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Mr. Tom Shantz
Caltrans

Subject: Site Characterization – Guidelines for Estimating V_s Based on In-Situ Tests
Stage 1 – Interim Report

Dear Mr. Shantz,

Overview:
The purpose of this letter is to summarize the results of our study to date. The objective of this study is to develop a methodology to assist Caltrans engineers in evaluating shear wave velocity in the absence of direct measurement. The first stage of our study consisted of a literature review of published correlations between shear wave velocity and other common in-situ geotechnical soil tests.

Introduction:
Shear wave velocity is a dynamic soil property commonly used for dynamic site response and site classification for seismic design. The average shear wave velocity of the top 30 meters of the soil profile (v_{s30}) is one of the soil properties used by Caltrans for seismic design (Caltrans, 2006) and is incorporated into the Next Generation Attenuation (NGA) relationships currently being evaluated. Shear wave velocity may also be used to evaluate liquefaction "triggering" (Andrus et al, 2004, Kayen et al, 2004) and to estimate the in-situ strength of granular soils (Cunning et al, 1995, Cha & Cho, 2007).

Shear wave velocity is primarily a function of soil density, void ratio, and effective stress, and may also be influenced by the age of the deposit, cementation, and stress history. Shear wave velocity can be measured by a number of intrusive geophysical methods: downhole logging, crosshole logging, suspension logging, and the seismic Cone Penetration Test (SCPT). Additionally, shear wave velocity can be measured by non-intrusive geophysical tests, including: spectral analysis of surface waves (SASW), seismic refraction, and seismic reflection. Shear wave velocity may also be measured in the laboratory using: resonant column tests, bender elements, ultrasonics, torsional shear tests, and modified triaxial tests.

Whenever possible, one of the above techniques should be performed to obtain a shear wave velocity profile. A v_{s30} profile can be readily obtained at a site using the SCPT for approximately $2,000 (one day of testing). This cost is minimal considering the scatter in the correlations (discussed below) and their subsequent impact on design

In the absence of direct measure of shear wave velocity, correlations have been developed between shear wave velocity and several commonly measured geotechnical properties: CPT tip and friction resistance, and standard penetration test (SPT) N-values.

Site Characterization:

The Caltrans seismic design procedure divides sites into six categories (Soil Profile Types A through F) based on the average properties of the top 100 feet (30 meters) of the soil profile. Sites are classified based on shear wave velocity, Standard Penetration Test (SPT) resistance, and undrained shear strength (Caltrans, 2006). Soil profile types are summarized in Table 1. Additional criteria, such as Plasticity Index, water content, organic content and collapse potential, must also be considered when assigning a Soil Profile Type.

The Caltrans classification system is consistent those presented in the *National Earthquake Hazard Reduction Program (NEHRP) Provisions for Seismic Regulations for New Buildings and Other Structures* (BSSC, 2003), *Improved Seismic Design Criteria for California Bridges* (ATC, 1996), *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2005), and the *2006 International Building Code* (ICBO, 2006).

In addition to Soil Profile Type selection, the shear wave velocity may be required for site specific seismic evaluation or dynamic analysis when required by the Seismic Design Criteria.

Literature Review:

In the absence of direct measurement, shear wave velocity can be estimated based on correlations with common in-situ tests such as the cone penetration test (CPT) and standard penetration test (SPT). The penetration resistance in both of these tests generally correlates with shear wave velocity, because penetration resistance is also influenced by density, void ratio, and effective stress. The first stage of our study consisted of review of approximately 60 published articles, reports, studies. A complete list of references is presented at the end of this report.

Correlations between penetration resistance and shear wave velocity are based on regression analysis of data sets. There is generally a significant amount of scatter in the measured data. Regression equations represent a best-fit of the data. Correlation coefficients are a measure of how well the equation fits the data. Higher correlation coefficients indicate increased agreement between measured data and predicted values.

Correlations are not meant to replace measurement of shear wave velocity, but rather to estimate a potential range of values when direct measurement is not available. It is therefore recommended that a few different correlations be used to develop an idea of the potential range of values. It is also important to recognize that the values estimated are not upper and lower bounds. The actual shear wave velocity may be beyond this range.

Recommended shear wave velocity correlations for CPT and SPT are presented in the following two sections of this report. Correlation coefficients and plots showing the scatter of the data for individual equations are included, if available. Comparisons of various SPT-based correlations are provided for each soil type in the SPT section of this report.

Cone Penetration Test Correlations:

A variety of Cone Penetration Test (CPT) systems are available. Our discussion will be limited to three of the most common for geotechnical site investigation: the conventional CPT, the piezocone penetration test (CPTu), and the seismic CPT (SCPT or SCPTu).

The conventional CPT involves advancing an instrumented penetrometer into the ground measuring the cone tip resistance (q_c) and sleeve friction (f_s) at selected intervals (typically 2 to 5 centimeters).

The piezocone penetration test (CPTu) incorporates a pore pressure transducer (typically located behind the cone tip) to measure pore water pressure (u_2) in saturated soils. The CPTu allows for correction of the tip resistance due to pore pressures acting on unequal areas of the cone. The corrected tip resistance (q_t) can be calculated by the equation:

$$q_t = q_c + (1-a_n)*u_2 \qquad (1)$$

where a_n is the net area ratio, which is a property of the cone determined by calibration tests. Typical values of a_n range from 0.5 to 1.0.

Many government agencies perform conventional CPT without measurement the pore pressure. In the absence of pore pressure measurement, the interpretations of soil parameters and application of direct CPT methodologies may be less reliable. For clean sands and dense granular soils, q_t is approximately equal to q_c (less than 10% error). In soft to stiff clays, the correction may be significant, depending on the consistency and permeability of the clay and the type of cone used. For cone penetrometers with large net area ratios ($a_n > 0.8$), the correction may relatively small (approximately 10%). Cone penetrometers with smaller net area ratios ($a_n < 0.6$) may have much higher correction factors (up to an above 40%) (Mayne, 2007, personal communication). In the absence of measured pore pressures and correction of the tip resistance, q_c may be substituted for q_t in the following correlations equations; however, additional caution and judgment are required when using uncorrected tip resitances for soft to stiff clays or when the device used has a small net area ratio.

The seismic cone penetration test (SCPT or SCPTu) is performed in the same manner as the CPT or CPTu with the addition of a geophone in the CPT tip. Measurement of shear wave velocity is performed at selected interval (typically 1 to 2 meters) by striking a steel beam pressed firmly against the ground. The shear wave velocity is calculated based on the difference in travel time of the shear wave between the source and the geophone at two consecutive depth measurements.

The following correlations based on CPT are recommended, most of which continue to be developed by Professor Mayne of Georgia Institute of Technology (Mayne, 2007). Except where noted, shear wave velocity (v_s) is measured in meters per second and tip resistance (q_t), sleeve friction (f_s), and effective overburden stress (σ'_{vo}) are measured in kilopascals.

All Soils:
The following relationship has been proposed for all soils (Hegazy & Mayne, 1995) as referenced by Mayne (2007).

$$v_s = [(10.1 \log_{10} q_t) - 11.4]^{1.67} [100 f_s/q_t]^{0.3} \quad (2)$$

The following relationship has been proposed for all soils (Mayne, 2006) as referenced by Mayne (2007).

$$v_s = 118.8 \log_{10} (f_s) + 18.5 \quad (3)$$

Sands:
The following relationship has been proposed for uncemented, unaged quartzitic sands, (Baldi et al., 1989) as referenced by Mayne(2007):

$$v_s = 277 (q_t)^{0.13}(\sigma'_{vo})^{0.27} \quad (4)$$

where q_t and σ'_{vo} are measured in megapascals (MPa).

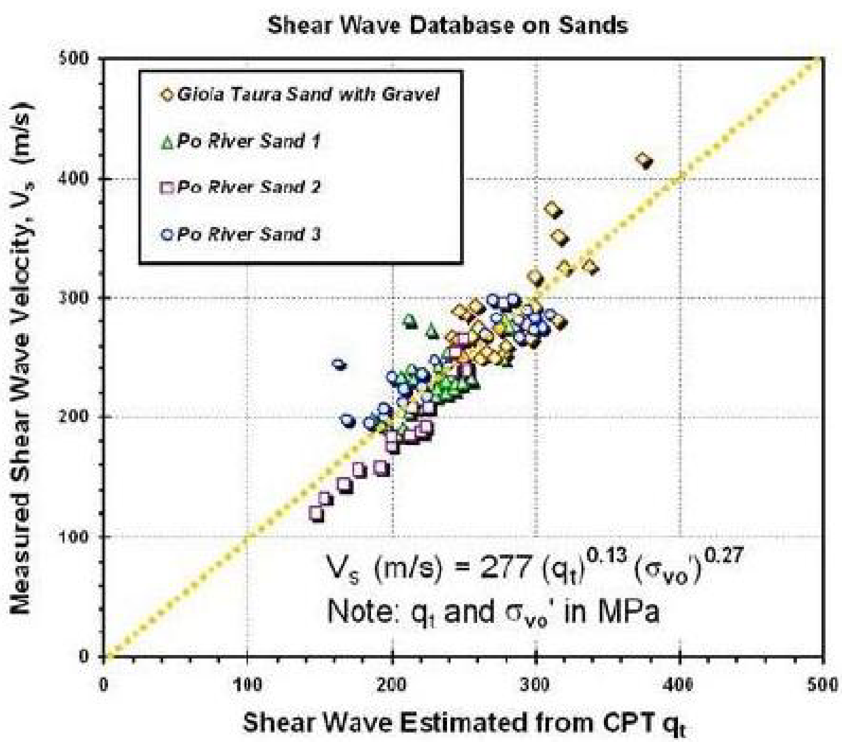

Figure 1. Shear wave velocity from CPT data in clean quartz sands by Baldi, et al. (1998) (adapted from Mayne, 2007).

Clays:
For soft to stiff, intact and fissured clays, Mayne & Rix (1995) proposed:

$$v_s = 1.75 (q_t)^{0.627} \qquad (5)$$

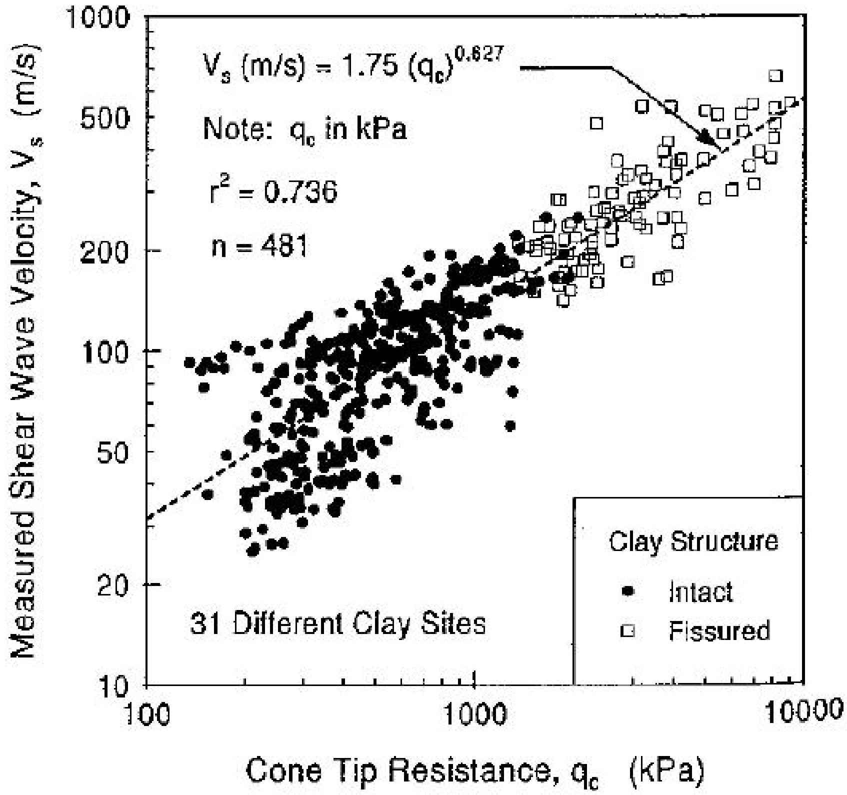

Figure 2. Shear wave velocity from CPT data of clayey soils (Mayne & Rix, 1995).

This relationship can be significantly improved for intact clays if void ratio is known. Void ratio can be determined by laboratory testing of intact samples. If void ratio is available, the following relationship may be used (Mayne & Rix, 1995).

$$v_s = 9.44\ (q_t)^{0.435}\ (e_0)^{-0.532} \qquad (6)$$

where e_0 = void ratio.

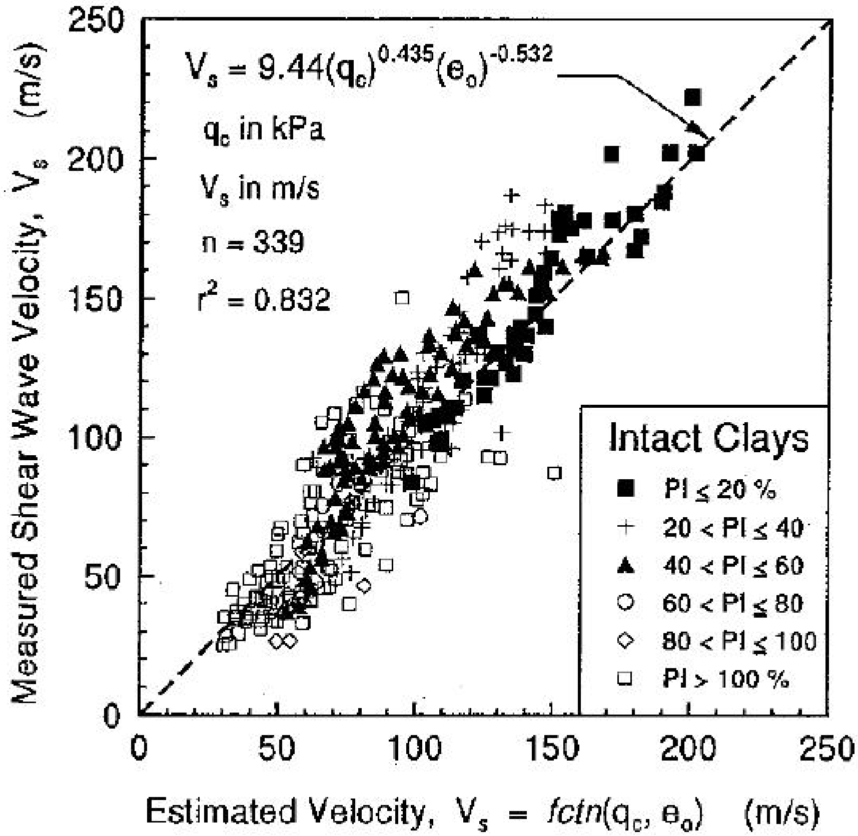

Figure 3. Shear wave velocity from CPT data of clayey soils with void ratio (Mayne & Rix, 1995).

When e_0 is known, the regression coefficient increases from 0.736 for Equation 5 to 0.832 for Equation 6. A comparison of the shear wave velocity profile estimated from equations 5 and 6, along with a shear wave velocity profile measured using the SASW method, are presented in Figure 4.

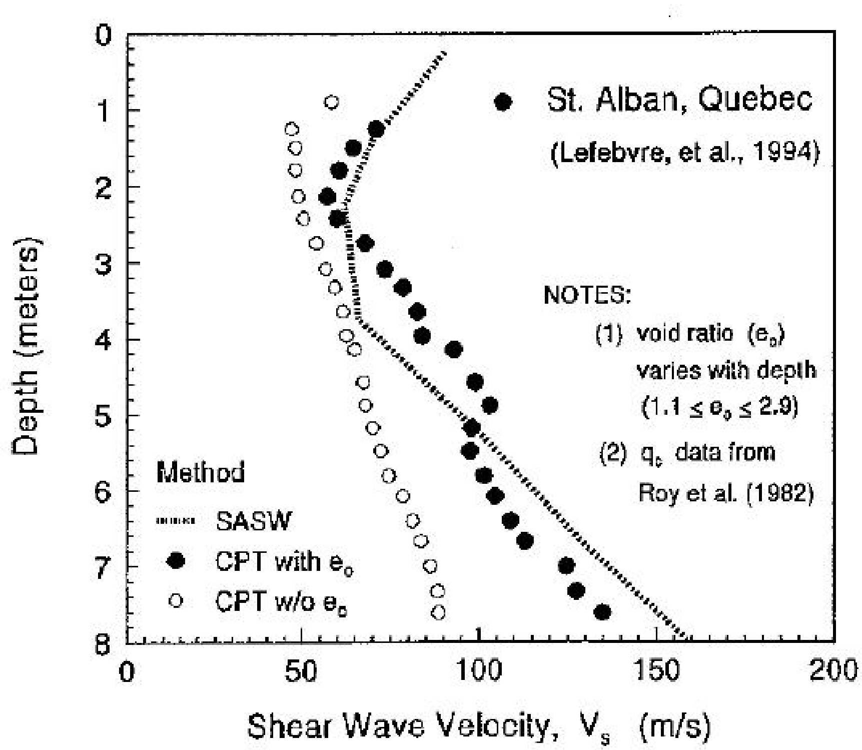

Figure 4. Comparison of estimated shear wave velocities with and without e_0 (Mayne & Rix, 1995).

Standard Penetration Test Correlations:

The standard penetration test (SPT) is the most commonly used geotechnical penetration test worldwide. Most published correlations are based on uncorrected field N-values. A correction of N-value for over-burden stress may not improve correlations (Sykora, 1987, indicated the correlations could be worse). It is not clear whether corrected N-values can reliably be used in the following correlations. Therefore, at present uncorrected N-values should be used. Additional investigation on this issue is underway.

SPT practices and measurements vary significantly due to differences in equipment and procedures around the world. This is particularly true for the amount of energy delivered to the sampler (Seed et al., 1985). As a result it is not unreasonable for uncorrected N values to vary by +/- 50% of the median value.

Approximately 30 correlations between shear wave velocity and SPT N-value were reviewed. Correlations are presented by soil type in Tables 2 through 5. Recommended correlations for each soil type are presented in the following sections. The recommended correlations generally had higher correlation coefficients and together represent a range of estimated shear wave velocity. For each soil type, a plot of the recommended correlations is presented along with the other correlations to illustrate the likely range of shear wave velocity.

In the following equations, shear wave velocity is measured in meters per second and N is measured in blow per foot (or blows per 0.3 meters). It should be noted that use of correlation equations for N-values less than 2 or greater than 50 is not recommended due to generally poor accuracy (Ohta & Goto, 1978).

All Soils:

The following relationships have been proposed for all soils.

$$v_s = 56\ N^{0.5} \qquad \text{(Seed et al, 1983)} \qquad (7)$$

$$v_s = 97\ N^{0.314} \qquad \text{(Imai \& Tonouchi, 1982)} \qquad (8)$$

$$v_s = 32.8\ N^{0.51} \qquad \text{(Sisman, 1995)} \qquad (9)$$

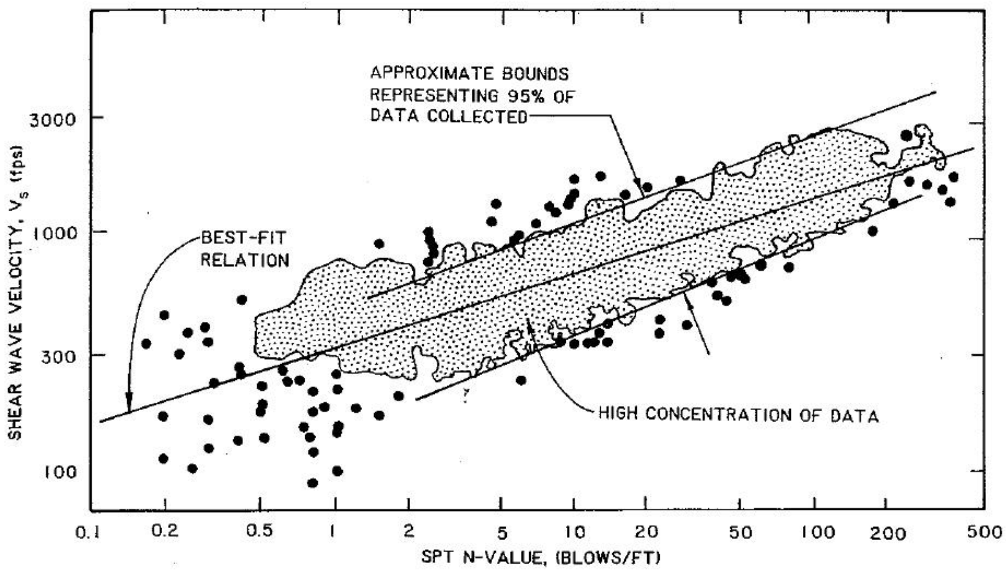

Figure 4. Correlation between SPT N-value and shear wave velocity by Imai and Tonouchi (1982) adapted from Sykora (1987).

Figure 5 presents a comparison of the estimated shear wave velocity values for the 13 all soils correlations considered in this study. Recommended equations are shown in bold.

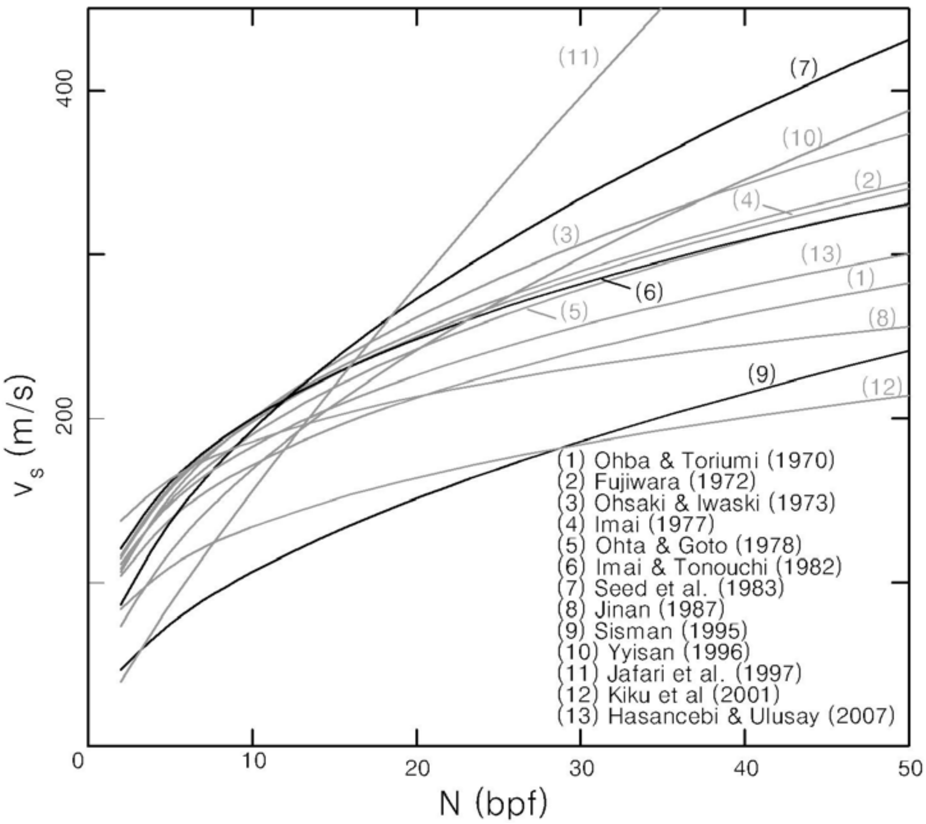

Figure 5. Comparison of estimated shear wave velocity from various SPT correlations – All Soils.

Sands:
The following relationships have been proposed for sands.

$$v_s = 157.13 + 4.74\ N \qquad \text{(Lee, 1992)} \qquad (10)$$

$$v_s = 100.5\ N^{0.29} \qquad \text{(Sykora \& Stokoe, 1983)} \qquad (11)$$

$$v_s = 80.6\ N^{0.331} \qquad \text{(Imai, 1977)} \qquad (12)$$

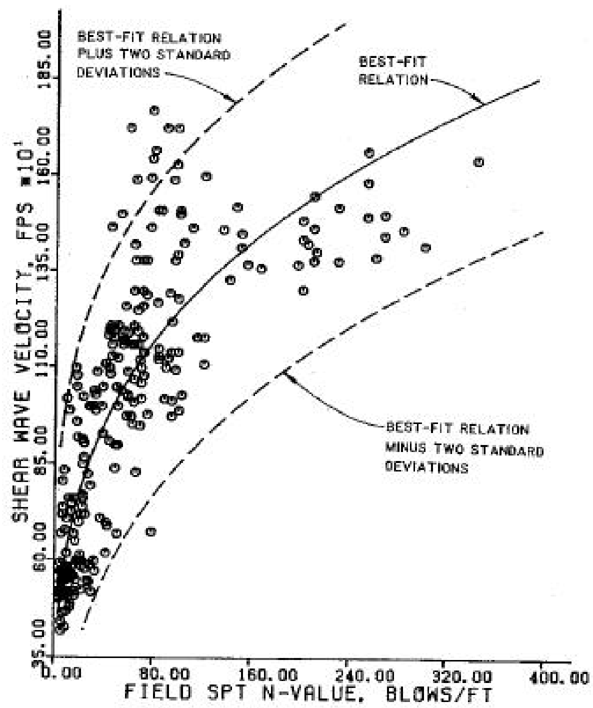

Figure 6. Correlation between SPT N-value and shear wave velocity by Sykora and Stokoe (1983) adapted from Sykora (1987).

Figure 7 presents a comparison of the estimated shear wave velocity values for the eight sand correlations considered in this study. Recommended equations are shown in bold.

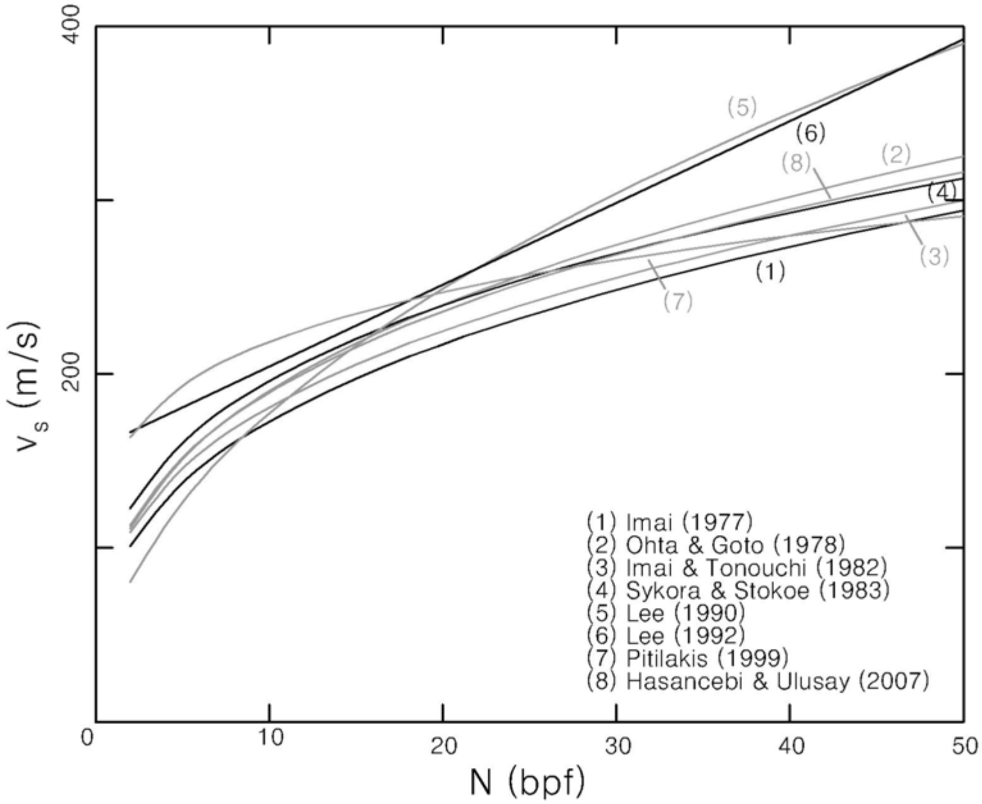

Figure 7. Comparison of estimated shear wave velocity from various SPT correlations – Sands.

Silts:
The following relationship has been proposed for silts.

$$v_s = 103.99\ (N + 1)^{0.334} \qquad \text{(Lee, 1992)} \qquad (13)$$

$$v_s = 145\ N^{0.178} \qquad \text{(Pitilakis, 1999)} \qquad (14)$$

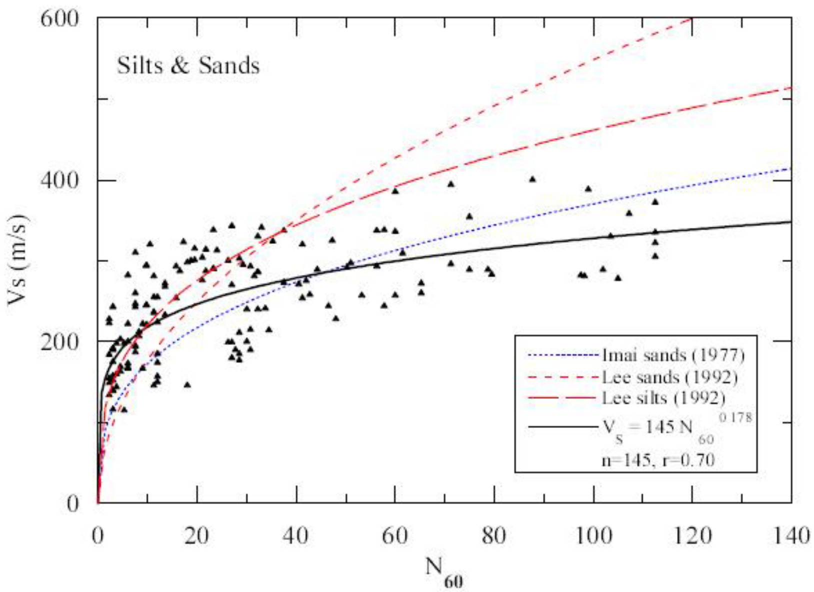

Figure 8. Correlation between SPT N-value and shear wave for silts and sands by Pitilakis (1999).

Figure 9 presents a comparison of the estimated shear wave velocity values for the three silt correlations considered in this study. Recommended values are shown in bold.

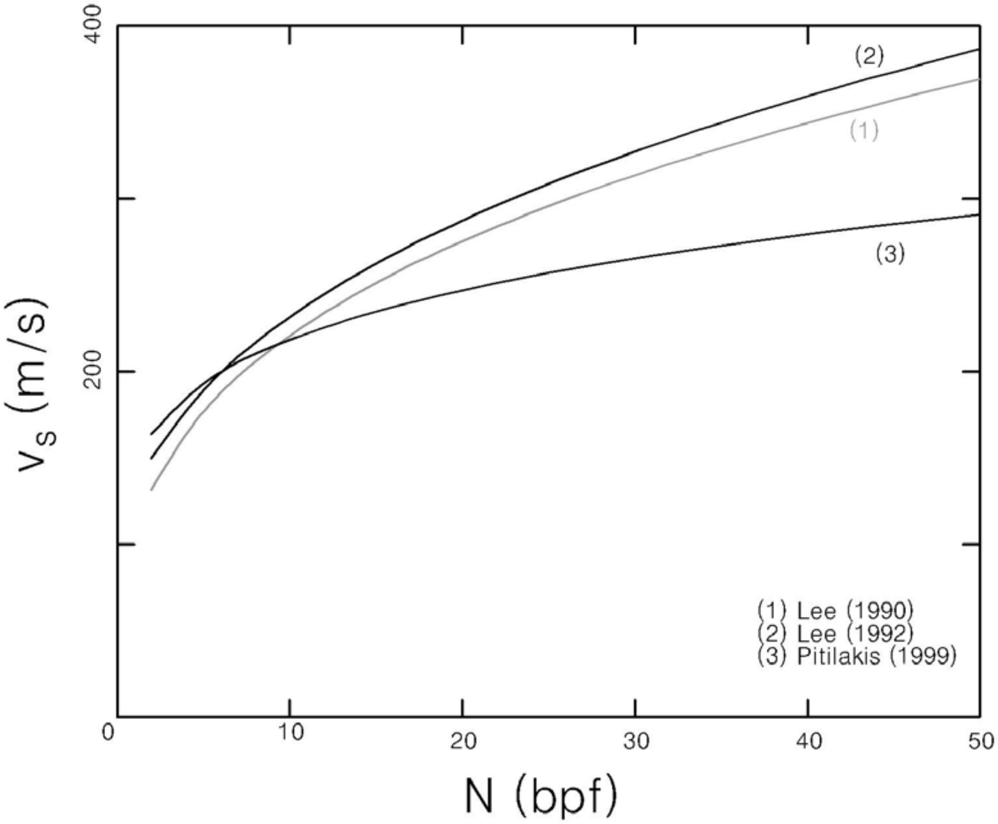

Figure 9. Comparison of estimated shear wave velocity from various SPT correlations – Silts.

Clays:
The following relationships have been proposed for clays.

$$v_s = 132\ N^{0.271} \quad \text{(Pitilakis, 1999)} \quad (15)$$

$$v_s = 86.9\ N^{0.333} \quad \text{(Ohta \& Goto, 1978)} \quad (16)$$

$$v_s = 80.2\ N^{0.292} \quad \text{(Imai, 1977)} \quad (17)$$

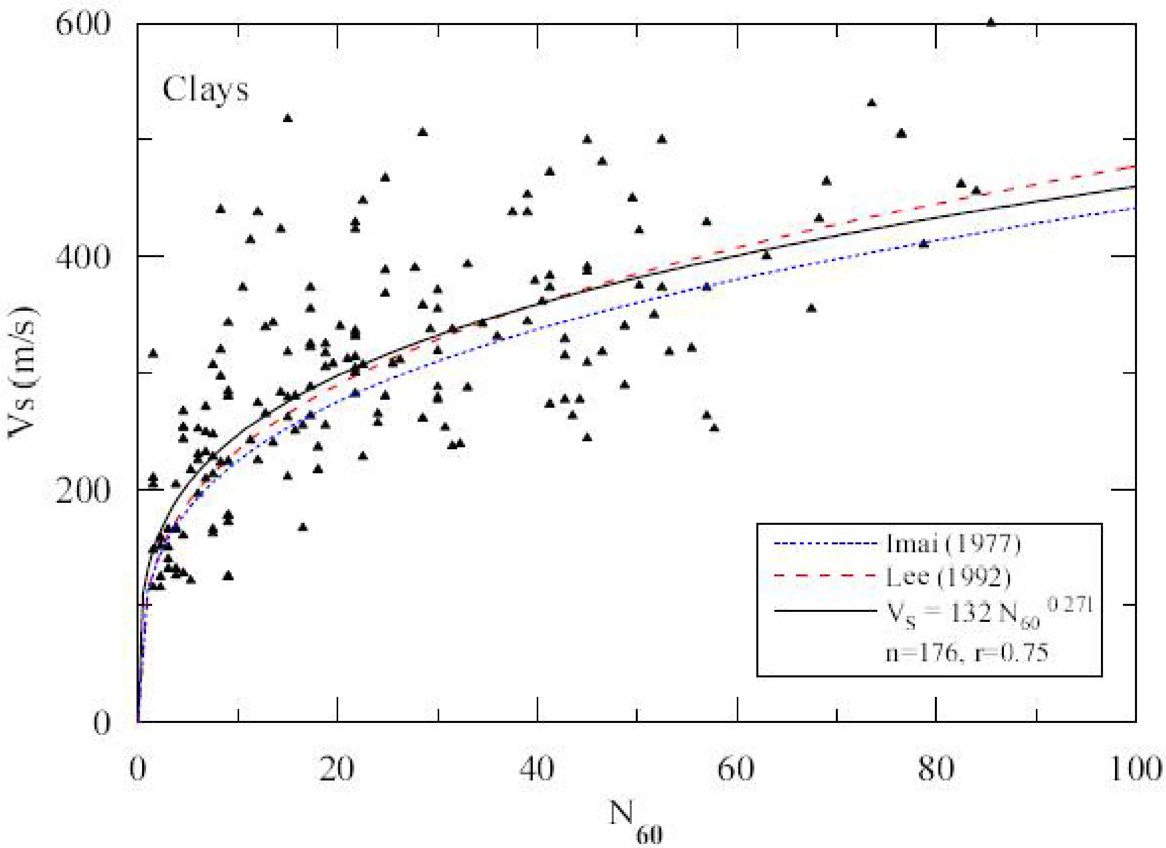

Figure 10. Correlation between SPT N-value and shear wave for clays by Pitilakis (1999).

Figure 11 presents a comparison of the estimated shear wave velocity values for the seven clay correlations considered in this study. Recommended values are shown in bold.

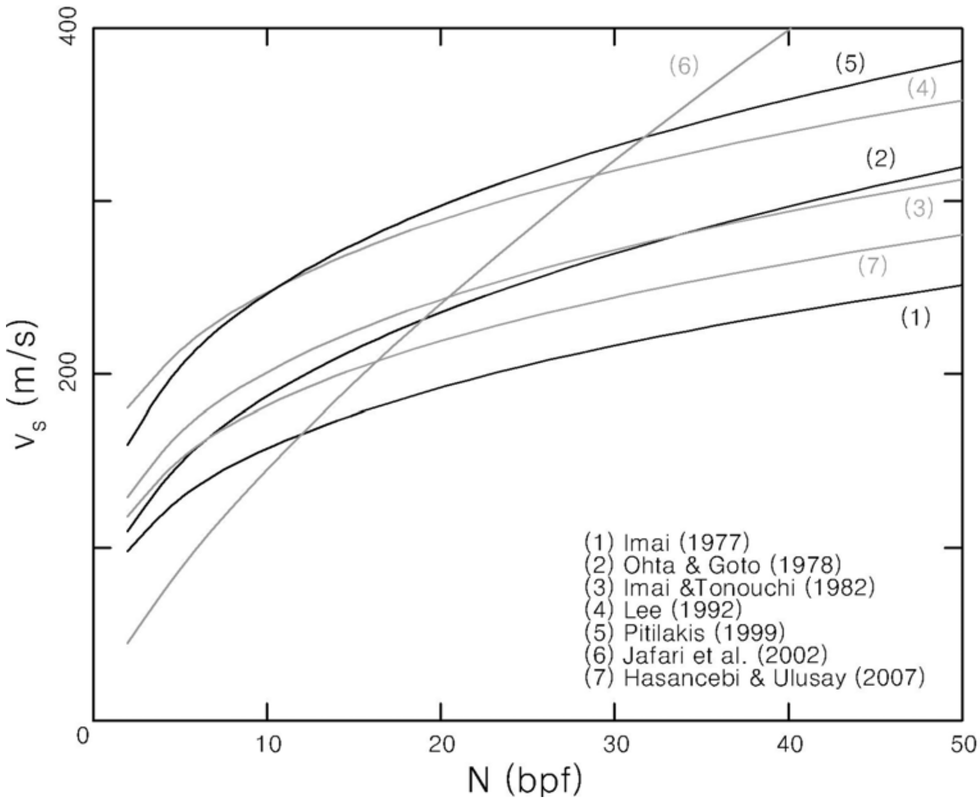

Figure 11. Comparison of estimated shear wave velocity from various SPT correlations – Silts.

Gravels:

The following relationship has been proposed for gravels by Ohta & Goto (1978) as referenced in Sykora (1987).

$$v_s = 75.3\,N^{0.351} \qquad \text{(Ohta \& Goto, 1978)} \qquad (18)$$

Limitations:
The correlations presented in this paper may be used by Caltrans engineers at their own discretion. Correlations are not meant to replace measurement of shear wave velocity, but rather to estimate shear wave velocity when direct measurement is not available. There is significant scatter associated with each correlation equation and disagreement between correlations. All of these factors should be considered when using correlations.

Future Study:
Future stages of this study will include:

- Review of published studies correlating shear wave velocity with effective stress, depth, soil type and geology.
- Review of published studies correlating shear wave velocity with geologic units in California.
- Comparison of shear wave velocity estimated by the proposed methodology with existing datasets where shear wave velocity was directly measured.
- Evaluation of potential variation in shear wave velocity across sites or within geologic units.
- Recommendations for assessment of shear wave velocity for future Caltrans projects.

We would appreciate your input regarding which information would be most beneficial to you as well.

Closure:
This letter represents the results of our study to date. This study consisted of review of published correlations between shear wave velocity and common in-situ tests.

It has been a pleasure working on this project with you. Please feel free to contact me to discuss this letter further and/or to provide additional input into the ongoing and future study.

Sincerely,

Jason T. DeJong

Table 1. Caltrans Soil Profile Types (Caltrans, 2006).

Soil Profile Type	Soil Profile Name	V_{s30} (m/s)	SPT N-Value	Undrained Shear Strength
A	Hard Rock	> 5000 ft/s > 1,500 m/s		
B	Rock	2,500 to 5,000 ft/s 760 to 1,500 m/s		
C	Very Dense Soil and Soft Rock	1,200 to 2,500 ft/s 360 to 760 m/s	> 50 bpf	> 2,000 psf > 100 kPa
D	Stiff Soil	600 to 1,200 ft/s 180 to 360 m/s	15 to 50 bpf	1,000 to 2,000 psf 50 to 100 kPa
E	Soft Soil[1]	< 600 ft/s < 180 m/s	< 15 bpf	< 1,000 psf < 50 kPa
F	Soils Requiring Site Specific Evaluation[2]			

[1]Site Class E also includes any profile with more than 10 feet (3 meters) of soft clay, defined as soil with Plasticity Index PI >20, and water content ≥ 40 percent, and undrained shear strength < 500 psf (25 kPa).

[2]Site Class F includes:
1. Soils vulnerable to failure or collapse underseismic loading (i.e. liquefiable soils, quick and highly sensitive clays, and collapsible weakly-cemented soils).
2. Peat and/or highly organic clay layersmore than 10 feet (3 meters) thick.
3. Very high plasticity clay (PI > 75) layers more than 25 feet (8 meters) thick.
4. Soft to medium clay layers more than 120 feet (36 meters) thick.

Table 2. Summary of SPT-Based Correlations – All Soils.

	Country	Soil Type	Equation	Correlation Coefficient
Ohba & Toriumi (1970)[1]	Japan	Alluvium	$Vs = 84N^{0.31}$	-----
Fujiwara (1972)[2]	Japan	-----	$Vs = 92.1N^{0.337}$	-----
Ohsaki & Iwasaki (1973)[1]	Japan	-----	$Vs = 81.3N^{0.39}$	0.886
Imai (1977)[2]	Japan	Quaternary and Pleistocene Alluvium	$Vs = 91N^{0.337}$	-----
Ohta & Goto (1978)	Japan	Quaternary and Pleistocene Alluvium	$Vs = 85.34N^{0.348}$	0.719
Imai & Tonouchi (1982)[1]	Japan		$Vs = 97N^{0.314}$	0.868
Seed et al (1983)	-----	-----	$Vs = 56N^{0.5}$	-----
Jinan (1987)	Shanghai	Soft Holocene Deposits	$Vs = 116.1(N+0.3185)^{0.202}$	0.7
Sisman (1995)[2]	-----	-----	$Vs = 32.8N^{0.51}$	-----
Iyisan (1996)[2]	-----	-----	$Vs = 51.5N^{0.516}$	-----
Jafari et al (1997)[2]	Iran	-----	$Vs = 22N^{0.85}$	-----
Kiku et al (2001)[2]	Turkey	-----	$Vs = 68.3N^{0.292}$	-----
Hasancebi & Ulusay (2007)	Turkey	Quaternary Aluvium and Detritus	$Vs = 90N^{0.308}$	0.73

[1]Referenced by Sykora (1987)
[2]Referenced by Hasancebi & Ulusay (2007)
[3]Referenced by Lee (1992)

Table 3. Summary of SPT-Based Correlations – Sands.

	Country	Soil Type	Equation	Correlation Coefficient
Imai (1977)[2]	Japan	Quaternary and Pleistocene Alluvium	$Vs = 80.6N^{0.331}$	-----
Ohta & Goto (1978b)[1]	Japan	Quaternary and Pleistocene Alluvium	$Vs = 88.4N^{0.333}$	0.719
Imai & Tonouchi (1982)[1]	Japan	Quaternary and Pleistocene Alluvium	$Vs = 87.8N^{0.314}$	0.69
Sykora & Stokoe (1983)[1]	-----	-----	$Vs = 100.5N^{0.29}$	0.84
Lee (1990)[3]	Taiwan	-----	$Vs = 57.4N^{0.49}$	0.62
Lee (1992)	Taiwan	-----	$Vs = 157.13 + 4.74N$	0.691
Pitilakis (1999)	Greece	Alluvium	$Vs = 145N^{0.178}$	0.70
Hasancebi & Ulusay (2007)	Turkey	Quaternary Aluvium and Detritus	$Vs = 90.82N^{0.319}$	0.65

[1]Referenced by Sykora (1987)
[2]Referenced by Hasancebi & Ulusay (2007)
[3]Referenced by Lee (1992)

Table 4. Summary of SPT-Based Correlations – All Silts.

	Country	Soil Type	Equation	Correlation Coefficient
Lee (1990)[1]	Taiwan	-----	$Vs = 105.64N^{0.32}$	0.73
Lee (1992)	Taiwan	-----	$Vs = 103.99(N+1)^{0.334}$	0.798
Pitilakis (1999)	Greece	Alluvium	$Vs = 145N^{0.178}$	0.70

[1]Referenced by Lee (1992)

Table 5. Summary of SPT-Based Correlations – All Clays.

	Country	Soil Type	Equation	Correlation Coefficient
Imai (1977)[2]	Japan	Quaternary and Pleistocene Alluvium	$Vs = 80.2N^{0.292}$	-----
Ohta & Goto (1978b)[1]	Japan	Quaternary and Pleistocene Alluvium	$Vs = 86.9N^{0.333}$	0.719
Imai & Tonouchi (1982)[1]	Japan	Quaternary and Pleistocene Alluvium	$Vs = 107N^{0.274}$	0.721
Lee (1992)	Taiwan	-----	$Vs = 138.36(N+1)^{0.242}$	0.695
Pitilakis (1999)	Greece	Alluvium	$Vs = 132N^{0.271}$	0.75
Jafari et al (2002)[2]	Iran	-----	$Vs = 27N^{0.73}$	-----
Hasancebi & Ulusay (2007)	Turkey	Quaternary Aluvium and Detritus	$Vs = 97.89N^{0.269}$	0.75

[1]Referenced by Sykora (1987)
[2]Referenced by Hasancebi & Ulusay (2007)

References:

American Society of Civil Engineers. (2005). "Minimum Design Loads for Buildings and Other Structures." *ASCE/SEI 7-05*, Chapter 20, 205-206.

Andrus, R.D., Stokoe, K.H., and Juang, C.H. (2004). "Guide for Shear-Wave-Based Liquefaction Potential Evaluation." *Eartquake Spectra*, 20 (2), 285-308.

Arieas, L., and Van Impe, W. (2004). "Interpretation of SCPT Data Using Cross-Over and Cross-Correlation Methods." *Lecture Notes in Earth Sciences*, 104, 110-116.

Bang, E.-S., and Kim, D.-S. (2007). "Evaluation of Shear Wave Velocity Profile Using SPT-Based Uphole Method." *Soil Dynamics and Earthquake Engineering*, 27, 741-758.

Boore, D.M. (2002). "Estimating Vs(30) (or NEHRP Site Classes) from Shallow Velocity Models (Depths < 30m)." *Bulletin of the Seismological Society of America*, 94 (2), 591-597.

Boore, D.M., and Thompson, E.M. (2007). "On Using Surface-Source Downhole-Receiver Logging to Determine Seismic Slownesses." *Soil Dynamics and Earthquake Engineering*, 27, 971-985.

Borcherdt, R.D. (1970). "Effects of Local Geology on Ground Motion Near San Francisco Bay." *Bulletin of the Seismological Society of America*, 60 (1), 29-61.

Borcherdt, R.D. (1994). "Estimates of Site Depending Response Spectra for Design (Methodology and Justifications)." *Earthquake Spectra*, 10 (4), 617-654.

Borcherdt, R.D., and Gibbs, J.F. (1976). "Effects of Local Geological Conditions in the San Francisco Bay Region on Ground Motions and Intensities of the 1906 Earthquake." *Bulletin of the Seismological Society of America*, 66 (2), 467-500.

Borcherdt, R.D., and Glassmoyer, G. (1992). "On Characteristics of Local Geology and Their Influence on Ground Motions Generated by the Loma Prieta Earthquake in the San Francisco Bay Region, California." *Bulletin of the Seismological Society of America*, 82 (2), 603-641.

Boulanger, R.W., Arulnathan, R., Harder, L.F., Torres, R.A., and Driller, M.W. (1998). "Dynamic Properties of Sherman Island Peat." *Journal Geotechnical and Geoenvironmental Engineering*, 124 (1), 12-20.

Building Seismic Safety Council. (2003). "2003 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures and Accompanying Commentary and Maps." *FEMA 450*, Chapter 3, 17-49.

California Department of Transportation. (2006). *Seismic Design Criteria*. Version 1.4, June.

Campanella, R.G., Stewart, W.P., Roy, D., and Davies, M.P. (1994). "Low Strain Dynamic Characteristics of Soils with the Downhole Seismic Piezecone Penetrometer." *Dynamic Geotechnical Testing II*, American Society for Testing and Materials, ASTM STP 1213, 73-87.

Cha, M., and Cho, G.-C. (2007). "Shear Strength Estimation of Sandy Soils Using Shear Wave Velocity." *Geotechnical Testing Journal*, 30 (6), 484-495.

Chavez-Garcia, F.J., and Faccioli, E. (2000). "Complex Site Effects and Building Codes: Making the Leap." *Journal of Seismology*, 4, 23-40.

Choi, Y., and Stewart, J.P. (2005). "Nonlinear Site Amplification as Function of 30 m Shear Wave Velocity." *Earthquake Spectra*, 21 (1), 1-30.

Cunning, J.C., Robertson, P.K., and Sego, D.C. (1995). "Shear Wave Velocity to Evaluate In Situ State of Cohesionless Soils." *Canadian Geotechnical Journal*, 32, 848-858.

Dobry, R., Borcherdt, R.D., Crouse, C.B., Idriss, I.M., Joyner, W.B., Martin, G.R., Power, M.S., Rinne, E.E., and Seed, R.B. (2000). "New Site Coefficients and Site Classification System Used in Recent Building Seismic Code Provisions." *Earthquake Spectra*, 16 (1), 41-67.

Hasancebi, N., and Ulusay, R. (2007). "Empirical Correlations between Shear Wave Velocity and Penetration Resistance for Ground Shaking Assessments." *Bulletin of Engineering Geology and the Environment*, 66, 203-213.

Holzer, T.L., Bennett, M.J., Noce, T.E., and Tinsley, J.C. (2005a). "Shear-Wave Velocity of Surfacial Geologic Sediments in Northern California: Statistical Distributions and Depth Dependence." *Earthquake Spectra*, 21 (1), 161-177.

Holzer, T.L., Padovani, A.C., Bennett, M.J., Noce, T.E., and Tinsley, J.C. (2005b). "Mapping NEHRP Vs30 Site Classes." *Earthquake Spectra*, 21 (2), 353-370.

Hunter, J.A., Benjumea, B., Harris, J.B., Miller, R.D., Pullan, S.E., Burns, R.A., and Good, R.L. (2002). "Surface and Downhole Shear Wave Seismic Methods for Thick Soil Site Investigations." *Soil Dynamics and Earthquake Engineering*, 22, 931-941.

International Council of Building Officials. (2006). "Earthquake Loads." *2006 International Building Code*, Section 1613, 302-306.

Jinan, Z. (1987). "Correlation Between Seismic Wave Velocity and the Number of Blow of SPT and Depth." *Selected Papers from the Chinese Journal of Geotechncial Engineering*, American Society of Civil Engineers, 92-100.

Karl, L., Haegeman, W., and Degrande, G. (2006). "Determination of the Material Damping Ratio and the Shear Wave Velocity with the Seismic Cone Penetration Test." *Soil Dynamics and Earthquake Engineering*, 26, 1111-1126.

Kayen, R., Seed, R.B., Moss, R.E., Cetin, O., Tanaka, Y., and Tokimatsu, K. (2004). "Global Shear Wave Velocity Database for Probabilistic Assessment of the Initiation of Seismic-Soil Liquefaction." *Proceedings of the 11th International Conference on Soil Dynamics and Earthquake Engineering* (The 3rd International Conference on Earthquake Geotechncial Engineering), U.C. Berkeley, California, Vol. 2, 506-513, January 7-9.

Kramer, S. (1996). *Geotechnical Earthquake Engineering*. Prentice Hall, New Jersey.

Kramer, S., (2000). "Dynamic Response of Mercer Slough Peat." *Journal Geotechnical and Geoenvironmental Engineering*, 126 (6), 504-510.

Landon, M.M., DeGroot, D.J., and Sheahan, T.C. (2006). "Nondestructive Sample Quality Assessment of a Soft Clay Using Shear Wave Velocity." *Journal of Geotechnical and Geoenvironmental Engineering*, 133 (4), 424-432.

Larkin, T.J., and Taylor, P.W. (1979). "Comparison of Down-Hole and Laboratory Shear Wave Velocities." *Canadian Geotechnical Journal*, 16, 152-162.

Larkin, T.J., and Taylor, P.W. (1982). "A Further Comparison of Shear-Wave Velocities." *Canadian Geotechnical Journal*, 19, 506-507.

Lee, S.H.-H. (1992). "Analysis of the Multicollinearity of Regression Equations of Shear Wave Velocities." *Soils and Foundations*, 32 (1), 205-214.

Mayne, P.W. (2007). *Cone Penetration Testing State-of-Practice*. NCHRP Project 20-05 Topic 37-14.

Mayne, P.W., and Rix, G.J. (1995). "Correlations between Shear Wave Velocity and Cone Tip Resistance in Natural Clays." *Soils and Foundations*, 35 (2), 107-110.

Ohta, Y., and Goto, N. (1978), "Empirical Shear Wave Velocity Equations in Terms of Characteristic Soil Indexes." *Earthquake Engineering and Structural Dynamics*. 6, 167-187.

Park, S., and Elrick, S. (1998). "Predictions of Shear-Wave Velocities in Southern California Using Surface Geology." *Bulletin of the Seismological Society of America*, 88 (3), 677-685.

Pitilakis, K., Raptakis, D., Lontzetidis, K., Tika-Vassilikou,T., Jongmans, D. (1999). "Geotechnical and Geophysical Description of Euro-Seistests, Using Field, and Laboratory Tests and Moderate Strong Ground Motions." *Journal of Earthquake Engineering*, 3 (3), 381-409.

Presti, D.L., Lai, C., and Foti, S. (2004). "Geophysical and Geotechnical Investigations for Ground Response Analyses." *Recent Advances in Earthquake Geotechnical Engineering and Microzonation*. Atilla Ansal, Editor, 101-138.

Rodriguez-Marek, A., Bray, J.D., and Abrahamson, N.A. (2001). "An Empirical Geotechnical Seismic Site Response Procedure." *Earthquake Spectra*, 17 (1), 65-87.

Romo, M.P., and Garcia, S.R. (2003). "Neurofuzzy Mapping of CPT Values into Soil Dynamic Properties." *Soil Dynamics and Earthquake Engineering*, 23, 473-482.

Schnaid, F., and Yu, H.S. (2007). "Interpretation of the Seismic Cone Test in Granular Soils." *Geotechnique*, 57 (3), 265-272.

Seed, H.B., Idriss, I.M., and Arango, I. (1983). "Evauluation of Liquefaction Potential Using Field Performance Data." *Journal Geotechnical Engineering*, 109 (3), 458-482.

Seed, H.B., Tokimatsu, K., Harder, L.F., and Chung, R.M. (1985). "Influence of SPT Prodecures in Soil Liquefaction Resistance Evaluations." *Journal Geotechnical Engineering*, 111 (12), 1425-1445.

Seed, H.B., Wong, R.T., Idriss, I.M., and Tokimatsu, K. (1986). "Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils." *Journal Geotechnical Engineering*, 112 (11), 1016-1032.

Stewart, J.P., Liu, A.H., and Choi, Y. (2003). "Amplification Factors for Spectral Acceleration in Tectonically Active Regions." *Bulletin of the Seismological Society of America*, 93, 332-352.

Sykora, D.W. (1987). "Examination of Existing Shear Wave Velocity and Shear Modulus Correlations in Soils." Department of the Army, Waterways Experiment Station, Corps of Engineers, Miscellaneous Paper GL-87-22.

Sykora, D.W., and Koester, J.P. (1988). "Correlations Between Dynamic Shear Resistance and Standard Penetration Resistance in Soils." *Earthquake Engineering and Soil Dynamics II: Recent Advances in Ground-Motion Evaluation*, J.L. Von Thun, Editor, Geotechnical Special Publication Vol. 20, 389–404.

Thelen, W.A., Clark, M., Lopez, C.T., Loughner, C., Park, H., Scott, J.B., Smith, S.B., Greschke, B., and Louie, J.N. (2006). "A Transect of 200 Shallow Shear-Velocity Profiles Across the Los Angeles Basin." *Bulletin of the Seismological Society of America*, 96 (3), 1055-1067.

Thompson, E.M., Baise, L.G., and Kayen, R.E. (2006). "Spatial Correlation of Shear-Wave Velocity within San Francisco Bay Sediments." *GeoCogress 2006.*

Thompson, E.M., Baise, L.G., and Kayen, R.E. (2007). "Spatial Correlation of Shear-Wave Velocity in the San Francisco Bay Area Sediments." *Soil Dynamics and Earthquake Engineering*, 27, 144-152.

Tokimatsu, K., Yamazaki, T., and Yoshimi, Y. (1986). "Soil Liquefaction Evaluations by Elastic Shear Moduli." *Soils and Foundations*, 26 (1), 25-35.

Wehling, T.M., Boulanger, R.W., Arulnathan, R., Harder, L.F., and Driller, M.W. (2003). "Nonlinear Dynamic Properties of a Fibrous Organic Soil." *Journal Geotechnical and Geoenvironmental Engineering*, 129 (10), 929-939.

Wills, C.J., and Clahan, K.B. (2006). "Developing a Map of Geologically Defined Site-Condition Categories for California." *Bulletin of the Seismological Society of America*, 96 (4A), 1483-1501.

Wills, C.J., Petersen, M., Bryant, W.A., Reichle, M., Saucedo, G.J., Tan, S., Taylor, G., and Treiman, J. (2000). "A Site-Conditions Map for California Based on Geology and Shear-Wave Velocity." *Bulletin of the Seismological Society of America*, 90 (6B), S187-S208.

Wills, C.J., and Silva, W. (1998). "Shear-Wave Velocity Characteristics of Geologic Units in California." *Earthquake Spectra*, 14 (3), 533-556.