horizontal components are averaged and then divided by the vertical. The resulting H/V ratios are plotted on frequency spectra for each time window. The mean of all the H/V ratios is made to provide a single averaged spectra line, along with lines indicating one standard deviation above and below the mean, as can be seen in Figure 1(a). The energy in the horizontal components also can be processed to evaluate energy propagation in a specific azimuth, and multiple azimuths can be combined to provide a view of how the peak frequency varies rotationally. A heat map of an azimuthal analysis is provided in Figure 1(b).

A peak in the H/V spectra indicates an impedance contrast between materials associated with that frequency. It is possible to have multiple impedance contrasts corresponding to interfaces between soil layers above the rock, for example between a soft clay and a dense sand. In such cases the lowest frequency peak is taken as the fundamental site frequency. The SESAME 2004 guidelines provide criteria for identification of a clear frequency peak to allow the user to assess the reliability of the indicated resonant frequency. Once the resonant frequency of the site is defined, the site period can be determined by

$$T_0 = 1/f_0 \tag{1}$$

where T_0 = fundamental site period and f_0 = fundamental resonant frequency.

The SESAME guidelines provide recommended recording times based on the peak frequency at the site, with a lower peak frequency requiring more recording time than higher peak frequency. Basic evaluation of the peak frequency can be carried out during recording on site, giving an indication of the peak frequency range, and allowing the required recording time to be calculated on site. To obtain a more defined peak with a lower degree of uncertainty some windows will be removed, so for this reason, especially on sites with a high degree of local noise, the recording times may be longer than the guidelines. A typical recording time at each station is usually between thirty minutes and one hour, although may need to be longer for very deep soil sites.

The example of a HVSR plot given in Figure 1 has been derived using the open source software, Geopsy (Wathelet et al. 2020). The data is from a site in Mangere, Auckland, on Puketoka Formation soils with a depth to rock of approximately 38 m. The graph shows a solid line that represents the mean of the data with dashed lines above and below representing one standard deviation either side of the mean. There is a distinct peak in the plot, which meets the SESAME 2004 criteria. The peak indicates a fundamental resonant frequency, f_0 = 1.5 Hz. This corresponds to a fundamental site period, T_0 = 0.67 s.

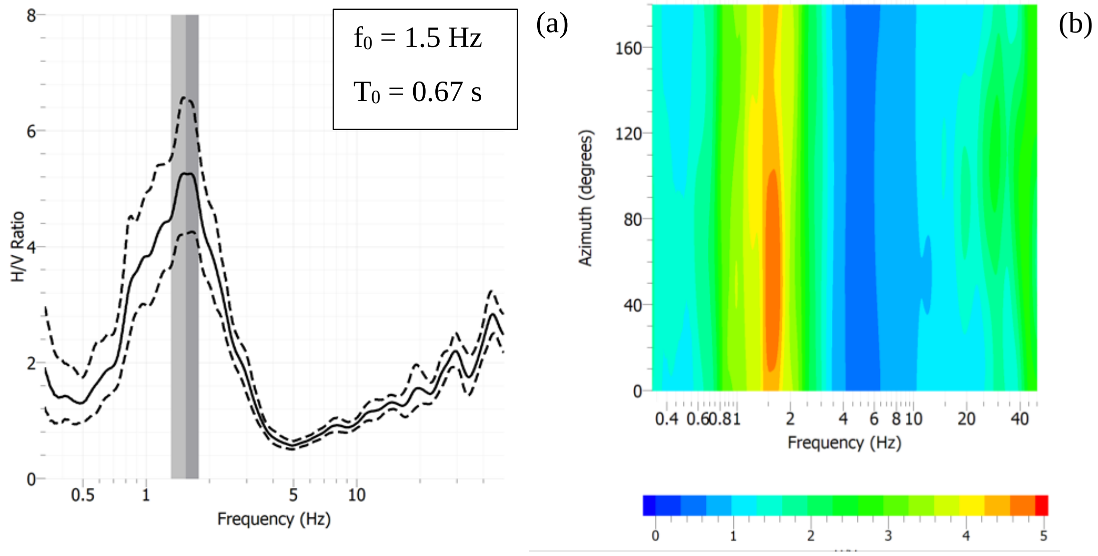

Figure 1: Example of HVSR for site in Mangere, Auckland: (a) squared average mean and standard deviation lines; (b) heat map considering frequency by azimuth, warm colours have a higher amplitude.

Due to the nature of the method there are some situations where it is not possible to define a peak frequency, such as when there is a very gradual transition to rock, or where the overlying soils have a shear wave velocity similar to that of the underlying rock, neither providing a detectable impedance contrast. In other circumstances, local noise from sources such as industrial machinery or building resonance cause by wind can mask H/V peaks.

H/V spectra displaying multiple peaks may suggest complex ground conditions and it may be necessary to consider the effects of the various impedance contracts and how their related resonant frequencies affect the dynamic response of the site for design purposes. Regardless of whether there is a single peak or multiple peaks, a good knowledge of the geological setting is especially important for correct interpretation of the results. HVSR should not be used as a standalone method. It should be supported by existing ground information or used in combination with other testing methods, such as SCPT.

3 SCPT

3.1 Determining V_s from SCPT

The seismic cone penetrometer test (SCPT) utilises a conventional CPT probe coupled with a seismic module, which enables a downhole seismic test to be done in conjunction with a normal CPT. The test is performed by direct push from a CPT rig. The seismic module that was used in the examples presented in this paper is a true-interval system with two geophones spaced at 0.5 m apart. Downhole seismic tests are carried out every 0.5 m depth by hitting a beam on the ground surface and recording the signals received at the two geophones. Computer software is used to cross-correlate the two signals using curve-fitting algorithms to obtain the shear wave velocity, V_s. This specific method is described in more detail by Marchetti, et al. (2008). The advantage of this system is that it provides real time estimation of V_s as the test is being carried out on site. Post-processing of the results can be undertaken to refine the results, if necessary.

The result is a shear wave velocity measurement of each 0.5 m interval over the full depth of the sounding. These tests have been conducted on many sites in Auckland in the Puketoka Formation, which is a geological unit comprising Pleistocene to Holocene Age sedimentary deposits of clay, silts and sands. The resulting V_s with depth for three of these sites is illustrated in Figure 2 as the red line in each plot.

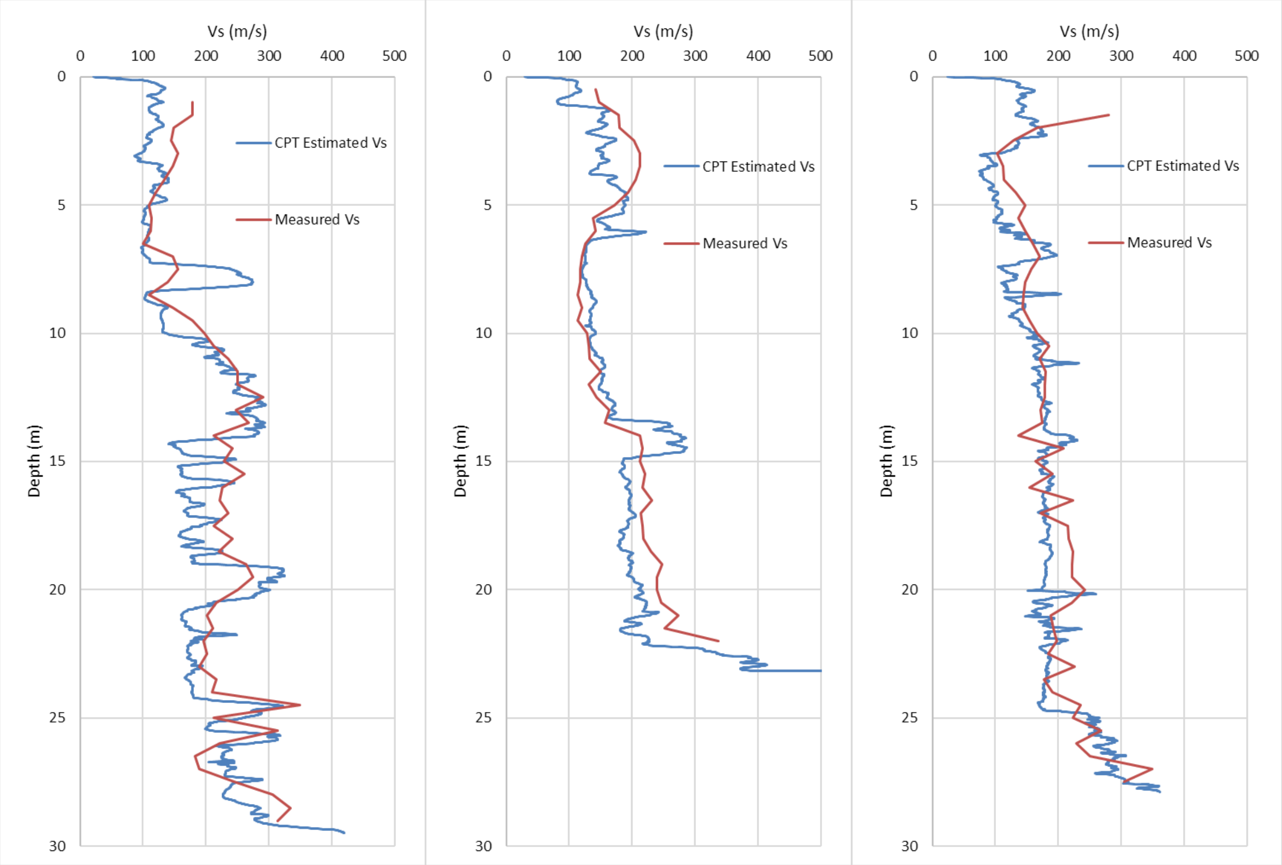

Figure 2: Examples of V_s measured from downhole seismic and estimated from CPT correlations for three sites in Puketoka Formation soils in Auckland

3.2 Estimating V_s from CPT

The seismic component (S) and the CPT component of the SCPT are independent tests that can be done concurrently in the same push or done as separate pushes. The CPT component provides cone resistance, q_c, sleeve friction, f_s and pore pressure, u_2, that can be correlated to various soil properties via empirical or semi-empirical correlations (e.g. Robertson 2009). There are many correlations that have been established for estimating V_s from CPT (e.g. Andrus, et al. 2007, Hegazy and Mayne 2006, Robertson 2009, Wair, et al. 2012). For this paper, we are considering the correlation developed by Robertson (2009), which is represented by Equation 2, below. This is also the equation that is utilised in the popular computer software program, CPeT-IT v3.0.3.2, by GeoLogismiki.

$$V_s = [\alpha_{vs} (q_t - \sigma_v)/p_a]^{0.5} \tag{2}$$

where $\alpha_{vs} = 10^{(0.55\, Ic\, +\, 1.68)}$, I_c = soil behaviour index, q_t = total cone resistance, σ_v = overburden stress.

The estimated V_s from the CPT data using Equation 2 is represented in Figure 2 as the blue lines in the plots. By plotting both the measured V_s from the downhole seismic test and the estimated V_s from the CPT correlation, a comparison between the results can be made. This can provide validation to the particular correlation that is used or allows a site-specific correlation to be developed. If the measured and estimated V_s

values are in agreement, as they generally appear to be in the plots in Figure 2, then some level of confidence is provided. It is the Authors' experience, that V_s estimated from CPT using Equation 2 compares reasonably well with V_s measured from downhole seismic testing in the Puketoka Formations soils.

A comprehensive study of empirical correlations to V_s from CPT was carried out in the Christchurch area using a large database of SCPT's (Wotherspoon, et al 2019). That study compared a number of published correlations, including that represented by Equation 2 (Robertson 2009). In that study, the function form represented by the Robertson equation was found to be one of least applicable for the Christchurch dataset, which are mainly sandy soils. Correlation to the Auckland Puketoka soils has not been as comprehensively studied. The purpose of this paper is to provide a mechanism for using V_s for site period and subsoil classification. It is not intended to be a comprehensive validation of the Robertson equation. The Robertson equation (Equation 2) was chosen in this paper due to its ease of use in the CPeT-IT software. More experimental evidence is required, however, for the purposes of this paper, it would appear that Equation 2 provides a reasonable estimation in these soils.

3.3 Time averaged shear wave velocity V_{sz}

The average shear wave velocity can be calculated by

$$V_{sz} = \frac{z}{t_z} \tag{3}$$

where V_{sz} = time averaged shear wave velocity to depth z from the ground surface, and

$$t_z = \sum_{i=1}^{n_z} \left(\frac{h_i}{V_{si}}\right) \tag{4}$$

where t_z is the total time (s) for a shear wave to travel from the surface to depth z (m), V_{si} is the shear wave velocity (m/s) over depth interval h_i (m), n_z is the number of depth intervals from the surface to depth z.

For the seismic component of the SCPT, each depth increment, h, will be equal to the interval depth; in this case, 0.5 m. There is potentially some error in the calculation of t_z in this approach as the depth intervals in practice may not necessarily be perfectly aligned in sequence. In addition, any minor errors in the calculation of V_s at each interval may present a larger cumulative error. For the CPT estimated V_s values, the depth increment, h_i, can be taken as the measuring interval of the CPT (e.g. 10 mm).

Figure 3(a) shows V_s with depth profiles from a SCPT on a site in Mangere, Auckland in Puketoka Formation soils. This is the same site as the HSVR example given in Figure 1, above. The measured V_s values are from the downhole seismic part of the test and the estimated V_s values are derived from the CPT data using Equation 2. The measured V_s and estimated V_s plots in Figure 3(a) do not compare overly favourably, but they do follow the same general trend.

Figure 3(b) shows the time averaged shear wave velocity, V_{sz}, plotted with depth from the same SCPT. Both those determined from measured and estimated V_s are plotted. These averaged V_{sz} plots show a better agreement than that suggested by the V_s plots, with the two V_{sz} lines coming together nicely.

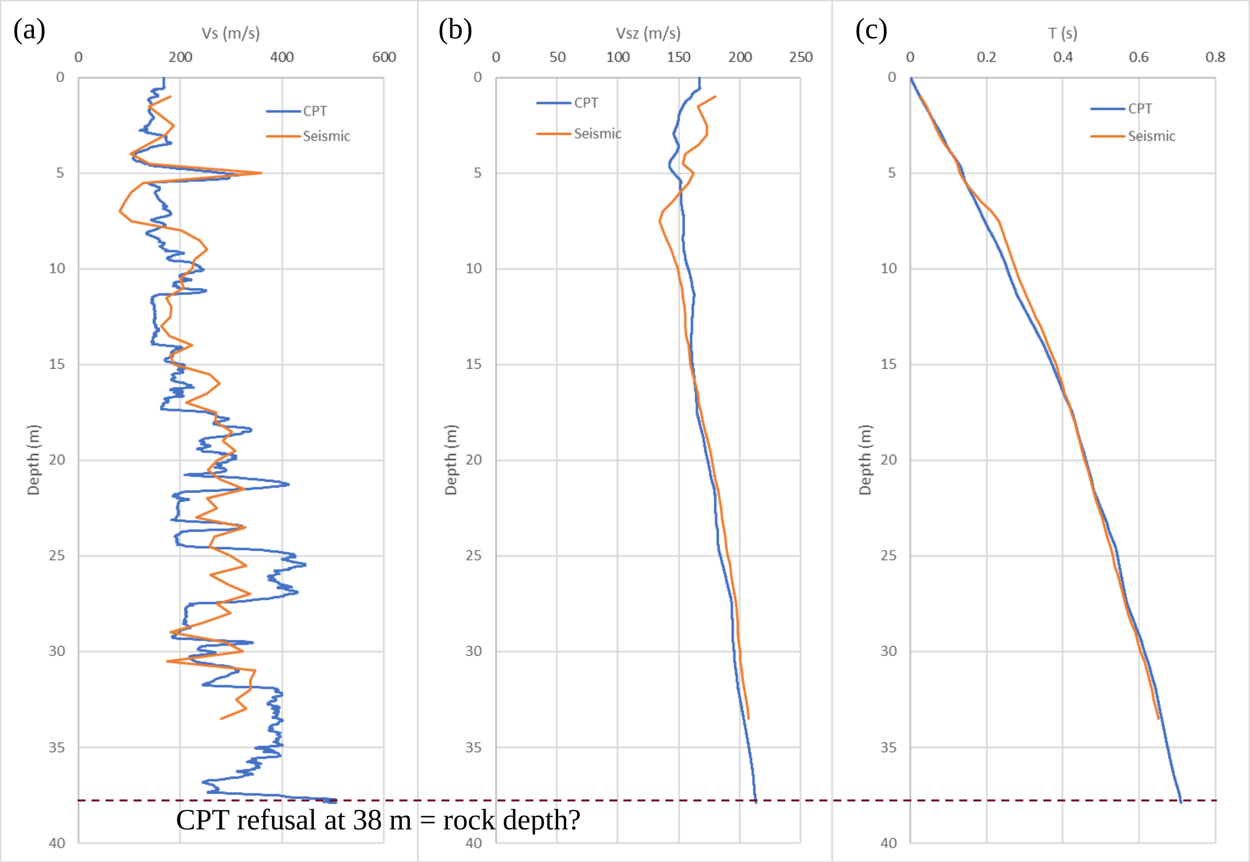

Figure 3: Plots of; (a) V_s ;(b) V_{sz} and; (c) T with depth for site in Mangere, Auckland

3.4 Determining site period and subsoil class

The site period, T, can be estimated by four times the shear wave travel time through the soil from the surface to the underlying rock (NZS 1170.5:2004).

$$T = 4t_H \tag{5}$$

where t_H = total shear wave travel time (s) from the ground surface to the underlying rock using Equation 4.

Alternatively, the site period can be calculated by

$$T = 4\frac{H}{V_{sH}} \tag{6}$$

Where H = total depth of soil from the ground surface to the underlying rock, V_{sH} = time averaged shear wave velocity at depth H.

It should be noted that Equations 5 and 6 are estimates of T for simple soil profiles only. For more complex profiles where there are layers of significantly different soil types, densities and shear wave velocities, a more detailed methodology would be required (e.g transfer function). It is assumed for the purposes of this paper that the example site, and other similar sites within the Puketoka Formation in Auckland represent a ‘simple’ soil profile; being one ‘layer’ of the same geological formation over a rock material.

Equation 6 can be presented as a plot with depth, as illustrated in Figure 3(c). The purpose of this plot is to show a trend with depth, but it is only the point at the underlying rock interface that provides the site period. The depth to the top of the rock as suggested by the CPT refusal is 38 m. At this depth, the CPT estimated curve in Figure 3(c) suggests a site period, T = 0.71 s. This is slightly higher than the 0.67 s estimate from the HVSR (see Figure 1). The downhole seismic testing stopped short at 33.5 m depth. By extrapolating the seismic curve in Figure 3(c) down to the rock depth, an estimate of site period, T = 0.69 s is obtained. A method for extrapolating the curve is explained further below.

We now have three independently derived estimates of site period from the same location. These are summarised in Table 1, below.

Table 1: Estimates of site period from the various methods.

Method	Estimated Site Period, T (s)
Downhole Seismic (SCPT)	0.69
HVSR	0.67
Empirical correlation from CPT	0.71

There is reasonable agreement between the three methods considering the potential uncertainty in these methods and in the ground conditions. More weight would be put on the downhole seismic and HVSR methods, although the use of all three at the same location provides a level of confidence. It would be reasonable to choose a site period, T = 0.7 s for design purposes. This is greater than 0.6 s, so the site would be classified as Class D in accordance with NZS 1170.5.

3.5 Extrapolation of V_{sz} and T with depth

In some cases, a SCPT may refuse before reaching rock. In those cases, it may be useful to extrapolate the V_{sz} and T curves. If the depth to rock is known from existing information, e.g. a borehole, then these curves can be extrapolated to that depth, thus allowing T to be estimated. If a HVSR test has also been done at the same location, the estimated T from that test can be used for comparison. In cases where the rock depth is not known, then the site period estimated from the HVSR test can help estimate the rock depth by the extrapolation of the T curve from SCPT.

The extrapolation of the curves is reasonable provided that a distinct trend can be seen in the curves and that the data is not extrapolated too far, say, no further than 25% beyond the bottom depth of the SCPT. If the SCPT has reached a significant depth and there is an obvious trend, then the average shear wave velocity, V_{sz}, is likely to continue to follow that same trend as changes in V_s below that depth will have little effect on the overall average; at least over a small additional depth and provided the shear wave velocity doesn't change dramatically.

In the above example site in Mangere, the downhole seismic test stopped about 5 m short of the rock. A clear trend can be seen in the plot and extrapolation over that relatively short distance would not seem unreasonable. In that case, the data correlated from the CPT continues to the rock depth and provides a guide for the potential extrapolation of the seismic data. From Figure 3(c), it can be seen that continuation of the orange downhole seismic line results in a value of T at the rock depth slightly less than that of the blue line that was estimated from the CPT.

To develop this extrapolation in a more quantitative manner, the V_{sz} with depth relationship can be estimated by a power function. This can be developed by plotting $(V_{sz})^2$ with depth and considering the straight-line portion of the graph as shown in Figure 4 below. This is using the data form the downhole seismic part of the SCPT for the Mangere example site and is a site-specific function.

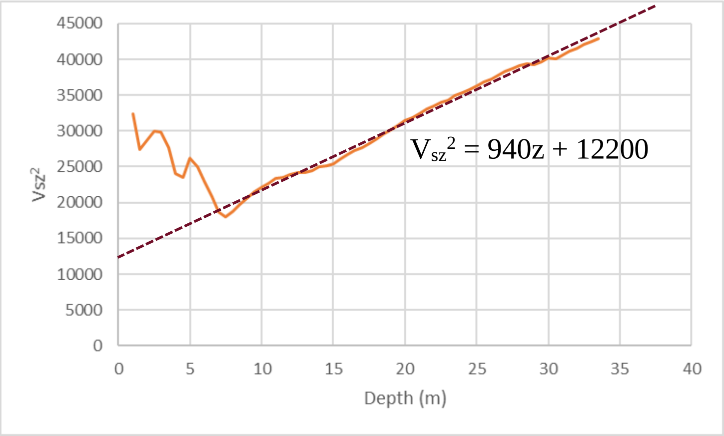

Figure 4: Development of relationship between V_{sz} and depth

This provides a site-specific function of V_{sz} with depth as

$$V_{sz} = \sqrt{940z + 12200} \tag{7}$$

A relationship for T with depth can be determined by combining equations (6) and (7). The resulting interpolated plots with depth for V_{sz} and T are shown in Figure 5, below. This shows only the downhole seismic data, but similar relationships can be determined this way for the CPT estimated V_{sz} and T.

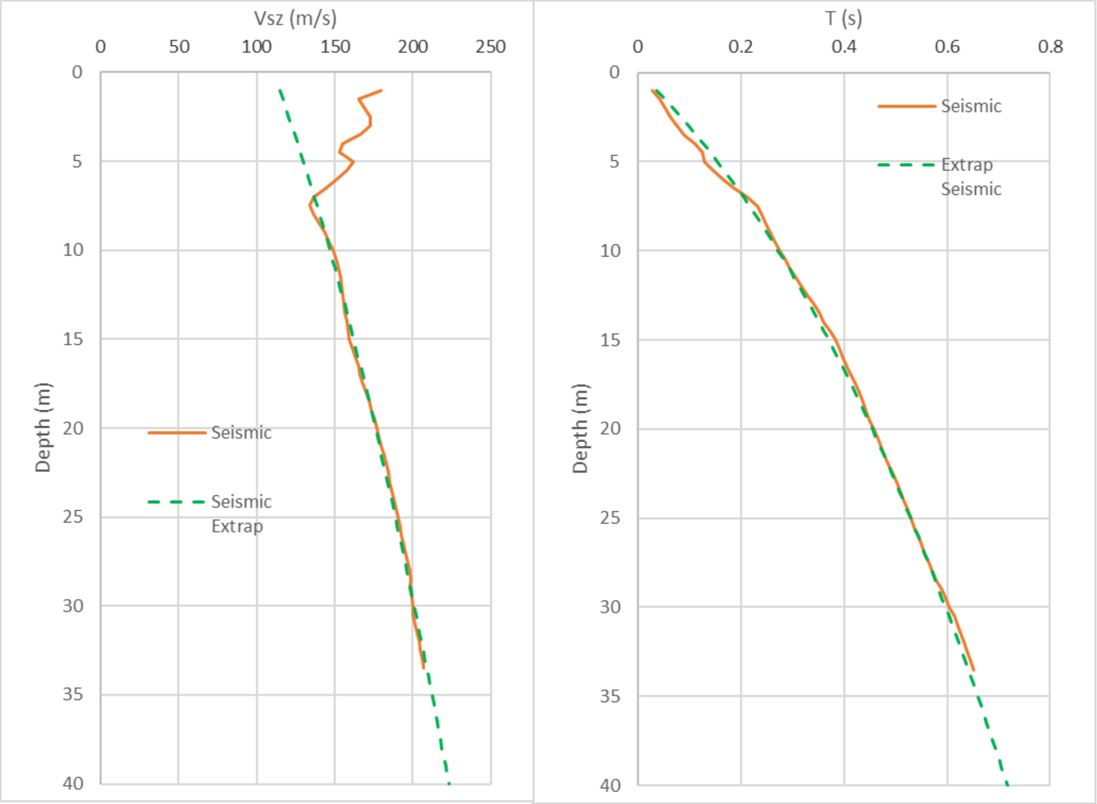

Figure 5: Interpolation and extrapolation of V_{sz} and T data

4 CONCULSIONS

Borehole information is considered a poor indicator of site period or subsoil class in soil sites (Larkin and van Houtte, 2014). In the authors' opinion the use of borehole information as a method of site subsoil class determination in NZS 1170.5:2004 should be given a much lower ranking. The hierarchy of test methods, in alignment with the believed intent of NZS 1170.5, would more aptly be:

1. Site period determined from in situ shear wave velocity testing
2. Site period determined from HVSR
3. Site period determined from CPT correlations to V_s (using verified correlations)

The combination of SCPT and HVSR methods allows all three of these methods to be obtained in a rapid and cost-effective manner. The SCPT provides two independent estimates of V_s: one measured from the downhole seismic part (S); and, the other estimated from empirical correlations from CPT. If done in combination with HVSR, three independent estimates of site period can be obtained. This provides a level of confidence in the results and allows for cross-validation of the methods.

In the example site at Mangere, Auckland, the three methods showed reasonable agreement in site period estimation (within 3%). This methodology is likely to be appropriate for the Puketoka Formation soils in Auckland but could also be suitable for other single layer soil sites where depth to rock is within 50 m depth. Further research, however, is required to verify these findings.

The empirical correlation for V_s from CPT used in this paper (Robertson 2009) appears to provide a reasonable estimate of V_s in the Puketoka Formation soils. However, this should not be relied on alone. Correlations of V_s from CPT data should only be relied upon if they can be validated on a site-specific basis or have been verified from research in the geological unit in question and shown to be reliable.

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