Correlation between standard penetration test and shear wave velocity in Wellington, New Zealand

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ABSTRACT

The New Zealand standard NZS1170.5:2004 (amendment 1; Sep 2016; Earthquake actions) recommends seven methods for the determination of site classification as defined in Section 3.1.3.1. The most preferable method is direct measurement of shear wave travel times or shear wave velocities (Vs). The second and third preferable methods are through obtaining shear wave velocities by inversion and empirical correlations. Shear wave velocities are also required, whether measured or estimated, for site specific seismic response studies. This paper provides an overview of existing standard penetration test (SPT) to shear wave velocity (Vs) relationships and leverages a limited dataset from boreholes in the Wellington Central area with SPT testing and downhole (DH) seismic testing. This paper provides a local calibrated correlation between shear wave velocity and SPT that may be used in some parts of Wellington.

1 INTRODUCTION

One of the main requirements for designing new structures or assessing existing structures is to assess the site seismic response which requires determining the site subsoil class. The New Zealand standard NZS1170.5:2004 (amendment 1; Sep 2016; Earthquake actions) recommends seven methods for the determination of site classification as defined in Section 3.1.3.1. The most preferable method is direct measurement of shear wave travel times or shear wave velocities (Vs). The second and third preferable methods are through obtaining shear wave velocities by inversion and empirical correlations.

Where the site period is required to be determined, a practice becoming common here in Wellington (especially in the CBD area at or near the C/D class boundary zone) is drilling a borehole down to bedrock with standard penetration test (SPT) at 1 m to 1.5 m intervals, then undertake downhole shear wave velocity measurements in the same borehole. As this has started to become a popular practice, geotechnical consultants are accumulating valuable data that comprise geological borehole logs, shear wave velocity measurements and SPT records. This data base will continue to grow in the future (including data that we expect to be provided by other interested geotechnical firms).

This paper explores existing SPT to Vs empirical relationships and individually assesses their suitability for use in the area of study. The relationship with the most suitable functional form is then calibrated to reflect local soil conditions.

2 AREA OF THE STUDY

The area of study is a localised area within Wellington City (Wellington Central) as presented in Figure 1 below. Further ongoing studies on locations outside the area will be included in future studies.

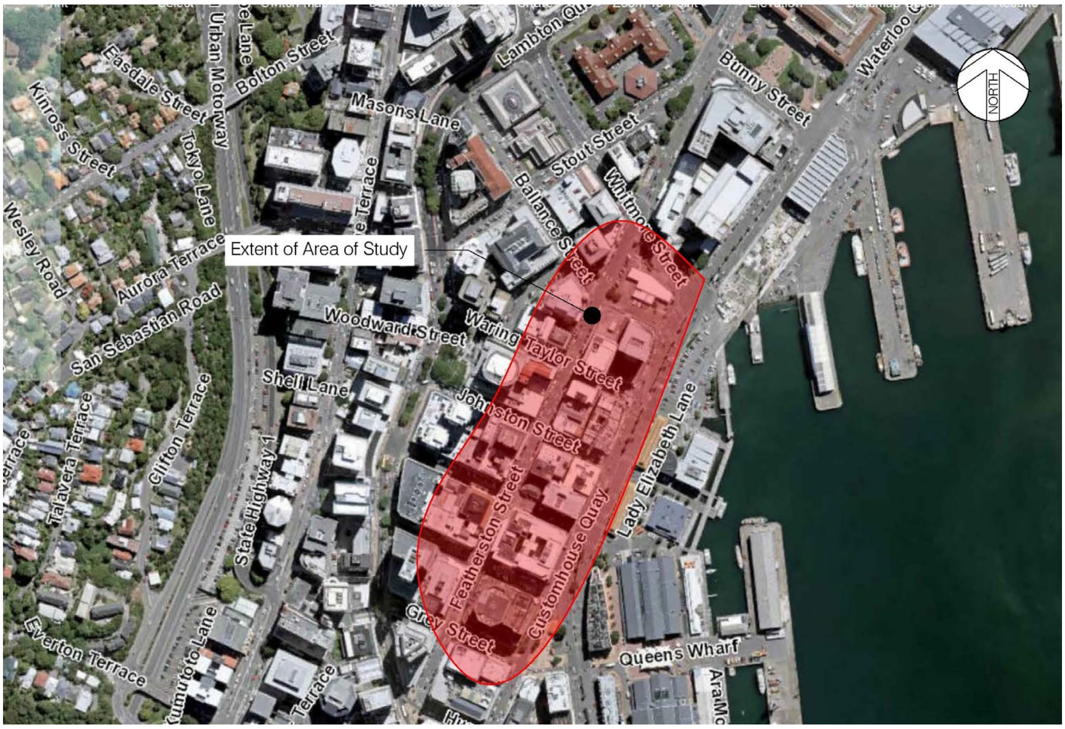


Figure 1: Extent of Area of Study

The measured shear wave velocity profiles are obtained from downhole seismic testing in three boreholes with measured SPT blow counts. Each borehole is from a different site within the area of study. In addition to these three boreholes, another five boreholes with SPT only (no seismic testing undertaken) were considered in the study.

The investigation depths varied between 30 m and 110 m. Bedrock was encountered between 25 m and 100 m below ground level.

The general ground profile for the area in study consists of Reclamation Fill material, underlain by Harbour Deposits and Alluvium, overlying Greywacke Bedrock.

Groundwater depth varied between 1 m and 2 m below ground surface.

3 REVIEW OF AVAILABLE CORRELATIONS (SPT AND V_S)

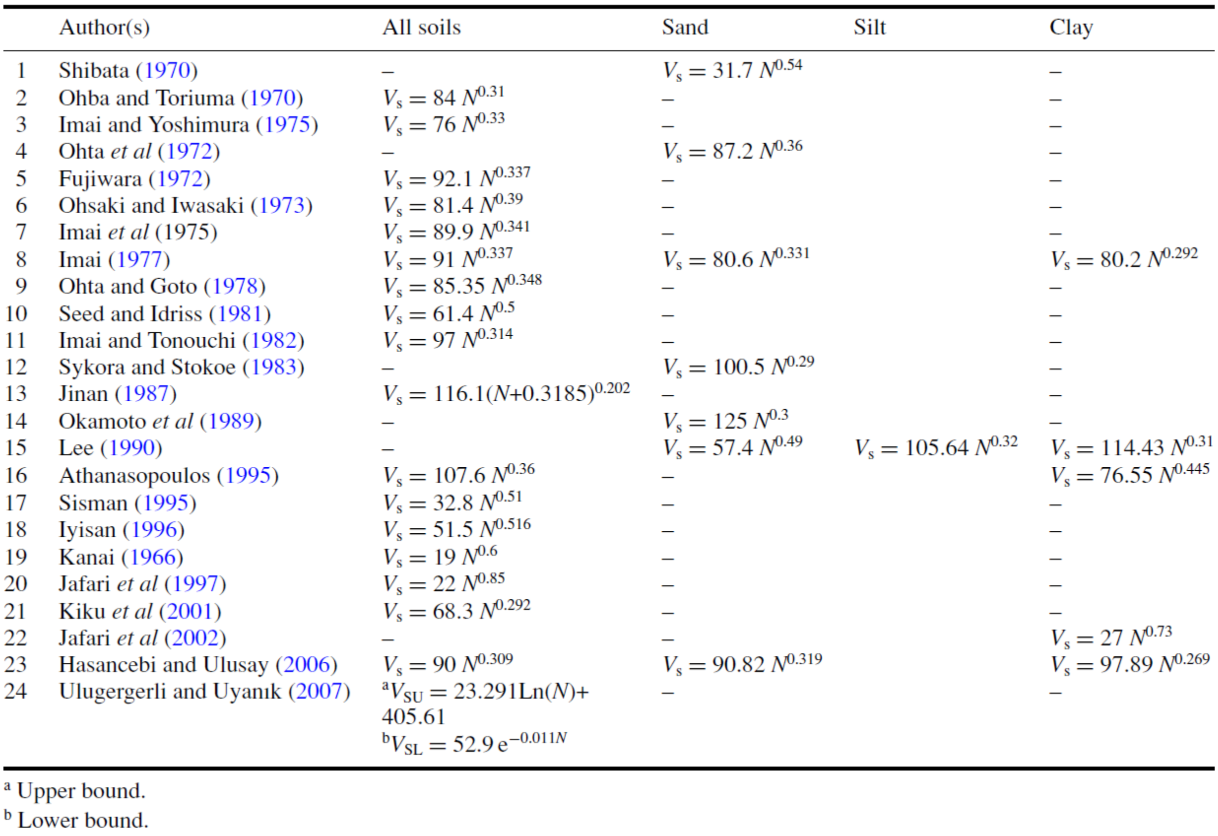
This section briefly describes the common correlations between SPT and Vs that were found in the literature. For more in-depth understanding or to understand the background and applicability of these correlations, refer to the corresponding referenced papers.

The SPT is represented in its field value N (hammer blows per foot (30 cm)) or via correction for hammer energy, rod length, sampler diameter, etc. to N_{60}. Optionally further correction for overburden to $N_{1,60}$.

Many studies were undertaken to correlate SPT with Vs. Some of these correlations were discussed in Dikmen 2009 (Figure 2) and were in the form of:

$$V_s = a\,.\,N^{\,b} \tag{1}$$

Where a and b are constants that correspond to different soil types.



	Author(s)	All soils	Sand	Silt	Clay
1	Shibata (1970)	–	$V_s = 31.7\ N^{0.54}$		–
2	Ohba and Toriuma (1970)	$V_s = 84\ N^{0.31}$	–		–
3	Imai and Yoshimura (1975)	$V_s = 76\ N^{0.33}$	–		–
4	Ohta *et al* (1972)	–	$V_s = 87.2\ N^{0.36}$		–
5	Fujiwara (1972)	$V_s = 92.1\ N^{0.337}$	–		–
6	Ohsaki and Iwasaki (1973)	$V_s = 81.4\ N^{0.39}$	–		–
7	Imai *et al* (1975)	$V_s = 89.9\ N^{0.341}$	–		–
8	Imai (1977)	$V_s = 91\ N^{0.337}$	$V_s = 80.6\ N^{0.331}$		$V_s = 80.2\ N^{0.292}$
9	Ohta and Goto (1978)	$V_s = 85.35\ N^{0.348}$	–		–
10	Seed and Idriss (1981)	$V_s = 61.4\ N^{0.5}$	–		–
11	Imai and Tonouchi (1982)	$V_s = 97\ N^{0.314}$	–		–
12	Sykora and Stokoe (1983)	–	$V_s = 100.5\ N^{0.29}$		–
13	Jinan (1987)	$V_s = 116.1(N{+}0.3185)^{0.202}$	–		–
14	Okamoto *et al* (1989)	–	$V_s = 125\ N^{0.3}$		–
15	Lee (1990)	–	$V_s = 57.4\ N^{0.49}$	$V_s = 105.64\ N^{0.32}$	$V_s = 114.43\ N^{0.31}$
16	Athanasopoulos (1995)	$V_s = 107.6\ N^{0.36}$	–		$V_s = 76.55\ N^{0.445}$
17	Sisman (1995)	$V_s = 32.8\ N^{0.51}$	–		–
18	Iyisan (1996)	$V_s = 51.5\ N^{0.516}$	–		–
19	Kanai (1966)	$V_s = 19\ N^{0.6}$	–		–
20	Jafari *et al* (1997)	$V_s = 22\ N^{0.85}$	–		–
21	Kiku *et al* (2001)	$V_s = 68.3\ N^{0.292}$	–		–
22	Jafari *et al* (2002)	–	–		$V_s = 27\ N^{0.73}$
23	Hasancebi and Ulusay (2006)	$V_s = 90\ N^{0.309}$	$V_s = 90.82\ N^{0.319}$		$V_s = 97.89\ N^{0.269}$
24	Ulugergerli and Uyanık (2007)	$^{a}V_{SU} = 23.291\mathrm{Ln}(N) + 405.61$ $^{b}V_{SL} = 52.9\,\mathrm{e}^{-0.011N}$	–		–

[a] Upper bound.

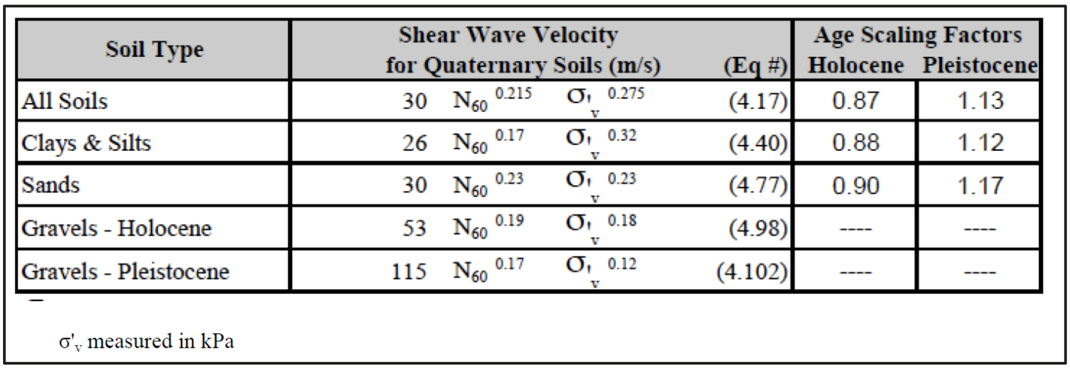
[b] Lower bound.

Figure 2: SPT to Vs correlations taken from Dikmen (2009)

Wair et al 2012 have added the vertical stress / overburden (σ) to the equation (as a multiplier) and this was in the form of:

$$V_s = a\,.\,N_{60}{}^{\,b}\,\sigma^{c} \tag{2}$$

Where a, b and c are constants corresponding to the several soil types (Figure 3).



Soil Type	Shear Wave Velocity for Quaternary Soils (m/s)	(Eq #)	Age Scaling Factors Holocene	Pleistocene
All Soils	$30\ N_{60}{}^{0.215}\ \sigma'_v{}^{0.275}$	(4.17)	0.87	1.13
Clays & Silts	$26\ N_{60}{}^{0.17}\ \sigma'_v{}^{0.32}$	(4.40)	0.88	1.12
Sands	$30\ N_{60}{}^{0.23}\ \sigma'_v{}^{0.23}$	(4.77)	0.90	1.17
Gravels - Holocene	$53\ N_{60}{}^{0.19}\ \sigma'_v{}^{0.18}$	(4.98)	----	----
Gravels - Pleistocene	$115\ N_{60}{}^{0.17}\ \sigma'_v{}^{0.12}$	(4.102)	----	----

σ'_v measured in kPa

Figure 3: SPT to Vs correlations taken from Wair et al 2012

A third variation was that of Brandenberg et al 2010 derived from data in California, which is in the form of:

$$\ln V_s = C_0 + C_1 \ln(N_{60}) + C_2 \ln \sigma' + \varepsilon\sigma_{\ln Vs} \tag{3}$$

Where as per Brandenberg et al 2010 …

- σ' is the vertical effective stress
- $\varepsilon\sigma_{\ln Vs}$ is a standard normal variation and deviation form
- C_0, C_1, C_2 are constants corresponding to different soil types

The equation by Brandenberg et al 2010 showed to be the most relevant to this study and will be discussed further in the next sections.

4 ANALYSIS

The obtained measured shear wave velocity data were in the format of arrival time with depth (the source is at surface and the receiver is descending down the hole). We have used this data to visually check the fit of the correlations. Accordingly, the derived shear wave velocities from the SPT data were converted to arrival times with depth for the purpose of checking the measured versus the derived results.

Equation (1) and Equation (2) were first considered to calibrate the arrival time's trend with depth. It was hard to regenerate the measured profile. After several trials, the authors decided to abandon these equations. It was found that overburden should be accounted for not as a multiplier but as an additional component that, due to its nature, increases with depth. Accordingly, more research and analysis was undertaken to find that equation (3) represents the trend in the local profile in the location of the study.

During the calibration process it was found that there is a change in the trend at a depth of 25 m below ground level. Plotting SPT N with depth (Figure 4) has shown that the ground is more of a normally consolidated granular material down to that depth, then starts to become over consolidated and dominantly very dense. Brandenberg et al 2010 also indicated a change in trend in sandy soils at an overburden of 200 kPa. Wellington's alluvium in the area of study showed similarity to California's sandy soils in Brandenberg et al 2010.

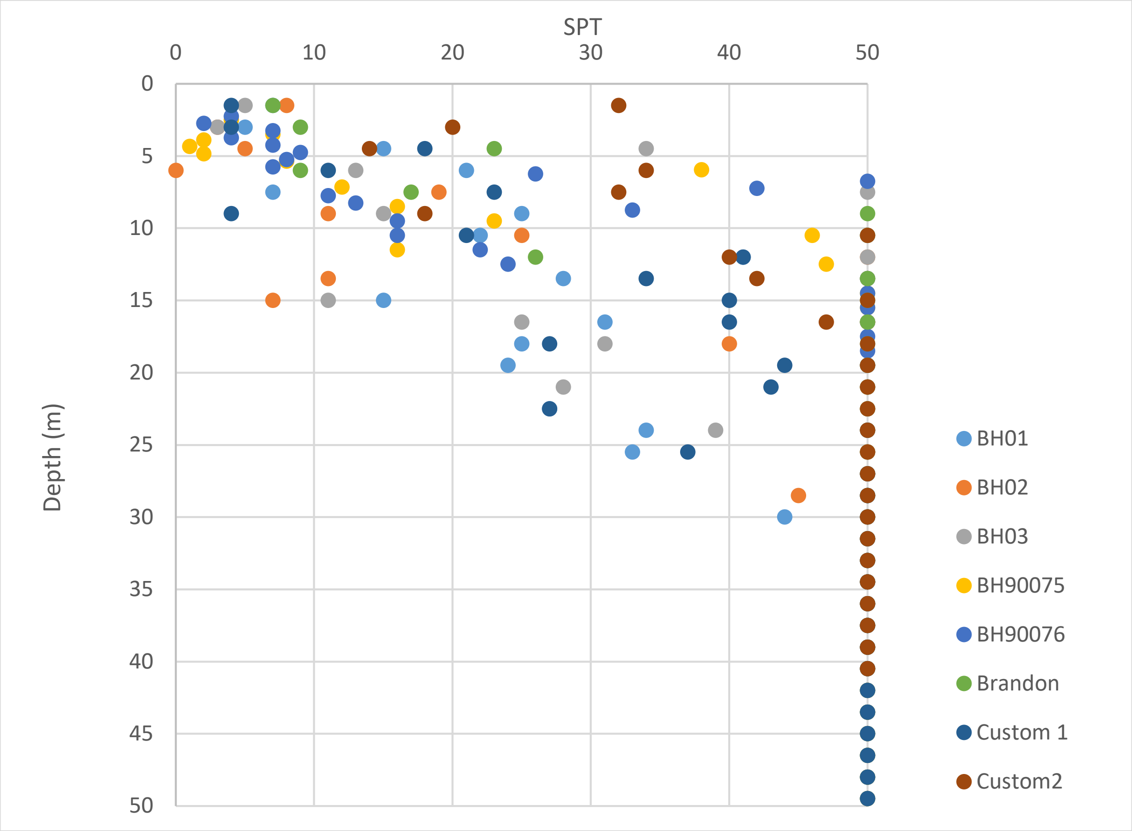


Figure 4: Raw SPT (N) with depth for the area of study from eight boreholes

The constants C_0, C_1, C_2 and C_3 were calibrated by trial and error to provide the best visual fit in the curves. Accordingly, the following equation was found to be representative:

$$ln\, V_s \;= C_0 + \; C_1\, ln\, N_{60} \; + C_2\, .\, C_3 \;\, ln\, fz \qquad (4)$$

Where:

- Vs = Estimated Shear Wave Velocity (m/s)
- C_0, C_1, C_2, and C_3 are the fitted parameters
- $C_0 = 4$
- $C_1 = 0.1$
- $C_2 = 0.27$
- $C_3 = 1$ down to a depth of 25 m (normally consolidate portion) and 1.15 below 25 m depth
- N_{60} = the energy corrected SPT N value
- fz = the actual depth below surface (m); assuming shallow groundwater

The plots of the fitted arrival time curves versus the measured ones showing an acceptable visual fit are included in Figure 5. The arrival times are the time for the shear wave to travel from surface to a specific point in depth. The correlated values are at 1 m to 1.5 m depth intervals since derived from SPT. The measured values are at 0.5 m to 1 m depth intervals as measured down the hole.

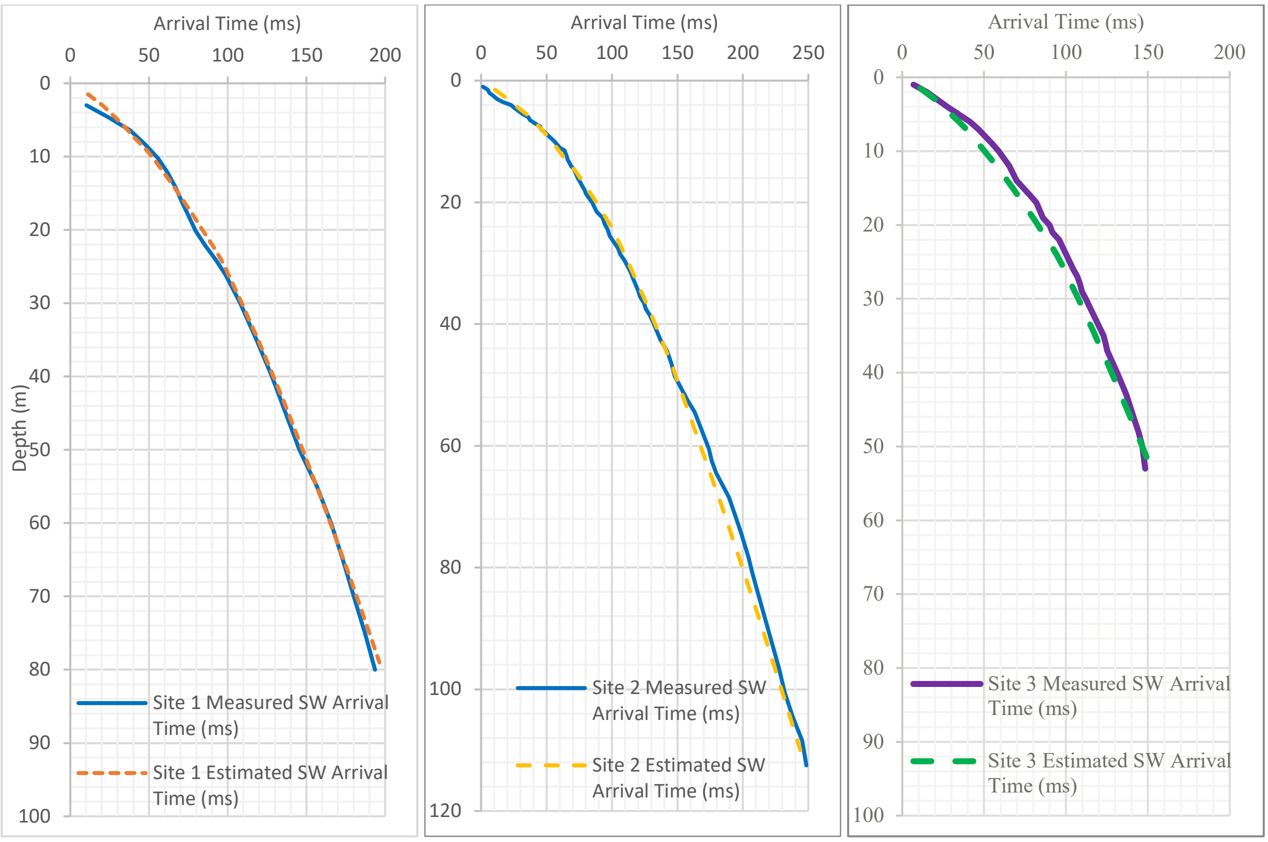


Figure 5: Shear wave (SW) arrival time with depth (measured and correlated)

The recommended equation is considered valid for N_{60} of up to approximately 60 blows. Above 60 can be used, but it was not found to be sensitive to the results and, for the sake of consistency, we suggest to limit the N_{60} to 60.

5 CONCLUSIONS

This paper has discussed several historic correlations between shear wave velocities and SPT N values. Analysis was undertaken on a specific area of study in Wellington's CBD area (Wellington Central) where deep boreholes were drilled, SPTs undertaken and downhole shear wave velocities were measured. The following equation was obtained through this study.

$$\ln V_s = C_0 + C_1 \ln N_{60} + C_2 . C_3 \ln fz \tag{5}$$

or

$$V_s = e^{C_0 + C_1 \ln N_{60} + C_2 . C_3 \ln fz} \tag{6}$$

Where:

- Vs = Estimated Shear Wave Velocity (m/s)
- C_0, C_1, C_2, and C_3 are the fitted parameters
- $C_0 = 4$
- $C_1 = 0.1$
- $C_2 = 0.27$
- $C_3 = 1$ down to a depth of 25 m (normally consolidate portion) and 1.15 below 25 m depth
- Fz = is the actual depth below surface (m); assuming shallow groundwater

- N_{60} = energy corrected SPT number; SPT N obtained from the field should be corrected for variations from the standard (non-standard sampler type, borehole diameter, rod length, and normalised to the reference energy ratio of 60%). It is not appropriate to normalise or correct penetration resistance for overburden. The recommended equation is considered valid for N_{60} of up to approximately 60 blows.

The above equation can be assumed to be applicable to the area of study of this paper. It could also be applicable to most of the reclaimed portion of the CBD that was underwater prior to the year 1800, but we recommend to confirm the correlation prior to applying it outside the area of study. Another area within Wellington is also being studied by the authors. Progress to date shows some slight variations to the above equation due to the difference in geological sequence.

A Wellington specific SPT to Vs relationship would provide insight to local practitioners in their initial geotechnical assessments and provide a means to plan site characterisation efforts which should (if not must) include geophysical testing, if a shear wave velocity profile is needed for design. This proposed relationship would be especially helpful in reviewing historical geotechnical borehole logs with SPT measurements or when undertaking initial seismic assessments of existing buildings.

This paper lacks the discussion on errors and also doesn't include a rigorous statistical regression. This will be considered in the future studies.

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