PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Guidelines for Estimation of Shear Wave Velocity Profiles

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ABSTRACT

Characterization of the small-strain shear modulus and the shear wave velocity of soils and rocks is an integral component of various seismic analyses, including site classification, hazard analysis, site response analysis, and soil–structure interaction. The Next Generation Attenuation ground motion prediction equations use the shear wave velocity of the top 30 m of the subsurface profile (V_{S30}) as the primary parameter for characterizing the effects of sediment stiffness on ground motions. This report presents guidelines for estimating the shear wave velocity profiles in the absence of site-specific shear wave velocity data. This study consisted of a review of published correlations between shear wave velocity and predictor variables, such as, surface geology, standard penetration test N-values, cone penetration test resistance, and undrained shear strength. This report also presents a method for extrapolation of V_{S30} for sites where subsurface data does not extend to a depth of 30 m.

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1 Study Overview

Characterization of the stress-strain behavior of soils is an integral component of many seismic analyses, including site classification, hazard analysis, site response analysis, and soil–structure interaction. The shear modulus (G) of geomaterials is highly dependent upon strain level. The small-strain shear modulus (G_{max} or G_0) is typically associated with strains on the order of 10^{-3}% or less. With knowledge of G_{max}, the shear response at various levels of strain can be estimated using published modulus reduction (G/G_{max}) curves.

Shear wave velocity (V_S) is a valuable indicator of the dynamic properties of soil and rock because of its relationship with G_{max}, given by Equation (1.1):

$$G_{max} = \rho \cdot V_S^2 \tag{1.1}$$

where soil density (ρ) is the total unit weight of the soil divided by gravity (9.81 m/sec^2 or 32.2 ft/sec^2). G_{max} has units of force per length squared (i.e., kPa or psf).

G_{max} and V_S are primarily functions of soil density, void ratio, and effective stress, with secondary influences including soil type, age, depositional environment, cementation, and stress history [Hardin and Drnevich 1972a, b]. Table 1.1 summarizes the effect of increasing various parameters on V_S.

G_{max} can be measured in the laboratory using a resonant column device or bender elements. While the void ratio and stress conditions can be recreated in a reconstituted specimen, other factors—such as soil fabric and cementation—cannot [Kramer 1996]. Laboratory testing requires very high-quality, undisturbed samples. High-quality sampling and testing is quite expensive and is often not possible for cohesionless soils. Additionally, laboratory tests only measure G_{max} at discrete sample locations, which may not be representative of the entire soil profile.

Table 1.1 Effect of increase of various factors on G_{max} and V_S.*

Increasing Factor/Parameter	Influence on G_{max} and V_S
Confining Pressure or Overburden Stress ↑	Increases with σ'_{vo} ↑
Void Ratio ↑	Decreases with increased Void Ratio ↓
Geologic Age ↑	Increases with Geologic Age ↑
Cementation ↑	Increases with Cementation ↑
Overconsolidation Ratio ↑	Increases with OCR ↑
Strain Rate or Frequency of Cyclic Loading ↑	Increases with Strain Rate ↑

*Dobry and Vucetic [1987] as reported by EPRI [1991].

Unlike laboratory testing, geophysical tests do not require undisturbed sampling, maintain *in situ* stresses during testing, and measure the response of a large volume of soil. EPRI [1991)] and Kramer [1996] discuss various geophysical methods for measuring the shear wave velocities of geomaterials. Geophysical methods can be divided into two categories: invasive and non-invasive.

Invasive methods require drilling into the ground. Common invasive methods include: downhole logging, crosshole logging, suspension logging, and the seismic cone penetration test (SCPT). The SCPT is a modified downhole measurement in conjunction with the conventional cone penetration test (CPT). The SCPT has become more common in recent years because it is a relatively rapid and cost-effective method of measuring V_S. Site characterization can be achieved using the SCPT for approximately $4000 to $5000 (one day of testing).

Non-invasive geophysical methods include: spectral analysis of surface waves (SASW), seismic refraction, and seismic reflection. Table 1.2 presents a comparison and summary of each of these methods [Andrus et al. 2004].

In situ measurement of V_S has become the preferred method for estimating the small-strain shear properties and has been incorporated into site classifications systems and ground motion prediction equations, as discussed in the following two sections.

Table 1.2 Comparison of various *in situ* V_S measurement methods.

Feature	Measurement Method				
	Crosshole	Downhole & Seismic Cone Penetrometer	Suspension Logger	Spectral Analysis of Surface Waves	Surface Reflection/ Refraction
Number of holes required	2 or more	1	1	None	None
Quality control and repeatability[1]	Good	Good	Good	Good to fair; complex interpretation technique at sites with large velocity contrasts	Fair; often difficult to distinguish shear wave arrival
Resolution of variability in stiffness of soil deposits[2]	Good; constant with depth	Good to fair; decreases with depth	Good at depth; poor very close (3 to 6 m) to the ground surface	Good to fair; decreases with depth; provides good global average	Fair to poor; provides coarse global average
Major component of particle motion or wave propagation in vertical direction?	Yes, with vertically polarized shear waves	Yes, with test depth greater than distance between hole and shear-beam source	Yes, with refracted shear waves traveling parallel to vertical borehole	Yes, with vertical source	Yes, with horizontal source for reflection and vertical source for refraction
Limitations	Possible refraction problems; senses stiffer material at test depth; most expensive test method	Possible refraction problems with shallow layers; wave travel path increases with depth	Fluid-filled hole required; may not work well near the surface in cased holes and soft soils	Horizontal layering assumed; poor resolution of thin layers and soft material adjacent to stiff layers; no samples recovered	In refraction test, only works for velocity increasing with depth; no samples recovered
Other	Highly reliable test; measurements at each depth independent of other depths; well suited for tomographic imaging; independent checking of saturation with compression waves is possible	Penetration data also obtained from seismic cone; detailed layered profile with cone	Well suited for deep borehole testing; method assumes shear waves travel in undisturbed soil	Well suited for tomographic imaging large areas and testing difficult to penetrate soils	Well suited for screening large areas; independent checking of saturation with compression waves is possible

[1] Good quality depends on good equipment and procedural details, and good interpretation techniques for all methods.
[2] Resolution depends on test spacing for all methods.

1.1 SITE CLASSIFICATION

The Caltrans Seismic Design Criteria classifies sites based on V_S of the top 30 m of the soil profile (V_{S30}). Sites are divided into the six categories (Soil Profile Types A through F) presented in Table 1.3. The Caltrans site classes are consistent with those used by other codes and standards, including the National Earthquake Hazard Reduction Program [BSSC 2003], American Society of Civil Engineers [ASCE 2006, 2010], and the California Building Code [CBSC 2010].

For site classification, V_{S30} is calculated as the time for a shear wave to travel from a depth of 30 m to the ground surface, not the arithmetic average of V_S to a depth of 30 m. As shown in Equation (1.2), the time-averaged V_{S30} is calculated as 30 m divided by the sum of the travel times for shear waves to travel through each layer. The travel time for each layer is calculated as the layer thickness (d) divided by V_S.

$$V_{S30} = 30 / \Sigma (d/V_S) \tag{1.2}$$

For example, the V_{S30} for a soil profile containing 18 m of soft clay (V_S = 90 m/sec) over 12 m of stiff clay (V_S = 260 m/sec) would be calculated: 30 / (18 / 90 + 12 / 260) = 122 m/sec [Dobry et al. 2000]. The time-average method typically results in a lower V_{S30} than the weighted average of velocities of the individual layers: (90 · 18 + 260 · 12) / 30 = 158 m/sec.

Table 1.3 Caltrans/NEHRP soil profile types.

Site Class	Soil Profile Name	V_{S30}	SPT N-Value	Undrained Shear Strength
A	Hard Rock	> 5,000 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 ft (3 m) of soft clay, defined as soil with Plasticity Index > 20, water content > 40%, and undrained shear strength < 500 psf (25 kPa).

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

For cases where measured V_S data is not available, alternative site class definitions are provided in terms of standard penetration test (SPT) resistance for cohesionless soils and undrained shear strength for cohesive soils. Additional criteria, such as plasticity index, water content, organic content, collapse potential, and liquefaction potential, must also be considered when assigning a soil profile type.

The Caltrans Seismic Design Criteria specifies using uncorrected SPT N-values for site classification [Caltrans 2006]. It is common geotechnical practice to correct field SPT N-values for variations from standard practice (i.e., hammer energy, sampler type, borehole diameter, and rod length). For some applications, it is also common practice to normalize N-values to a reference overburden stress (typically, 1 atmosphere). For the purpose of site classification, it is appropriate to apply correction factors intended to account for deviations from the standard test method, such as hammer energy or non-standard samplers, but not appropriate to normalize N-values by the overburden pressure. In addition to site classification, V_S may be required for site-specific seismic evaluation or dynamic analysis when required by the seismic design criteria.

1.2 NEXT GENERATION ATTENUTATION PROJECT

The Next Generation Attenuation (NGA) project is a multidisciplinary research program coordinated by the Pacific Earthquake Engineering Research Center (PEER) Lifelines Program [Power et al. 2008]. Most previous ground motion prediction equations used broad site categories, such as “deep soil,” “soft rock,” and “hard rock,” to describe site conditions [Abrahamson et al. 2008]. The NGA ground motion relationships use V_{S30} as the primary parameter for characterizing the effects of sediment stiffness on ground motions.

The use of V_{S30} in place of generic soil and rock categories has the advantage that it is consistent with the site classification used in current building codes. This should not imply that 30 m is the key depth range for the site response, but rather that V_{S30} is correlated with the entire soil profile. Several of the NGA models incorporate the depth to V_S equal to 1 to 2.5 km/sec ($Z_{1.5}$ or $Z_{2.5}$) in addition to V_{S30} to distinguish between shallow soil sites, average depth soil sites, and deep soil sites [Abrahamson and Silva 2008].

Two of the NGA models [Abrahamson and Silva 2008; Chiou and Youngs 2008] recommend lower standard deviations in ground motion models where V_{S30} is measured rather than estimated. The standard deviation models for estimated V_{S30} incorporate approximately 30% uncertainty in V_{S30}; therefore, it is not necessary to consider a range of V_{S30}s if the estimated V_{S30} is accurate to within 30% [Abrahamson and Silva 2008].

1.3 V_{S30} ESTIMATION METHODOLOGY

Site-specific measurement of V_S is the preferred method of determination of V_{S30} and should be used whenever practical. In the absence of site-specific measurement, the following guidelines for estimating the V_S profiles based on correlations with surface geology (Chapter 2), *in situ* penetration tests (Chapters 3 through 5), and undrained shear strength (Chapter 6) may be used, recognizing that these indirect methods introduce greater uncertainty. Chapter 7 discusses a method for extrapolation of V_S data when data to a depth of 30 m is not available.

It is recommended to use multiple indirect methods when possible in selection of the design V_{S30} when direct measurements of the V_S profile are not available. Engineering judgment should also be used to assess (1) the quality of data, (2) agreement between methods, (3) the size and nature of project, and (4) the potential impacts of under-predicting or over-predicting V_{S30} on structural performance.

2 Geologic Considerations

Geologic processes influence the stiffness and compressibility geomaterials through loading and unloading cycles (sedimentation, glaciation, uplift, etc.), fluctuations in ground water level, desiccation due to wetting and drying cycles, freezing and thawing cycles, chemical reactions (precipitation, oxidation, etc.), and cementation.

Most soil deposits in California are Quaternary, with some older deposits dating to the Pliocene (late Tertiary). The Quaternary period is divided into Holocene and Pleistocene. Surficial bedrock units in California are generally Jurassic or younger. A geologic time scale is presented in Figure 2.1, with approximate boundaries between geologic epochs [USGS 2010].

Era	Period	Epoch	Years Ago
Cenozoic	Quaternary	Holocene	11,700
		Pleistocene	2.6 M
	Tertiary	Pliocene	
		Milocene	
		Oligocene	
		Eocene	
		Paleocene	65.5 M
Mesozoic	Cretaceous	Late	
		Early	145 M
	Jurassic	Late	
		Middle	
		Early	200 M
	Triassic	Late	
		Early	251 M
Paleozoic			

Figure 2.1 Geologic time scale.

Geologic considerations can aid in the estimation of V_S profiles through correlation between V_S and soil and rock properties, statistical correlations between V_{S30} and geologic units, and comparison of V_S measurements from sites within the same or similar geologic units.

2.1 ROCK PROPERTIES

The relationship between V_S and bedrock units in the San Francisco Bay Area was studied by Fumal [1978]. Fumal compiled V_S measurements for 59 sites in the San Francisco Bay Area. Fumal described the rock hardness and fracture spacing based on the classification system developed by Ellen et al. [1972]. Hardness descriptions were based on response to hand tests and blows with a geologic hammer. The hardness scale ranged from "friable," described as "material can be crumbled into individual grains by hand," to "hard," described as "hammer bounces off with solid sound." The fracture spacing scale ranged from "very close" (fracture spacing less than 1/2 in.) to "very wide" (fracture spacing greater than 36 in.). Fumal described the degree of weathering based on the classification system described in Aetron-Blume-Atkinson (1965). The weathering scale ranged from "decomposed" to "fresh." The classification system used by Fumal is consistent to the system described in the Caltrans' *Soil and Rock Logging, Classification, and Presentation Manual* [Caltrans 2007], with similar descriptors for hardness and weathering. The Caltrans system describes fracturing based on fracture density (fractures per in.) rather than fracture spacing.

The influence of rock properties on V_S is summarized in Table 2.1. As discussed in Sections 2.3 and 2.4, bedrock descriptions, which are typically found on Caltrans' boring logs, can be used to estimate V_{S30} from published correlations or from V_S measurements made within the same geologic unit at different sites.

Table 2.1 Effect of increase of rock properties on V_S.

Increasing Factor/Parameter	Influence on V_S
Fracture Spacing ↑	Increases with increased fracture spacing ↑
Fracture Density ↑	Decreases with increased fracture density ↓
Hardness ↑	Increases with increased hardness ↑
Weathering ↑	Decreases with increased weathering ↓

2.2 SOIL PROPERTIES

As discussed in Chapters 3 through 6, a number of correlations have been developed between V_S and commonly measured geotechnical properties (such as SPT and CPT penetration resistance, and undrained shear strength). For soil units, site-specific evaluation of V_S based on geotechnical data is the preferred methods. Incorporation of geologic age by use of Age Scaling Factors (ASFs) can further increase prediction accuracy [Ohta and Goto 1978; Andrus et al. 2007]. Similar to rock units, V_{S30} can be estimated by review of available V_S data from nearby sites within the same geologic unit and with similar geotechnical characteristics.

Statistical correlations between V_{S30} and surficial geology, as discussed in Section 2.3, can be used to confirm that estimates of V_S based on geotechnical data are within a reasonable range.

2.3 STATISTICAL CORRELATIONS BETWEEN VS30 AND SURFACE GEOLOGY

Several researchers have compiled datasets of V_S measurements and developed statistical distributions of V_{S30} (mean and standard deviation) for geologic units (or groups of similar units) in California. The most recent and comprehensive study was performed by Wills and Clahan [2006] in conjunction with the NGA project. This study divided sites into 19 geologically-defined categories and describes the statistical distribution of V_{S30} for each category in terms of mean and standard deviation for both normal and log normal distributions. Table 2.2 presents a geologic description and summary of statistical data for each category. Figure 2.2 presents an example of the distribution of measured V_{S30} for Holocene fine-grained alluvium and the mean and +/- one standard deviation V_S profiles.

Site-specific bedrock properties may be used to select the appropriate design value from the published data. For fresh, intact bedrock with wide fracture spacing, it would be appropriate to select a mean (or mean plus one standard deviation) V_{S30} for design. For highly fractured or deeply weathered rock, it would be appropriate to select a value of one to two standard deviations below the mean.

Table 2.2 Shear wave velocity characteristics of geologic units in California from Wills and Clahan [2006].

Geologic Unit	Geologic Description	No. of profiles	Mean Vs30	S.D.	Vs30 from Mean of ln	S.D. of ln	Mean of ln of Vs30
Qi	Intertidal Mud, including mud around the San Francisco Bay and similar mud in the Sacramento/San Joaquin delta and in Humboldt Bay	20	160	39	155	0.243	5.046
af/qi	Artificial fill over intertidal mud around San Francisco Bay	44	217	94	202	0.357	5.310
Qal, fine	Quaternary (Holocene) alluvium in areas where it is known to be predominantly fine	13	236	55	229	0.238	5.437
Qal, deep	Quaternary (Holocene) alluvium in areas where the alluvium (Holocene and Pleistocene) is more than 30 m thick; generally much more in deep basins	161	280	74	271	0.250	5.604
Qal, deep, Imperial V	Quaternary (Holocene) alluvium in the Imperial Valley, except sites in the northern Coachella Valley adjacent to the mountain front	53	209	31	207	0.135	5.335
Qal, deep, LA Basin	Quaternary (Holocene) alluvium in the Los Angeles basin, except sites adjacent to the mountain fronts	64	281	85	270	0.275	5.599
Qal, thin	Quaternary (Holocene) alluvium in narrow valleys, small basins, and adjacent to the edges of basins where the alluvium would be expected to be underlain by contrasting material within 30 m	65	349	89	338	0.244	5.825
Qal, thin, west LA	Quaternary (Holocene) alluvium in part of west Los Angeles where the Holocene alluvium is known to be thin, and is underlain by Pleistocene alluvium	41	297	45	294	0.150	5.684
Qal, coarse	Quaternary (Holocene) alluvium near fronts of high, steep mountain ranges and in major channels where the alluvium is expected to be coarse	18	354	82	345	0.223	5.845
Qoa	Quaternary (Pleistocene) alluvium	132	387	142	370	0.273	5.916
Qs	Quaternary (Pleistocene) sand deposits, such as the Merritt Sand in the Oakland area	15	302	46	297	0.171	5.697
QT	Quaternary to Tertiary (Pleistocene–Pliocene) alluvial deposits such as the Saugus Formation of southern California, Paso Robles Formation of central coast ranges, and the Santa Clara Formation of the Bay Area.	18	455	150	438	0.266	6.083
Tsh	Tertiary (mostly Miocene and Pliocene) shale and siltstone units such as the Repetto, Fernando, Puente, and Modelo Formations of the Los Angeles area	55	390	112	376	0.272	5.930
Tss	Tertiary (mostly Miocene, Oligocene, and Eocene) sandstone units such as the Topanga Formation in the Los Angeles area and the Butano sandstone in the San Francisco Bay area	24	515	215	477	0.386	6.169
Tv	Tertiary volcanic units including the Conejo Volcanics in the Santa Monica Mountains and the Leona Rhyolite in the East Bay Hills	3	609	155	597	0.240	6.392
Kss	Cretaceous sandstone of the Great Valley Sequence in the central Coast Ranges	6	566	199	539	0.332	6.291
serpentine	Serpentine, generally considered part of the Franciscan complex	6	653	137	641	0.204	6.464
KJf	Franciscan complex rock, including melange, sandstone, shale, chert, and greenstone	32	782	359	712	0.432	6.569
xtaline	Crystalline rocks, including Cretaceous granitic rocks, Jurassic metamorphic rocks, schist, and Precambrian gneiss	28	748	430	660	0.489	6.493

Wills and Clahan [2006].

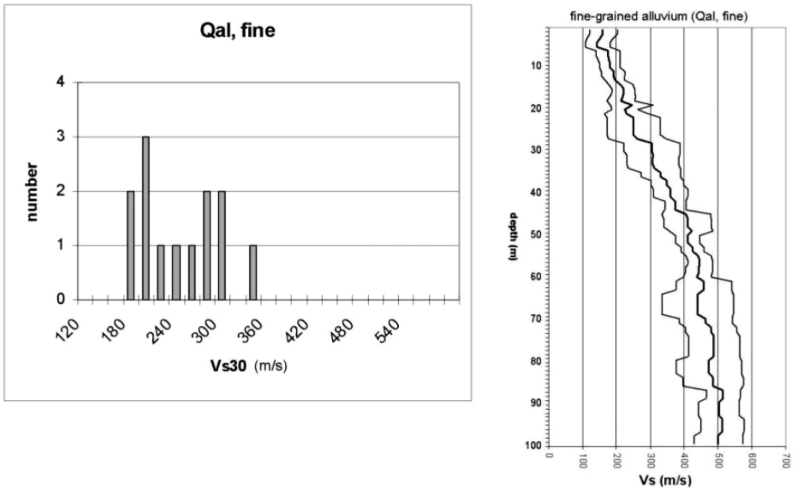

Figure 2.2 Histogram of V_{S30} and mean +/-1 standard deviation profiles for fine-grained alluvium [Wills and Calhan 2006].

Additional statewide resources include Wills and Silva [1998] and Wills et al. [2000]. Additional resources for the San Francisco Bay Area and northern California include Fumal [1978] and Holzer et al. [2005a; 2005b]. Campbell and Duke [1976], Campbell et al. [1979), Park and Elrick [1998], and Thelen et al. [2006] all provide estimates of V_{S30} for soil and bedrock units in southern California.

2.4 AVAILABLE SHEAR WAVE VELOCITY DATA

V_{S30} can be estimated based on review of existing V_S measurements. For rock units, estimation of V_S can be based on comparison of rock properties (fracture spacing, weathering, and hardness) at the project site relative to the measurement site. Similarly, for soil units, estimation of V_S can be based on comparison of the measured geotechnical data at the project site relative to the geotechnical data at the measurement site. The use of V_S data from other sites should be limited to sites within the same geologic unit and with an equal or greater degree of weathering and fracturing and/or similar geotechnical properties.

Sources of existing data include Caltrans' or other agencies' files, as well as, publicly available information. Sources of publicly available information are discussed in the following sections.

2.4.1 United States Geological Survey Open-File Reports

The United States Geological Survey (USGS) has published a number of Open File Reports (OFRs) containing velocity measurements for sites in California. Available OFRs are tabulated in Table 2.3. Download information for each report is included in the "References" section of this report. To aid in the search for data, the relevant Caltrans county abbreviations are listed in Column 3. A list of Caltrans county abbreviations may be found at: http://sv08data.dot.ca.gov/contractcost/map.html.

The OFRs 84-862 [Shields and White 1984], 02-107 [Borcherdt and Fumal 2002], and 03-191 [Boore 2003] are compilations of previous reports, with 03-191 being the most recent and comprehensive. The notes in Column 4 of Table 2.3 describe which OFRs are included in each compilation.

Table 2.3 Summary of USGS Open-File Reports.

Publication	Authors	Counties	Notes
OFR 75-564	Gibbs, et al.	SCL, SM	a
OFR 76-731	Gibbs, et al.	ALA, SCL, SM	a
OFR 81-399	Fumal, et al.	LA, ORA, VEN	a, b, c
OFR 82-407	Fumal, et al.	KER, SCL, SLO	a, c
OFR 82-833	Fumal, et al.	LA	a, b, c
OFR 84-681	Fumal, et al.	KER, LA, SB, SBD, VEN	a, c
OFR 84-562	Porcella	IMP, RIV, SD	a
OFR 89-630	Gibbs	RIV	a
OFR 90-248	Gibbs, et al.	MON, SLO	a
OFR 91-311	Fumal, et al.	ALA, CC, MON, MRN, SBT, SCL, SCR, SF, SJ, SM	
OFR 92-287	Gibbs, et al.	ALA, SCL, SF, SM	a
OFR 93-376	Gibbs, et al.	ALA, SCL, SF, SM	a
OFR 94-552	Gibbs and Fumal	ALA, SBT, SCL	a
OFR 94-222	Gibbs, et al.	ALA, MRN, SCL, SM	a
OFR 94-706	Gibbs, et al.	SF	a
OFR 96-261	Williams, et al.	LA	
OFR 99-446	Gibbs, et al.	LA, VEN	a, c
OFR 00-470	Gibbs, et al.	LA, SBD, VEN	a, c
OFR 01-506	Gibbs, et al.	LA, SBD	a
OFR 02-107	Borcherdt and Fumal	LA, ORA, SB, VEN	
OFR 02-203	Gibbs, et al.	HUM	a
OFR 03-191	Boore	Compilation of previous OFRs. See Notes Column.	
OFR 2005-1365	Kayen, et al	LA, ORA, RIV, SBD, RIV	
OFR 2005-1366	Kayen, et al	ALA, CC, KER, LA, MON, ORA, RIV, SBD, SBT, SCL, SF, SM, VEN	
OFR 2006-1014	Catchings, et al.	SCL	
OFR 2007-1039	Catchings, et al.	SCL	
OFR 2010-1168	Thompson, et al.	MON, SLO	

Notes: [a]Included in OFR 03-191
[b]Included in OFR 84-861
[c]Included in OFR 02-107

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2.4.2 USGS Seismic Cone Penetration Test Database

The USGS has performed approximately 600 SCPTs in California. The SCPT data is available on-line as tab-delimited text files and graphical logs in PDF format at: http://earthquake.usgs.gov/regional/nca/cpt/data/. The SCPT data was collected in the Alameda (211 SCPTs), Santa Clara (165), San Luis Obispo (37), Los Angeles (45), Solano (13), and San Bernardino (133) Counties.

Tip and sleeve resistance were measured at 0.05-m intervals. The V_S measurements were typically made at 2-m intervals. Further details are provided in USGS OFR 2010-1136 [Holzer et al. 2010] and USGS Fact Sheet 028-03 [Noce and Holzer 2003].

2.4.3 ROSRINE Boring Database

The ResOlution of Site Response Issues from the Northridge Earthquake (ROSRINE) project has collected data at approximately 60 sites in central and southern California. Information for each site generally includes: boring logs, geophysical logs, lab test results, photographs, and a site plan. The ROSRINE data may be downloaded from: http://geoinfo.usc.edu/rosrine.

2.4.4 NGA Flatfile

As part of the NGA project, the developers estimated V_{S30} at each of the approximately 1600 strong ground motion recording stations. The majority of these stations are located in California. Information about each site is contained in a spreadsheet or “flatfile.” The flatfile is searchable by longitude, latitude, or geologic unit. The flatfile also indicates the method of V_{S30} determination (i.e., measured, inferred from surface geology, etc.). The NGA flatfile and documentation may be downloaded from: http://peer.berkeley.edu/nga/flatfile.html.

3 Penetration-Based V_S Correlations

Various researchers have studied the relationships between V_S and penetration tests, such as the CPT, the SPT, and the Becker Penetration Test (BPT). As previously discussed, G_{max} and V_S are small-strain properties measured at shear strains on the order of 10^{-3}% or less. Penetration-based tests are typically large-strain measurements associated with failure of the soil surrounding the sampler or cone. Similar to small-strain soil properties, penetration-based tests are primarily dependent on void ratio, confining stress, and stress history. Even though G_{max} and penetration measurements are affected by soil behavioral factors occurring at opposite ends of the strain spectrum, this common association may be used to develop correlations between the two parameters [Mayne and Rix 1993].

In addition to penetration resistance, estimation of V_S is improved when additional parameters such as confining stress (depth), geology (depositional environment, aging, etc.), and soil type are considered [Sykora 1987].

3.1 OVERBURDEN NORMALIZATION

For many engineering applications, it is common practice to normalize measured CPT tip resistance (q_c) and SPT N-values to a reference effective overburden stress, typically 1 atmosphere (approximately 1 ton/ft^2 or 101 kPa). Several studies concluded that use of stress-normalized N- or q_c-values in V_S correlations proved to be considerably less accurate than correlations based on non-normalized values [Sykora and Stokoe 1983; Lodge 1994; Hasancebi and Ulusay 2007; Piratheepan 2002]. Additionally, for the purpose of site classification in accordance with design codes and calculation of V_{S30}, it is not appropriate to normalize penetration resistance for overburden stress.

For some applications, such as liquefaction triggering assessment, it may be necessary to normalize V_S estimates to a reference stress level. In such cases, V_S can be estimated from non-normalized penetration resistance, and then normalized for overburden.

3.2 EVALUATION OF CORRELATIONS

Correlations between penetration resistance and V_S are based on regression analysis of datasets. These datasets typically contain a significant amount of scatter in the measured data (as evident in Figures 4.1 through 4.9). Regression equations represent a best fit of the data. Correlation coefficients (r) are used to assess the strength of the relationships between variables. Higher correlation coefficients indicate greater agreement between two (or more) variables. Perfect correlation between variables would result in an "r" of 1.0. The coefficient of determination (r^2) can be interpreted as the proportion of the variance in "y" attributable to the variance in "x." For example, an r of 0.85 corresponds to an r^2 of 0.72, indicating that 72% of the variance of y is due to x.

The V_S correlations for SPT and CPT are presented in Chapters 4 and 5, respectively. Coefficients of determination are presented in Tables 4.2 through 4.7 and Table 5.3.

4 Standard Penetration Test Correlations

The SPT has historically been the most widely used *in situ* geotechnical test throughout the world. Researchers have studied the relationship between V_S and SPT N values since the 1960s.

The SPT practices vary significantly from region to region due to differences in equipment and procedures. In the United States, the SPT is generally performed in accordance with ASTM D 1586 [ASTM 2011]. It is common geotechnical practice to correct field SPT N-values for variations from standard practice (i.e., hammer energy, sampler type, borehole diameter, and rod length). Corrections are discussed extensively in literature [Martin and Lew 1999; Youd et al. 2001; Idriss and Boulanger 2008].

As discussed in the previous section, it is common engineering practice to normalize SPT N-values to a reference effective overburden stress. For the purpose of site classification, estimation of V_S from penetration data, and/or calculation of V_{S30}, it is not appropriate to normalize penetration resistance for overburden stress.

Section 4.1 presents a brief summary of previous studies between V_S and SPT N-value. Section 4.2 presents V_S-SPT correlation equations developed by various researchers.

4.1 PREVIOUS STUDIES

The following sections present a brief review of available published studies between SPT and V_S. Table 4.1 summarizes pertinent details of previous studies: location, number of sites, number of borings, number of data pairs, and V_S measurement method. A brief discussion of each study is presented in the following sections.

Table 4.1 Studies between the Standard Penetration Test and V_S.

Study	Location	# Sites	# Borings	# Data Pairs	Method of V_S Measurement
Kanai (1966)	Japan	----	----	70	Microtremor
Shibata (1970)	Japan	----	----	----	Review of Previous Studies
Ohba & Toriuma (1970)	Japan	----	----	----	Rayleigh Wave Velocity Measurement
Ohsaki & Iwasaki (1973)	Japan	200	----	220	Downhole
Ohta & Goto (1978)	Japan	----	----	289	Seismic Prospecting
Imai & Tonouchi (1982)	Japan	250	386	1,654	OYO Suspension
Seed, Idriss, & Arango (1983)	----	----	----	----	----
Sykora & Stokoe (1983)	United States	----	----	229	Crosshole
Lin, et al. (1984)	Taipei Basin, Taiwan	----	----	----	----
Jinan (1987)	Shanghai, China	1	6	98	Crosshole
Yoshida et al. (1988)	Japan	----	----	----	Geophones
Lee (1992)	Taipei Basin, Taiwan	----	----	491	Downhole
Andrus (1994)	Idaho, United States	4	----	----	Crosshole, SASW
Dickenson (1994)	San Francisco Bay Area	----	----	----	----
Lum & Yan (1994)	Hugh Keenlyside Dam, Canada	1	----	----	Crosshole, Downhole, SASW
Sisman (1995)	----	----	----	----	----
Iyisan (1996)	----	----	----	----	----
Jafari et al. (1997)	----	----	----	----	----
Rollins et al. (1998)	----	7	----	291	----
Pitilaki et al. (1999)	Greece	1	----	321	Crosshole, Downhole, Seismic Refraction
Kiku et al. (2001)	----	----	----	----	----
Jafari et al. (2002)	----	----	----	----	----
Hasancebi & Ulusay (2007)	Yenisehir, Turkey	1	9	97	Seismic Refraction
Piratheepan (2002)	California, Canada, Japan, Taiwan	----	----	44	----

4.1.1 Early Studies

The earliest published studies between SPT N-value and V_S were performed by Japanese researchers in the 1960s and early 1970s. The original studies were not available for review; however, Sykora [1987] provided a brief review of several early studies including Kanai [1966], Shibata [1970], Ohba and Toriuma [1970], and Ohsaki and Iwasaki [1973]. The hammer energy ratio for these studies was not stated. Seed et al. (1985) reported that typical Japanese SPT practices result in approximately 67% of the theoretical SPT free-fall energy.

Kanai [1966] developed a relationship (Equation [4.43]) between V_S and N-value based on approximately 70 microtremor measurements performed in predominantly sandy soils. N-values included in the Kanai dataset ranged from approximately 1 to 50 blows per foot (bpf).

Shibata [1970] combined the results of previous studies in the relationship between relative density and N-value and theoretical studies between V_S, relative density, and effective stress of sands into one relationship between V_S and N-value [Equation (4.44)].

Ohba and Toriuma [1970] developed an empirical relationship [Equation (4.1)] between V_S and N-value for alluvial soils in the vicinity of Osaka, Japan. This study was reported by Ohsaki and Iwasaki [1973]; no further information was reported [Sykora 1987].

Ohsaki and Iwasaki [1973] performed statistical analyses on over 200 sets of data from seismic explorations (predominantly down-hole) throughout Japan. Ohsaki and Iwasaki developed relationships between N-value and G. The dataset included Holocene, Pleistocene, and Tertiary (Pliocene) soils with N-values ranging from approximately 1 to 100 bpf. Figure 4.1 presents a plot of Ohsaki and Iwasaki's G versus N-value data, as presented in Sykora [1987]. Based on the Ohsaki and Iwasaki shear modulus correlation equation, along with the assumption of a typical unit weight for Japanese soils of 112.4 pcf, Sykora [1987] developed a relationship between SPT N-value and V_S [Equation (4.2)]. Note that Ohsaki and Iwasaki use the term diluvium, which is considered to be synonymous with Pleistocene alluvium [Sykora 1987; Bates and Jackson 1984].

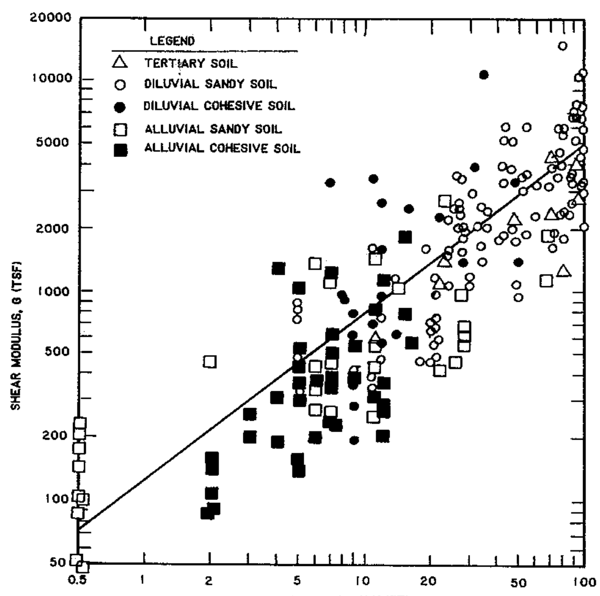


Figure 4.1 Shear modulus versus SPT N-value [Ohsaki and Iwasaki 1973].

4.1.2 Ohta and Goto [1978]

Ohta and Goto [1978] developed empirical V_S correlation equations based on 289 data pairs obtained mostly from alluvial plains in Japan. N-values in the dataset ranged from approximately 2 to 200 bpf. Ohta and Goto identified four index properties that were related to V_S: SPT N-value, depth, geologic age, and soil type. Data points were divided categories based on geologic age (Holocene and Pleistocene) and soil type (clay, fine sand, medium sand, coarse sand, sand and gravel, and gravel). Silty soils were placed in the clay category.

Ohta and Goto performed regression analyses for each index property as well as on each combination of index properties (a total of 15 combinations). Based on comparison of regression coefficients, they determined that the strongest correlations included all four index properties.

The Ohta and Goto "All Soils" equations—Equations (4.3) through (4.5) and (4.14) though (4.16)—represent the regression analyses that did not isolate soil type (i.e., all six soil types were grouped together). Similarly, the Quaternary equations correspond to regression analyses where geologic age was not considered (i.e., Holocene and Pleistocene soils were grouped together). The data presented in Figure 4.2 represents the regression analysis that considered N-value as the only variable [Equation (4.3)].

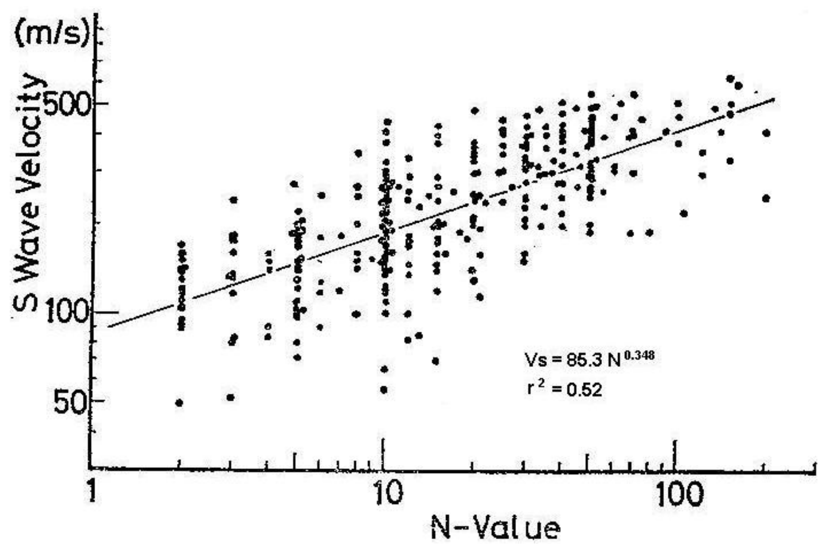


Figure 4.2 V_S **versus SPT N-value [Ohta and Goto 1978].**

4.1.3 Imai and Tonouchi [1982]

Imai and Tonouchi [1982] analyzed the largest dataset, containing 1654 data pairs from 386 borings at 250 sites throughout Japan. Imai and Tonouchi developed V_S correlation equations based on N-value, soil type, and geologic age. N-values ranged from less than one bpf to nearly 400 bpf. The complete dataset and regression line [Equation (4.6)] are presented in Figure 4.3 below.

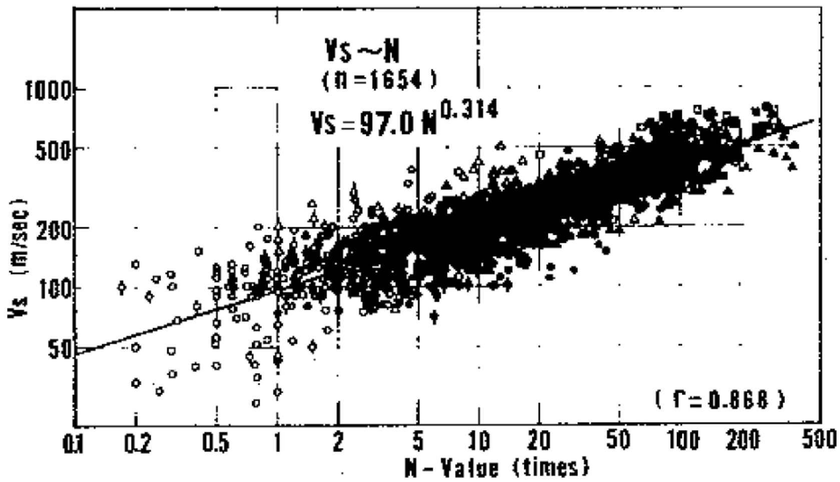


Figure 4.3 V_S versus SPT N-value [Imai and Tonouchi 1982].

4.1.4 Seed et al. (1983)

Seed et al. [1983] developed a relationship for G_{max} for sands as a function of N-value based on a review of previous studies. Based on their G_{max} equation and an assumed unit weight of 120 pcf, Seed et al. proposed Equation (4.50) for estimating V_S from SPT data.

4.1.5 Sykora and Stokoe [1983]

Sykora and Stokoe [1983] developed a correlation equation between V_S and N-value for granular soils [Equation (4.47)] based on 229 data points obtained from crosshole and interval downhole logging methods. The SPT energy ratio was not reported. The authors note that their data were not normalized to a uniform energy. The Sykora and Stokoe database is included in Appendix A of Lodge [1994]. Based on review of reported N and N_{60} values, the SPT hammer energy ratio ranged from 50 to 80%. N-values ranged from approximately 1 to 350 bpf. The dataset and regression line [Equation (4.47)] are presented in Figure 4.4.

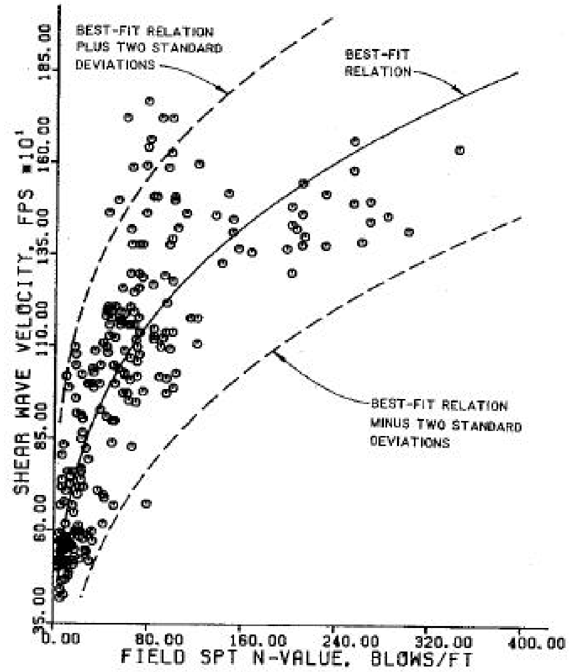


Figure 4.4 V_S **versus SPT N-value [Sykora and Stokoe 1983].**

4.1.6 Seed et al. [1986]

Seed et al. [1986] developed a relationship for granular soils by simplifying a previous equation by Ohta and Goto [1976]. Since Seed et al. were primarily interested in liquefiable soils, they developed Equation (4.71) based on Ohta and Goto's equation using average coefficients for Quaternary soils and granular soils and modifying the equation for use with N_{60}.

4.1.7 Jinan [1987]

Jinan (1987) studied the relationship between V_S and SPT N-value for a site in Shanghai, China. The soil profile consisted of approximately 25 m of relatively soft, Holocene clays and silts over firmer Pleistocene clays, silts, and sands to a depth of approximately 60 m, the maximum depth explored. SPT N-values in the top 20 m were generally less than 5 bpf and generally ranged from 10 to 40 bpf below a depth of 20 m. The SPT energy ratio was not reported.

4.1.8 Yoshida et al. [1988]

The original Yoshida et al. [1988] study was not available; details of the study are described in Piratheepan [2002]. Yoshida et al. performed Large Penetration Tests (LPTs) and V_S measurements on 2-m-diameter by 1.5-m-high laboratory samples with different grain-size distributions, densities, and overburden pressures. The three soil types studied were poorly graded fine sand, poorly graded fine to coarse sand, and well-graded gravelly sand. Measured blow counts ranged from approximately 5 to 120 bpf. The LPT hammer energy was not reported.

4.1.9 Lee [1992]

Lee [1992] presented various V_S correlation equations based on combinations of N-value, depth, effective stress, soil type, and geologic age for soils in the Taipei basin. Lee reports an approximate SPT energy ratio of 73.5% efficiency for Taiwanese SPT practices based on an earlier study by Wang et al. [1986]. Lee does not present specific data points, but does plot the proposed correlation equations for N-values ranging from 1 to 50 bpf. Lee also reports a correlation equation [Equation (4.8)] between V_S and N-value for All Soils proposed by Lin et al. [1984]. This study was performed in the Taiwan area; no further details were reported.

4.1.10 Andrus [1994]

Piratheepan [2002] describes the details of the Andrus [1994] study. Andrus developed V_S regression equations based on data collected at four gravels sites in Idaho where liquefaction had occurred during the 1983 Borah Peak Earthquake. Soils at two of the sites consisted of Holocene fluvial sandy gravels with few fines. Soils at the other two sites consisted of sandy, silty gravel, likely of Pleistocene age. Energy measurements were performed to measure the SPT efficiency. SPT N-values were normalized to 60% energy ratio; correlation equations were presented in terms of N_{60}. Andrus developed Equations (4.95) and (4.99) for Holocene and Pleistocene sandy gravels, respectively.

4.1.11 Dickenson [1994]

Dickenson [1994] studied the relationships between V_S and SPT N-values of sandy soils in the San Francisco Bay Area. Dickenson included data from Fumal [1978] as well as new data. The SPT energy ratio was not reported. N-values ranged from approximately 5 to 90 bpf. Dickenson's dataset and regression equation [Equation (4.48)] are shown in Figure 4.5. For comparison, Figure 4.5 also shows the Sykora and Stoke [1983] equation [Equation (4.47)] and the Seed et al. [1983] equation (Equation [4.50]). The three equations are very similar at low SPT N-values. Above approximately 20 bpf Dickenson's equation plots below the other two, with Seed et al. being the highest.

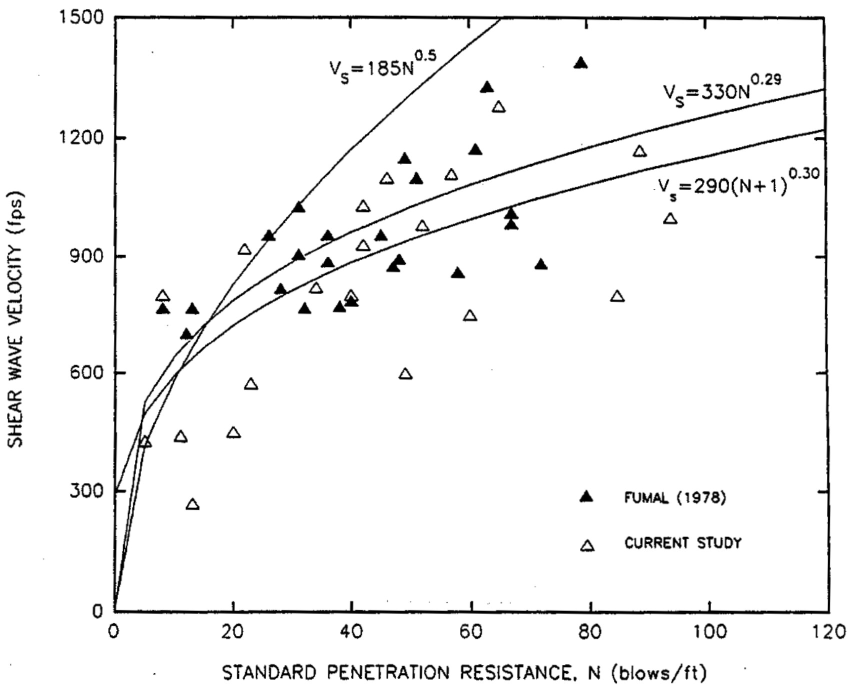


Figure 4.5 V_S **versus SPT N-value [Dickenson 1994].**

4.1.12 Lum and Yan [1994]

The Lum and Yan [1994] study is described in Piratheepan [2002]. Lum and Yan developed a regression equation for gravelly soils at the Hugh Keenlyside Dam on the Columbia River in Canada. Soils consisted of unconsolidated, fluvial, and glaciofluvial sands; gravels and sand; and gravel fill. Field measurements included SPT, BPT, and crosshole, downhole, and SASW V_S measurements. Equivalent SPT N_{60}-values were determined based on the BPT–SPT regression equations by Harder and Seed [2005]. N_{60}-values ranged from approximately 5 to 50 bpf.

4.1.13 Rollins et al. [1998]

Rollins et al. [1998] developed correlation equations between V_S and N_{60} for Holocene and Pleistocene gravels [Equations (4.98) and (4.102)] based a review of previous studies and datasets including: Ohta and Goto [1978], Imai and Tonouchi [1982], Lum and Yan [1994], Andrus and Youd [1987], Harder [1988], Andrus [1994], Sy et al. [1995], and Diehl and Rollins [1997]. Much of the data was based on N_{60}-values estimated from BPTs. Plots of V_S versus N_{60} for Holocene and Pleistocene gravels are shown in Figure 4.6.

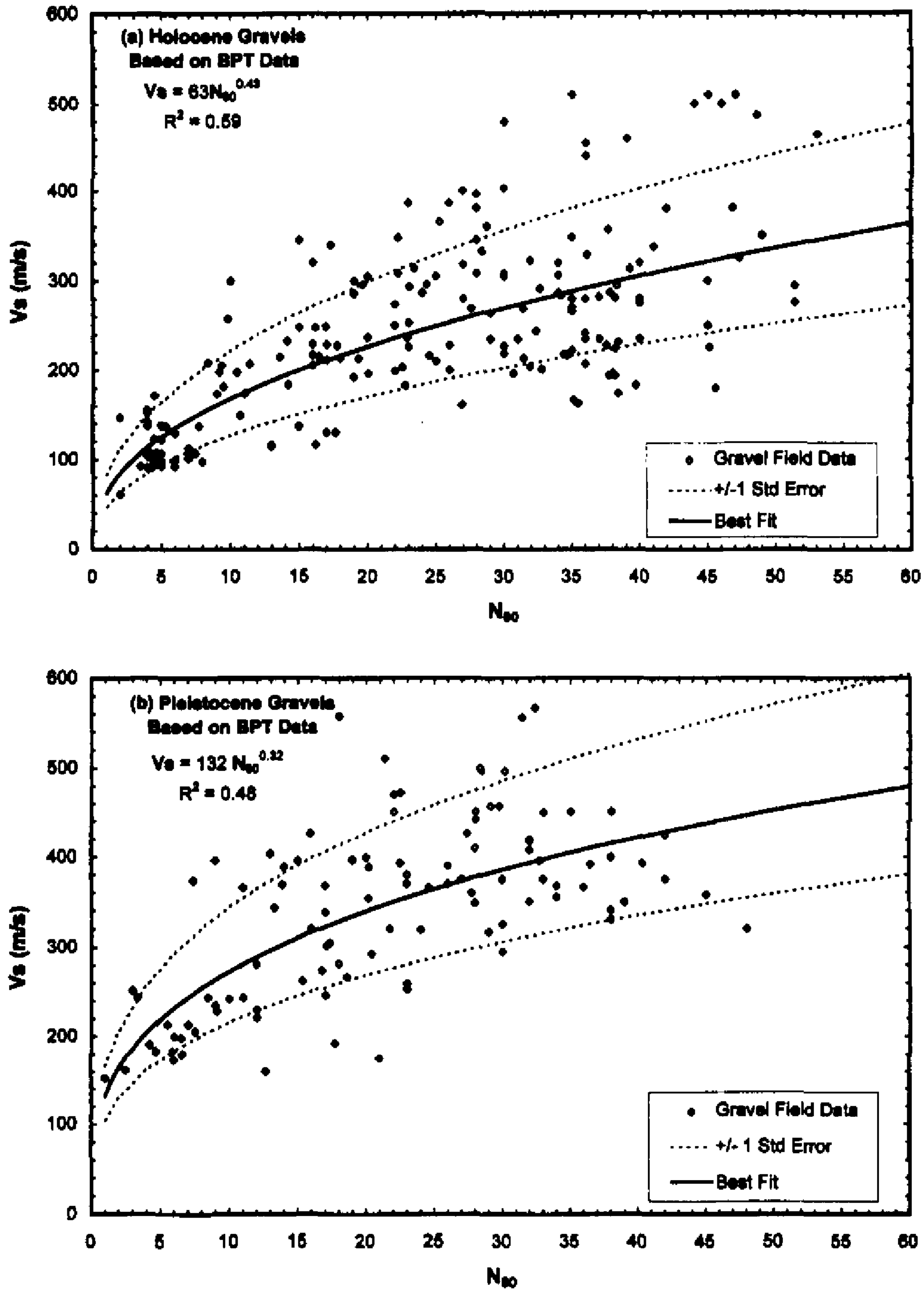


Figure 4.6 **V_S versus SPT N_{60} [Rollins et al. 1998].**

4.1.14 Pitilakis et al. [1999]

Pitilakis et al. [1999] developed correlation equations between V_S and N_{60} for clays and for silts and sands [Equations (4.27) and (4.52)] based on over 300 pairs of SPT N-value and V_S measurements (crosshole, downhole, and seismic refraction) at the EURO-SEISTEST test site near Thessaloniki, in northern Greece. The two datasets and regression equations are shown in Figure 4.7.

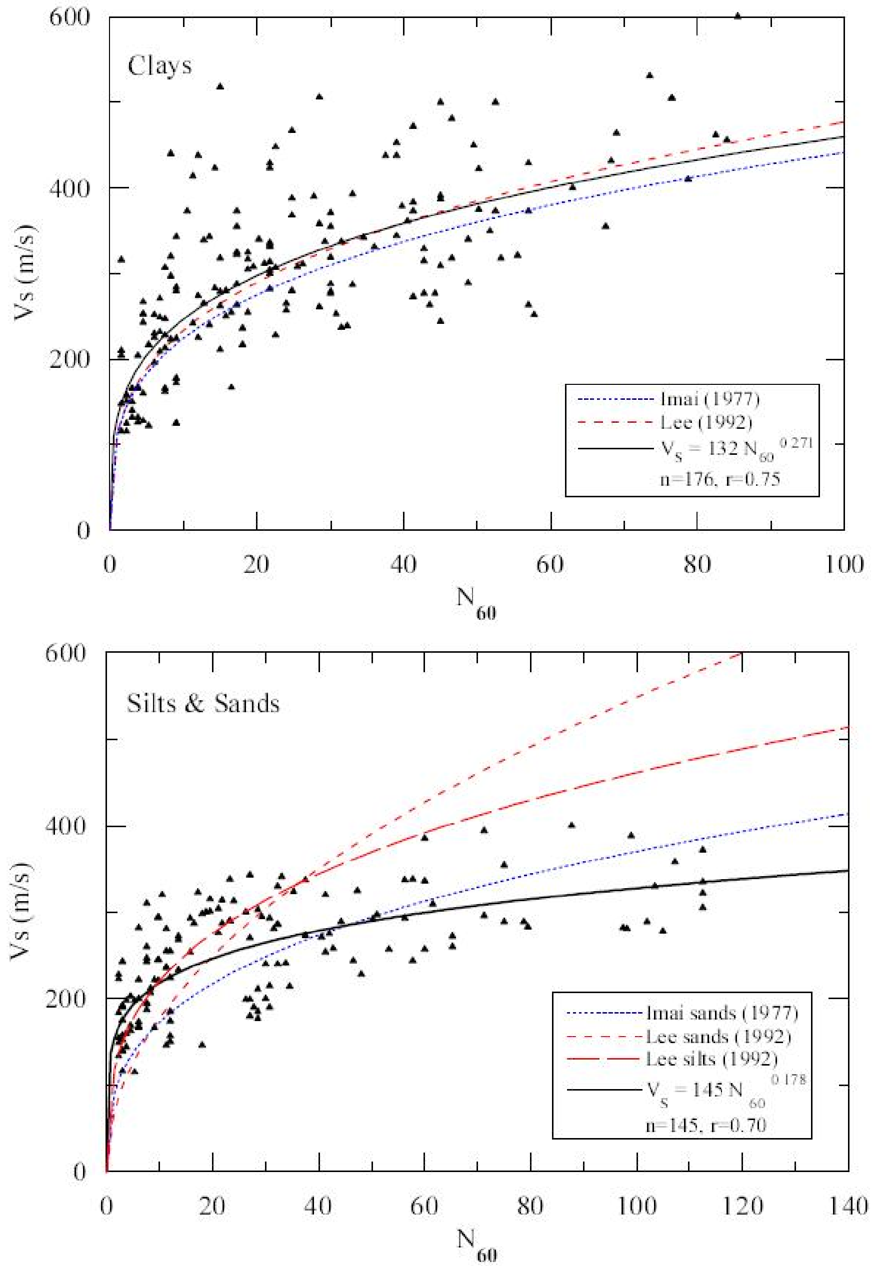


Figure 4.7 V_S versus SPT N_{60} [Pitilakis et al. 1999].

4.1.15 Piratheepan [2002]

Piratheepan [2002] developed V_S correlation equations based on data from sites in the United States, Canada, and Japan. Piratheepan developed equations for Holocene sands with varying fines content based on N_{60} and depth [Equations (4.74) through (4.76)]. N_{60}-values in the Piratheepan database generally ranged from 5 to 50. Piratheepan's data and Equation (4.76) are presented in Figure 4.8.

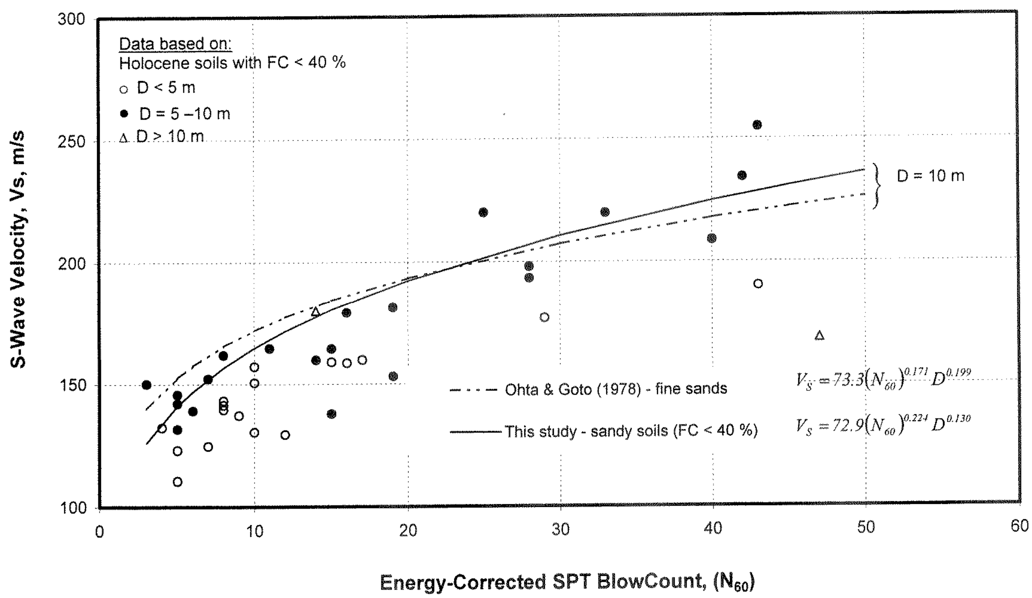


Figure 4.8 V_S versus SPT N_{60} for Holocene Sands [Piratheepan 2002].

4.1.16 Hasancebi and Ulusay [2007]

Hasancebi and Ulusay [2007] investigated the relationship between V_S and N-value at a site in Yenisehir, Turkey. Yenisehir is located within an alluvial basin. Seismic velocities were measured using seismic refraction. The SPT energy ratio was not reported; however, V_S correlation equations were given based on both N and N_{60}. N-values generally ranged from 5 to 45 bpf. Data points and regression equations for All Soils [Equation (4.13)], sands [Equation (4.49)], and clays [Equation (4.29)] are presented in Figure 4.9. Hasancebi and Ulusay also included correlation equations from previous studies: Equation (4.9) from Sisman [1995]; Equation (4.10) from Iyisan [1996]; Equation (4.11) from Jafari et al. [1997]; Equation (4.12) from Kiku et al. [2001]; and Equation (4.28) from Jafari et al. [2002]. Details of these studies, such as SPT energy ratio and geology, were not reported.

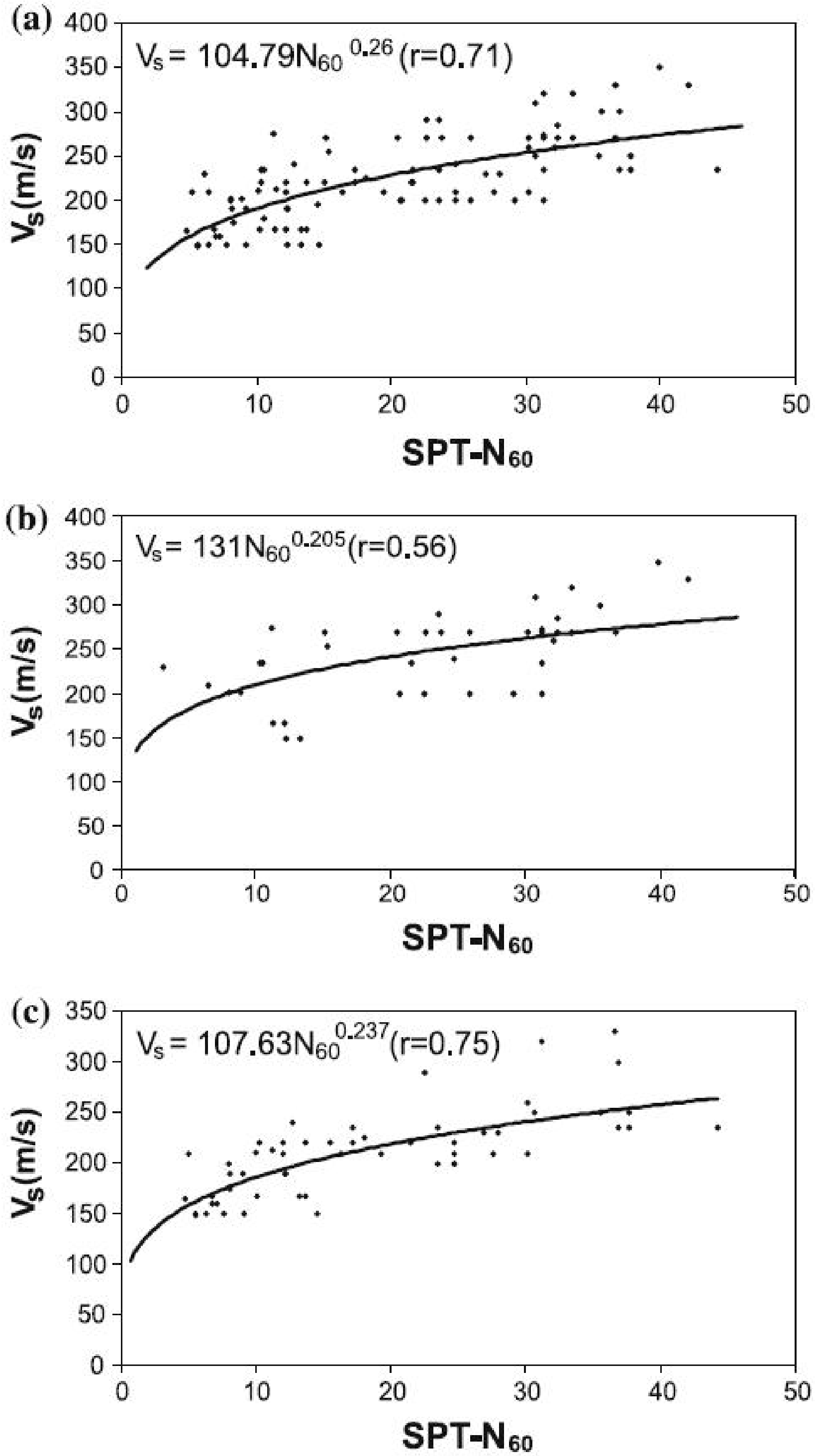


Figure 4.9 V_S **versus SPT** N_{60} **for (a) all Soils, (b) sands, and (c) clays [Hasancebi and Ulusay 2007].**

4.2 CORRELATION EQUATIONS

Correlation equations from the studies discussed above are presented in the following sections for All Soils, Clays and Silts, Sands, and Gravels. Each section contains two tables: the first for V_S–N correlations, and the second for V_S–N–Stress (or depth) correlations. The equations presented in the fourth column of each table have been modified to use consistent units, but are otherwise unchanged. The V_S, *in situ* effective stress, and depth are presented in units of m/sec, kPa, and m, respectively.

One of the primary variables in the SPT is the amount of energy transmitted to the sampler, which depends on the hammer type and release mechanism. The hammer energy ratio is defined as the amount of energy transmitted to the sampler divided by the theoretical maximum SPT energy (350 ft-lbs, or 140 lbs dropped at through a height of 30 in.). In an attempt to minimize the variability, SPT N-values are often converted to a uniform reference energy ratio of 60% of the theoretical SPT energy (N_{60}). The reported (or assumed) hammer energy ratios for each study are reported in Column 7 of Tables 4.2 through 4.9. The original equations have been modified for use with N_{60} values and are presented in Column 8. The tables also include available information on geologic age, deposition, number of data pairs, and coefficients of determination (r^2).

The SPT N_{60}-Stress equations generally provide better correlation with V_S based on comparison of coefficients of determination from studies that included equations with and without stress or depth terms. The V_S-stress equations generally follow the form of the equation:

$$V_S = a \cdot N_{60}^{\,b} \cdot \sigma'_v{}^{c}$$

Based on our review of previous correlation equations, representative equations for each soil type were developed. The new equations approximate the average value from several of the stronger previously proposed equations. As such they are not site specific and should only be considered to provide an estimate of V_S for the given soil type. The strength of previous correlations was generally judged based on the size of the dataset, coefficients of determination, and documentation of hammer energy. Further discussion of the new correlation equations is presented in the following sections.

4.2.1 All Soils

A summary of SPT–V_S correlation equations for All Soils is presented in Table 4.2 [Equations (4.1) through (4.13)]. The modified N_{60} equations are plotted on Figure 4.10. SPT–Stress–V_S correlation equations are presented in Table 4.3 [Equations (4.14) through (4.19)] and Figure 4.11.

Table 4.2 PT–V_S correlation equations for all soils: Equations (4.1) through (4.13).

Study	Geology		V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
	Age[a]	Deposition[b]						
Ohba & Toriuma (1970)	----	A	$85.3\ N^{0.31}$	----	----	67[c]	$82.5\ N_{60}^{0.31}$	(4.1)
Ohsaki & Iwasaki (1973)	----	----	$81.4\ N^{0.39}$	220	----	67[c]	$78.0\ N_{60}^{0.39}$	(4.2)
Ohta & Goto (1978)	Q	A	$85.3\ N^{0.35}$	----	0.52	67[c]	$82.1\ N_{60}^{0.35}$	(4.3)
Ohta & Goto (1978)	H	A	$92.2\ N^{0.27}$	----	0.61	67[c]	$89.5\ N_{60}^{0.27}$	(4.4)
Ohta & Goto (1978)	P	A	$134.2\ N^{0.27}$	----	0.61	67[c]	$130.3\ N_{60}^{0.27}$	(4.5)
Imai & Tonouchi (1982)	H, P, T	A, F	$97.0\ N^{0.31}$	1,654	0.75	67[c]	$93.7\ N_{60}^{0.31}$	(4.6)
Imai & Tonouchi (1982)	T	----	$109.0\ N^{0.32}$	108	0.51	67[c]	$105.2\ N_{60}^{0.32}$	(4.7)
Lin et al. (1984)	----	----	$65.6\ N^{0.50}$	31	----	73.5[d]	$62.0\ N_{60}^{0.50}$	(4.8)
Sisman (1995)	----	----	$32.8\ N^{0.51}$	----	----	60[e]	$31.0\ N_{60}^{0.51}$	(4.9)
Iyisan (1996)	----	----	$51.5\ N^{0.52}$	----	----	60[e]	$48.6\ N_{60}^{0.52}$	(4.10)
Jafari et al. (1997)	----	----	$22.0\ N^{0.85}$	----	----	60[e]	$20.0\ N_{60}^{0.85}$	(4.11)
Kiku et al. (2001)	----	----	$68.3\ N^{0.29}$	----	----	60[e]	$66.1\ N_{60}^{0.29}$	(4.12)
Hasncebi & Ulusay (2007)	Q	A	$90.0\ N^{0.31}$	----	0.53	----	$104.8\ N_{60}^{0.26}$	(4.13)

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary, T = Tertiary

[b]Geologic Deposition: A = Alluvium, F = Fill

[c]SPT energy ratio assumed to be 67% for Japanese practices.

[d]SPT energy ratio assumed to be 73.5% for Taiwanese practices.

[e]SPT energy ratio unknown. Assumed to be 60%.

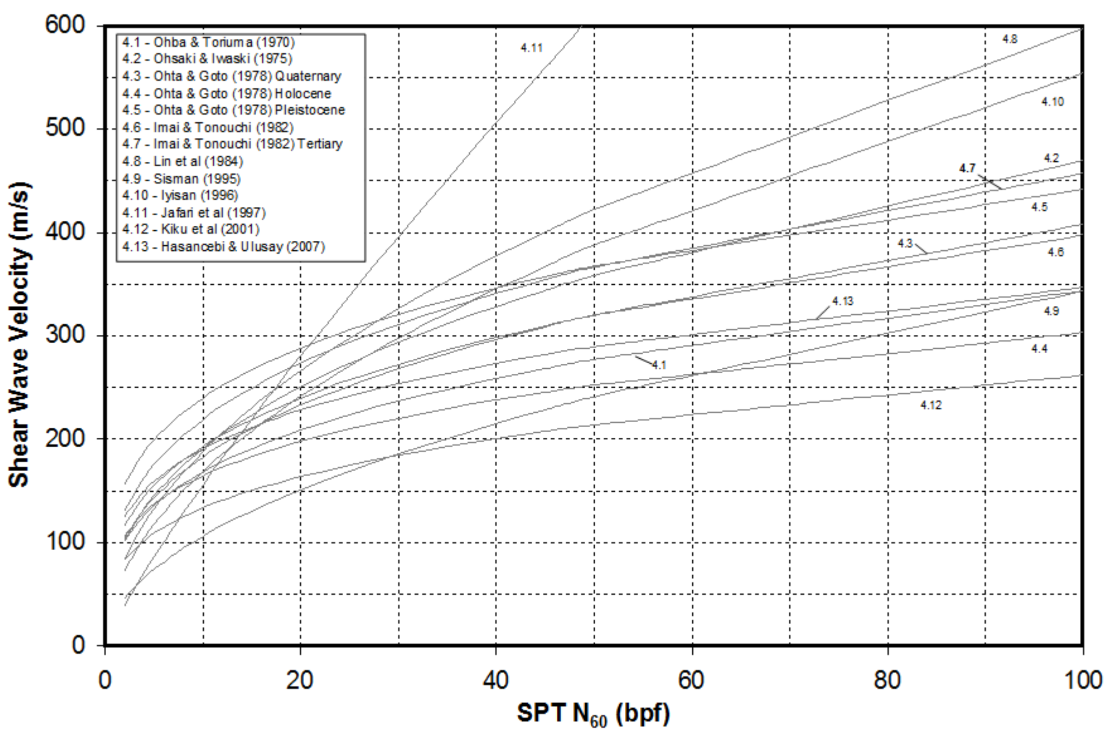


Figure 4.10 SPT N_{60}–V_S correlation equations for all soils.

This study included development of representative equations based on a review of previous studies. The proposed equations for each soil type follow the functional form given in Section 4.2. Only one previous study [Ohta and Goto 1978] had proposed All Soils-V_S correlations in terms of SPT N-values and either stress or depth.

Development of the new equations required converting the uncorrected SPT N-values to N_{60} and converting the depth term to effective stress. SPT N-values were converted to N_{60} based on the assumption the Japanese SPT practices generally deliver approximately 67% of the theoretical SPT energy [Seed et al. 1985]. The depth term was converted to effective stress by assuming typical depths to ground water of 5 to 10 m and assuming densities of 1.84 and 1.92 mg/m^3 (115 pcf and 120 pcf) for soils above and below the ground water table, respectively.

The Ohta and Goto equations and the newly developed equations (bold) are plotted in Figure 4.11. The new equations are generally within a few percent of the values predicted by the Ohta and Goto equations, with the greatest differences of up to 15% corresponding at low blow counts (less than approximately 5 bpf) and low overburden stress.

Table 4.3 SPT–Stress–V_S correlation equations for all Soils: Equations (4.14) through (4.19).

Study	Geology Age[a]	Geology Deposition[b]	V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
Ohta & Goto (1978)	Q	A	$61.6\ N^{0.25}\ D^{0.22}$	----	0.67	67[c]	$59.9\ N_{60}^{0.25}\ D^{0.22}$	(4.14)
Ohta & Goto (1978)	H	A	$68.4\ N^{0.21}\ D^{0.19}$	----	0.72	67[c]	$66.9\ N_{60}^{0.21}\ D^{0.19}$	(4.15)
Ohta & Goto (1978)	P	A	$89.5\ N^{0.21}\ D^{0.19}$	----	0.72	67[c]	$87.5\ N_{60}^{0.21}\ D^{0.19}$	(4.16)
This Study	Q	----	----	----	----	----	$30.0\ N_{60}^{0.215}\ \sigma'_v{}^{0.275}$	(4.17)
This Study	H	----	----	----	----	----	$26.0\ N_{60}^{0.215}\ \sigma'_v{}^{0.275}$	(4.18)
This Study	P	----	----	----	----	----	$34.0\ N_{60}^{0.215}\ \sigma'_v{}^{0.275}$	(4.19)

D measured in m; σ'_v measured in kPa

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary

[b]Geologic Deposition: A = Alluvium

[c]SPT energy ratio assumed to be 67% for Japanese practices.

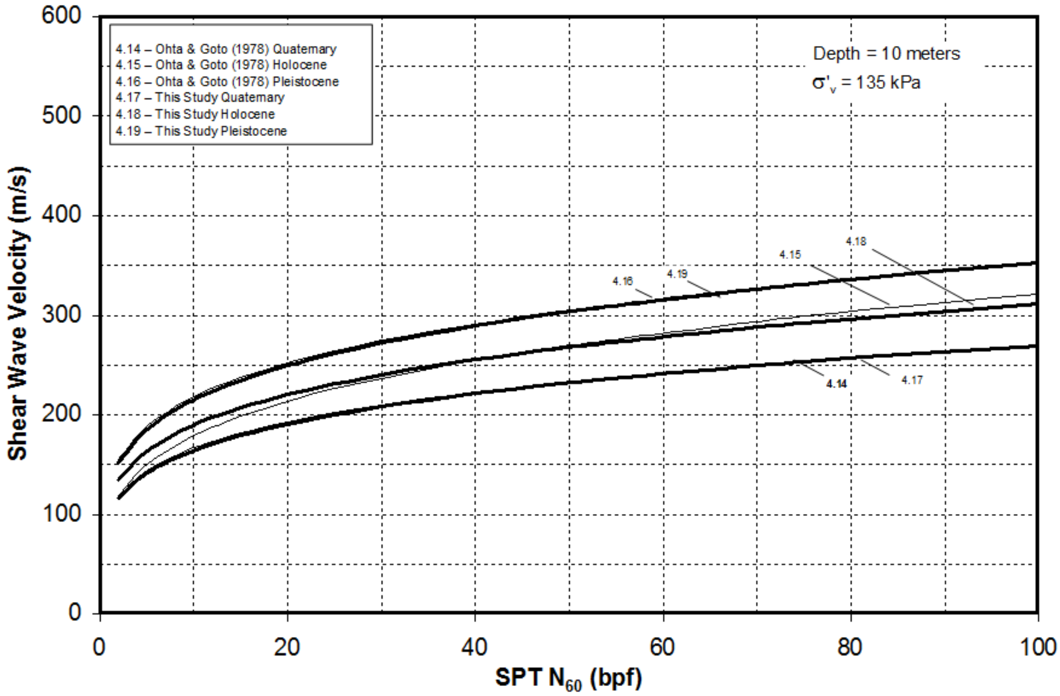


Figure 4.11 SPT N_{60}–Stress–V_S Correlation equations for all soils.

4.2.2 Clays and Silts

A summary of SPT–V_S correlation equations for clays and silts are presented in Table 4.4 [Equations (4.20) through (4.33)]. The modified N_{60} equations are plotted on Figure 4.12. SPT–Stress–V_S correlation equations are presented in Table 4.5 [Equations (4.34) through [4.42]) and Figure 4.13.

Following the methodology in the introduction to Section 4.2, a single set of representative equations was developed for clays and silts. Equation (4.41) was developed for Holocene clays and silts by approximating the average of the Ohta and Goto [1978] Holocene clay equation [Equation (4.35)] and the Lee [1992] silt and clay equation [Equation (4.39)]. Ohta and Goto were the only researchers to propose correlation equations for Quaternary and Pleistocene clays and silts that include a depth or effective stress term. Quaternary [Equation (4.40)] and Pleistocene [Equation (4.42)] clay and silt equations were developed by multiplying Equation (4.41) by ASFs of 1.13 and 1.26, respectively. The ASFs were selected based on a review of previous studies. ASFs are discussed further in Section 4.3. The recommended equations are shown bold on Figure 4.13.

Table 4.4 SPT–Vs correlation equations for clays and silts: Equations (4.20) through (4.33).

Study	Soil Type	Geology Age[a]	Geology Deposition[b]	V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
Ohta & Goto (1978)	Clay	Q	A	$85.6\ N^{0.34}$	----	0.53	67[c]	$82.4\ N_{60}^{0.34}$	(4.20)
Ohta & Goto (1978)	Clay	H	A	$93.1\ N^{0.25}$	----	0.62	67[c]	$90.6\ N_{60}^{0.25}$	(4.21)
Ohta & Goto (1978)	Clay	P	A	$134.8\ N^{0.25}$	----	0.62	67[c]	$131.2\ N_{60}^{0.25}$	(4.22)
Imai & Tonouchi (1982)	Clay	H	F	$98.4\ N^{0.25}$	63	0.33	67[c]	$95.7\ N_{60}^{0.25}$	(4.23)
Imai & Tonouchi (1982)	Clay	H	A	$107.0\ N^{0.27}$	325	0.52	67[c]	$103.8\ N_{60}^{0.27}$	(4.24)
Imai & Tonouchi (1982)	Clay	P	A	$128.0\ N^{0.26}$	222	0.51	67[c]	$124.4\ N_{60}^{0.26}$	(4.25)
Lee (1992)	Clay	H	A	$138.4\ (N+1)^{0.24}$	265	0.48	73.5[d]	$131.7\ (N_{60}+1.2)^{0.24}$	(4.26)
Pitilakis, et al. (1999)	Clay	Q	A	$132.0\ N^{0.27}$	176	0.56	60	$128.1\ N_{60}^{0.27}$	(4.27)
Jafari et al. (2002)	Clay	----	----	$27.0\ N^{0.73}$	----	----	60[e]	$24.9\ N_{60}^{0.73}$	(4.28)
Hasncebi & Ulusay (2007)	Clay	Q	A	$97.9\ N^{0.27}$	----	0.56	----	$95.0\ N_{60}^{0.27}$	(4.29)
Jinan (1987)	Silt & Clay	H	A	$116.1\ (N+0.32)^{0.20}$	59	0.49	60[e]	$116.1\ (N_{60}+0.32)^{0.20}$	(4.30)
Lee (1992)	Silt & Clay	H	A	$129.4\ (N+1)^{0.26}$	365	0.51	73.5[d]	$122.7\ (N_{60}+1.2)^{0.26}$	(4.31)
Lee (1992)	Silt	H	A	$104.0\ (N+1)^{0.33}$	100	0.64	73.5[d]	$97.2\ (N_{60}+1.2)^{0.33}$	(4.32)
Imai & Tonouchi (1982)	Peat	H	A	$63.6\ N^{0.45}$	17	0.59	67[c]	$104.8\ N_{60}^{0.45}$	(4.33)

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary

[b]Geologic Deposition: A = Alluvium, F = Fill

[c]SPT energy ratio assumed to be 67% for Japanese practices.

[d]SPT energy ratio assumed to be 73.5% for Taiwanese practices.

[e]SPT energy ratio unknown. Assumed to be 60%.

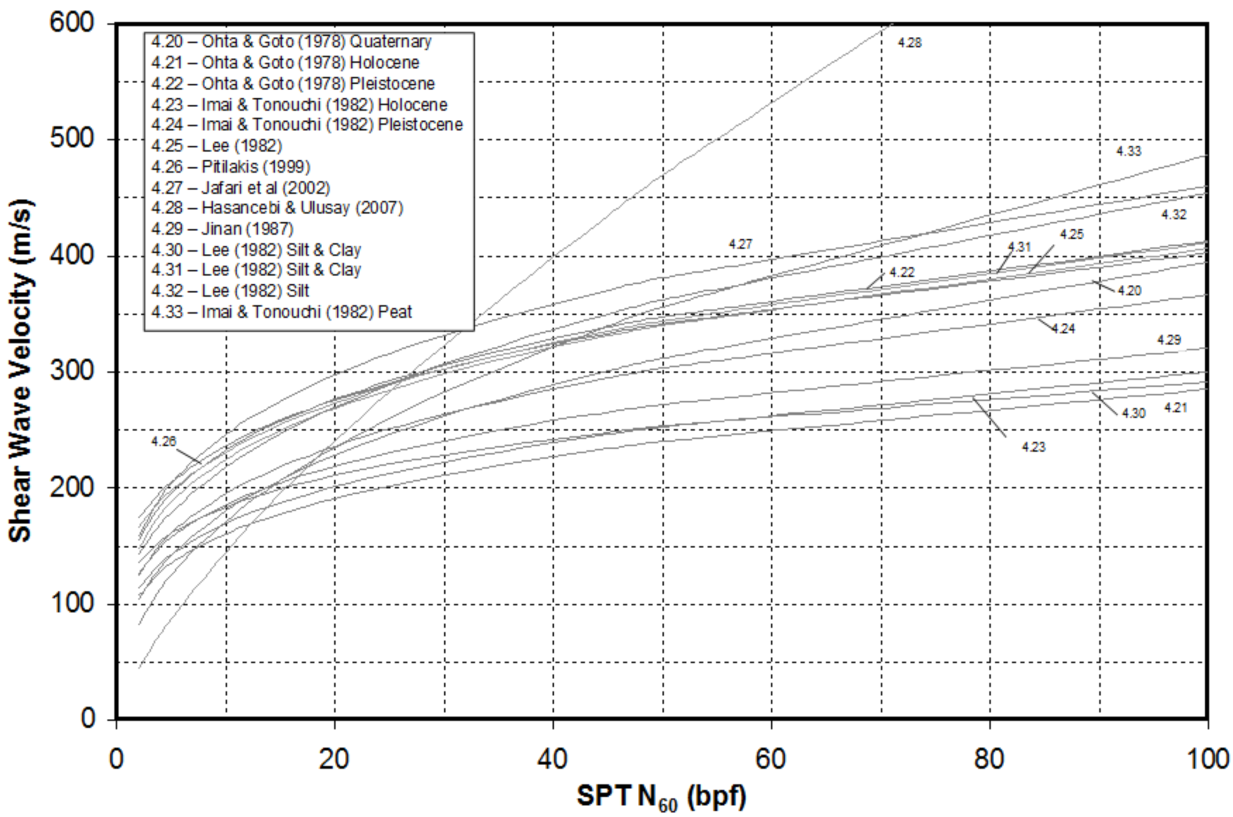


Figure 4.12 SPT N_{60}–V_S correlation equations for clays and silts.

Table 4.5 SPT–Stress–Vs correlation equations for clays and silts: Equations (4.34) through (4.42).

Study	Soil Type	Geology Age[a]	Geology Deposition[b]	V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
Ohta & Goto (1978)	Clay	Q	A	$62.1\ N^{0.22}\ D^{0.23}$	----	0.69	67[c]	$60.7\ N_{60}^{0.22}\ D^{0.23}$	(4.34)
Ohta & Goto (1978)	Clay	H	A	$68.8\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$67.5\ N_{60}^{0.17}\ D^{0.20}$	(4.35)
Ohta & Goto (1978)	Clay	P	A	$89.6\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$88.0\ N_{60}^{0.17}\ D^{0.20}$	(4.36)
Lee (1992)	Clay	H	A	$86.1\ N^{0.12}\ (D+1)^{0.22}$	265	0.79	73.5[d]	$84.1\ N_{60}^{0.12}\ (D+1)^{0.22}$	(4.37)
Lee (1992)	Silt	H	A	$82.8\ N^{0.13}\ (D+1)^{0.23}$	100	0.83	73.5[d]	$80.6\ N_{60}^{0.13}\ (D+1)^{0.23}$	(4.38)
Lee (1992)	Silt & Clay	H	A	$84.5\ N^{0.12}\ (D+1)^{0.25}$	365	0.80	73.5[d]	$82.5\ N_{60}^{0.12}\ (D+1)^{0.25}$	(4.39)
This Study	Silt & Clay	Q	----	----	----	----	----	$26.0\ N_{60}^{0.17}\ \sigma'^{0.32}_v$	(4.40)
This Study	Silt & Clay	H	----	----	----	----	----	$23.0\ N_{60}^{0.17}\ \sigma'^{0.32}_v$	(4.41)
This Study	Silt & Clay	P	----	----	----	----	----	$29.0\ N_{60}^{0.17}\ \sigma'^{0.32}_v$	(4.42)

D measured in m; σ'_v measured in kPa

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary

[b]Geologic Deposition: A = Alluvium

[c]SPT energy ratio assumed to be 67% for Japanese practices.

[d]SPT energy ratio assumed to be 73.5% for Taiwanese practices.

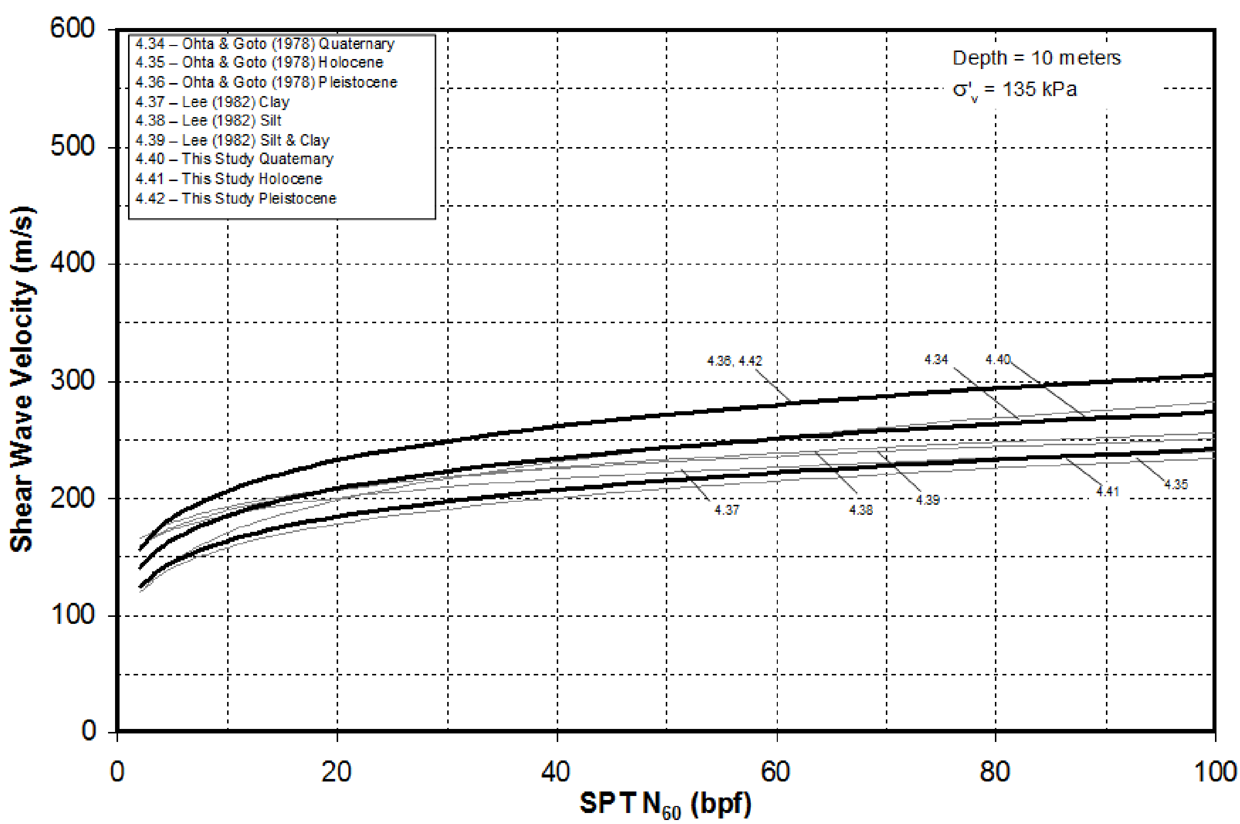


Figure 4.13 SPT N_{60}–Stress–V_S correlation equations for clays and silts.

4.2.3 Sands

A summary of SPT–V_S correlation equations for sands are presented in Table 4.6. The modified N_{60} equations are plotted on Figure 4.14. SPT–Stress–V_S correlation equations are presented in Table 4.7 and Figure 4.15.

A single set of representative equations was developed for sands. Equation (4.78) was developed for Holocene sands by approximating the average of the Ohta and Goto (1978) equations for Holocene sands (Equations [4.65] through [4.67]) and the Piratheepan (2002) equations for Holocene sands (Equations [4.74] through [4.76]). Quaternary (Equation [4.40]) and Pleistocene (Equation [4.42]) equations were developed by multiplying Equation (4.78) by ASFs of 1.11 and 1.30, respectively. The recommended equations are shown bold on Figure 4.15.

Table 4.6 SPT–V_S correlation equations for sands: Equations (4.43) through (4.61).

Study	Soil Type	Geology		V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
		Age[a]	Deposition[b]						
Kanai (1966)	Sand	----	----	$18.9\ N^{0.6}$	70	----	67[c]	$17.7\ N_{60}^{0.6}$	(4.43)
Shibata (1970)	Sand	----	----	$31.7\ N^{0.5}$	----	----	67[c]	$30.0\ N_{60}^{0.5}$	(4.44)
Imai & Tonouchi (1982)	Sand	H	A	$87.8\ N^{0.29}$	294	0.48	67[c]	$85.0\ N_{60}^{0.29}$	(4.45)
Imai & Tonouchi (1982)	Sand	P	A	$110.0\ N^{0.29}$	338	0.51	67[c]	$106.6\ N_{60}^{0.29}$	(4.46)
Sykora & Stokoe (1983)	Sand	----	-----	$100.6\ N^{0.29}$	97	0.71	60[d]	$100.6\ N_{60}^{0.29}$	(4.47)
Dickenson (1994)	Sand	----	----	$88.4\ (N+1)^{0.3}$	----	----	60[d]	$88.4\ (N_{60}+1)^{0.3}$	(4.48)
Hasncebi & Ulusay (2007)	Sand	Q	A	$90.8\ N^{0.32}$	----	0.42	----	$131.0\ N_{60}^{0.21}$	(4.49)
Seed et al. (1983)	Silty Sand & Sand	Q	-----	$56.4\ N^{0.5}$	----	----	60[d]	$56.4\ N_{60}^{0.5}$	(4.50)
Lee (1992)	Silty Sand	H	A	$104.7\ N^{0.30}$	126	0.45	73.5[e]	$98.6\ N_{60}^{0.30}$	(4.51)
Pitilakis et al. (1999)	Silt & Sand	----	A	$145.0\ N_{60}^{0.18}$	145	0.49	60	$145.0\ N_{60}^{0.18}$	(4.52)
Ohta & Goto (1978)	Fine Sand	Q	A	$90.1\ N^{0.34}$	----	0.53	67[c]	$86.8\ N_{60}^{0.34}$	(4.53)
Ohta & Goto (1978)	Fine Sand	H	A	$98.3\ N^{0.25}$	----	0.62	67[c]	$95.6\ N_{60}^{0.25}$	(4.54)
Ohta & Goto (1978)	Fine Sand	P	A	$142.4\ N^{0.25}$	----	0.62	67[c]	$138.5\ N_{60}^{0.25}$	(4.55)
Ohta & Goto (1978)	Medium Sand	Q	A	$81.3\ N^{0.34}$	----	0.53	67[c]	$78.3\ N_{60}^{0.34}$	(4.56)
Ohta & Goto (1978)	Medium Sand	H	A	$94.3\ N^{0.25}$	----	0.62	67[c]	$91.8\ N_{60}^{0.25}$	(4.57)
Ohta & Goto (1978)	Medium Sand	P	A	$135.6\ N^{0.25}$	----	0.62	67[c]	$131.9\ N_{60}^{0.25}$	(4.58)
Ohta & Goto (1978)	Coarse Sand	Q	A	$80.1\ N^{0.34}$	----	0.53	67[c]	$77.2\ N_{60}^{0.34}$	(4.59)
Ohta & Goto (1978)	Coarse Sand	H	A	$96.7\ N^{0.25}$	----	0.62	67[c]	$94.1\ N_{60}^{0.25}$	(4.60)
Ohta & Goto (1978)	Coarse Sand	P	A	$140.1\ N^{0.25}$	----	0.62	67[c]	$136.3\ N_{60}^{0.25}$	(4.61)

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary

[b]Geologic Deposition: A = Alluvium

[c]SPT energy ratio assumed to be 67% for Japanese practices.

[d]SPT energy ratio assumed to be 60% for U.S. practices.

[e]SPT energy ratio assumed to be 73.5% for Taiwanese practices.

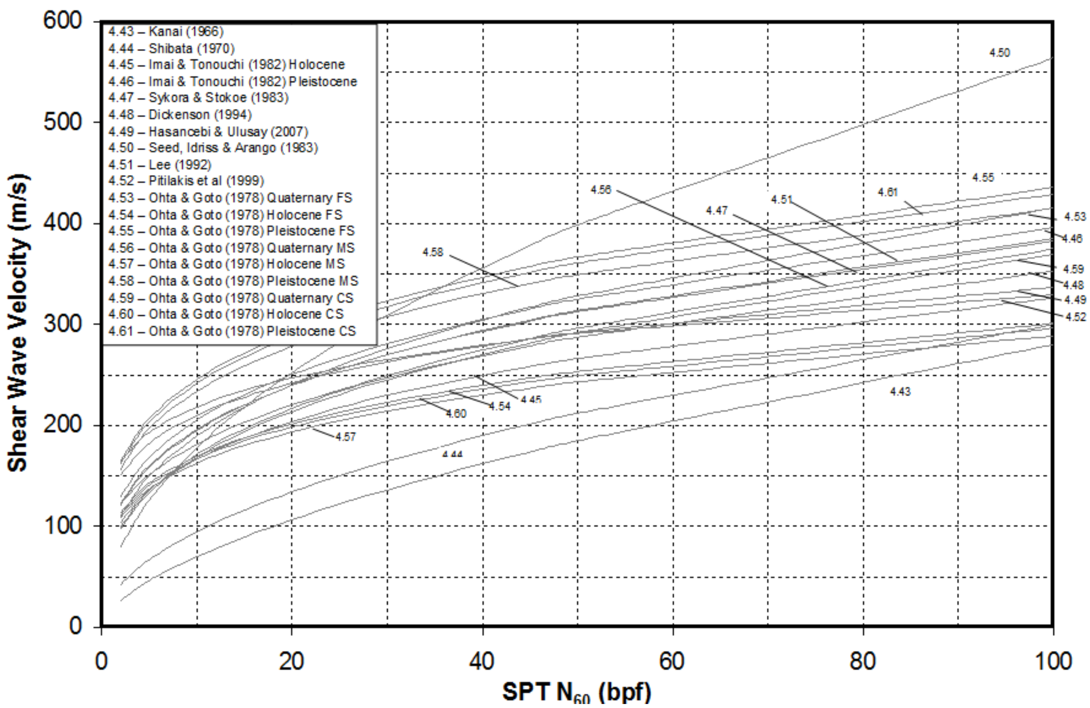


Figure 4.14 SPT N_{60}–V_S correlation equations for sands.

Table 4.7 SPT–Stress–V_S correlation equations for sands: Equations (4.62) through (4.79).

Study	Soil Type	Geology Age[a]	Geology Deposition[b]	V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
Ohta & Goto (1978)	Fine Sand	Q	A	$67.8\ N^{0.22}\ D^{0.23}$	----	0.69	67[c]	$66.2\ N_{60}^{0.22}\ D^{0.23}$	(4.62)
Ohta & Goto (1978)	Medium Sand	Q	A	$63.9\ N^{0.22}\ D^{0.23}$	----	0.69	67[c]	$62.4\ N_{60}^{0.22}\ D^{0.23}$	(4.63)
Ohta & Goto (1978)	Coarse Sand	Q	A	$66.7\ N^{0.22}\ D^{0.23}$	----	0.69	67[c]	$65.1\ N_{60}^{0.22}\ D^{0.23}$	(4.64)
Ohta & Goto (1978)	Fine Sand	H	A	$74.7\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$73.3\ N_{60}^{0.17}\ D^{0.20}$	(4.65)
Ohta & Goto (1978)	Medium Sand	H	A	$73.3\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$72.0\ N_{60}^{0.17}\ D^{0.20}$	(4.66)
Ohta & Goto (1978)	Coarse Sand	H	A	$78.1\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$76.6\ N_{60}^{0.17}\ D^{0.20}$	(4.67)
Ohta & Goto (1978)	Fine Sand	P	A	$97.3\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$95.5\ N_{60}^{0.17}\ D^{0.20}$	(4.68)
Ohta & Goto (1978)	Medium Sand	P	A	$95.5\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$93.8\ N_{60}^{0.17}\ D^{0.20}$	(4.69)
Ohta & Goto (1978)	Coarse Sand	P	A	$101.7\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$99.8\ N_{60}^{0.17}\ D^{0.20}$	(4.70)
Seed et al. (1986)	Sand	Q	A	$85.0\ N_{60}^{0.17}\ D^{0.2}$	----	----	60	$85.0\ N_{60}^{0.17}\ D^{0.2}$	(4.71)
Yoshida et al. (1988)	Fine Sand	----	F	$49.0\ N^{0.25}\ \sigma'^{0.14}_{v}$	----	----	60[d]	$49.0\ N_{60}^{0.25}\ \sigma'^{0.14}_{v}$	(4.72)
Yoshida et al. (1988)	Fine to Coarse Sand	----	F	$56.0\ N^{0.25}\ \sigma'^{0.14}_{v}$	----	----	60[d]	$56.0\ N_{60}^{0.25}\ \sigma'^{0.14}_{v}$	(4.73)
Piratheepan (2002)	Sand (FC < 10%)	H	----	$66.7\ N_{60}^{0.25}\ D^{0.14}$	25	0.82	60	$66.7\ N_{60}^{0.25}\ D^{0.14}$	(4.74)
Piratheepan (2002)	Sand (10 < FC < 35%)	H	----	$72.3\ N_{60}^{0.23}\ D^{0.15}$	10	0.95	60	$72.3\ N_{60}^{0.23}\ D^{0.15}$	(4.75)
Piratheepan (2002)	Sands (FC < 40%)	H	----	$72.9\ N_{60}^{0.22}\ D^{0.13}$	39	0.85	60	$72.9\ N_{60}^{0.22}\ D^{0.13}$	(4.76)
This Study	Sand	Q	----	----	----	----	----	$30.0\ N_{60}^{0.23}\ \sigma'^{0.25}_{v}$	(4.77)
This Study	Sand	H	----	----	----	----	----	$27.0\ N_{60}^{0.23}\ \sigma'^{0.25}_{v}$	(4.78)
This Study	Sand	P	----	----	----	----	----	$35.0\ N_{60}^{0.23}\ \sigma'^{0.25}_{v}$	(4.79)

D measured in m; σ'_v measured in kPa

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary

[b]Geologic Deposition: F = Fill, A = Alluvium

[c]SPT energy ratio assumed to be 67% for Japanese practices.

[d]SPT energy ratio unknown. Assumed to be 60%.

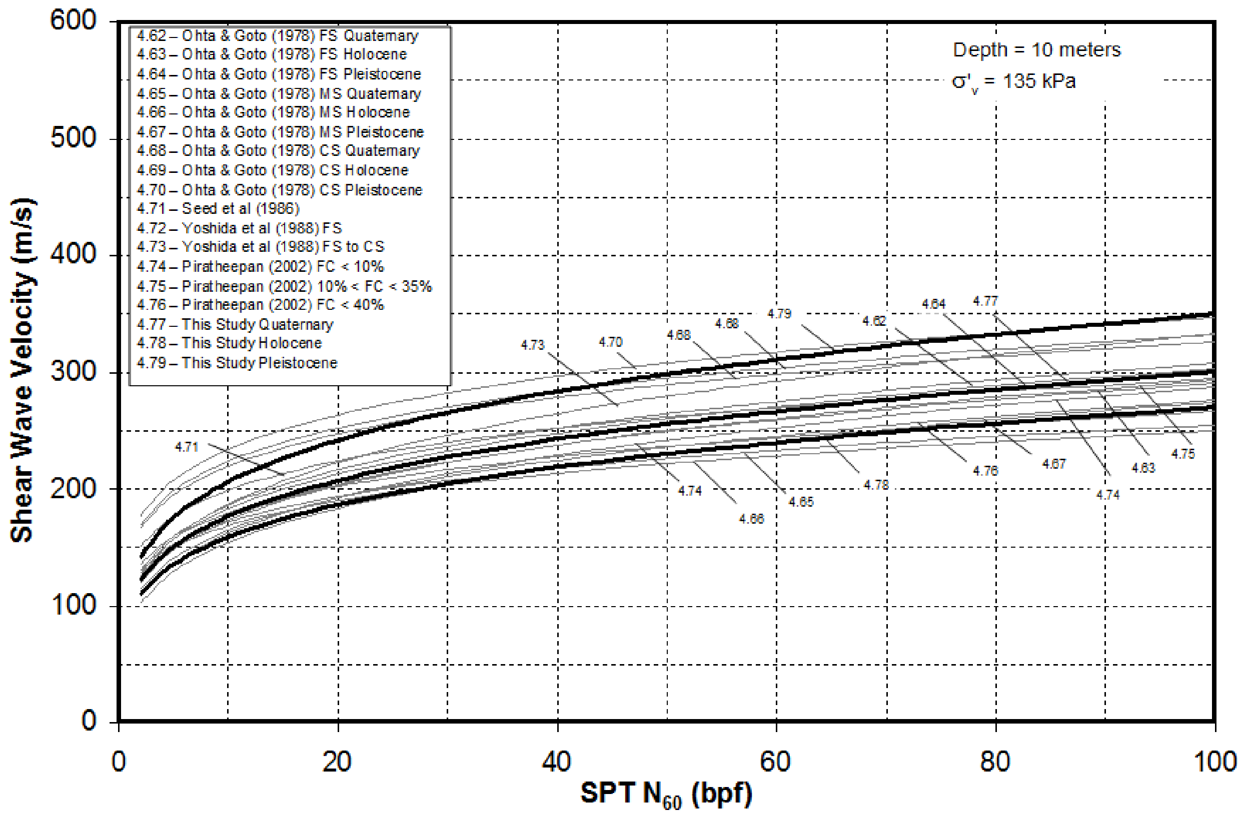


Figure 4.15 SPT N_{60}–Stress–V_S correlation equations for sands.

4.2.4 Gravels

A summary of SPT–V_S correlation equations for gravels are presented in Table 4.8 [Equations (4.80) through (4.91)]. The modified N_{60} equations are plotted on Figure 4.16. SPT–Stress–V_S correlation equations are presented in Table 4.9 [Equations (4.92) through (4.102)] and Figure 4.17.

Rollins et al. [1998] performed a thorough review of previous correlations between V_S and penetration resistance for gravelly soils as part of their study of the shear modulus and damping ratio of gravelly soils. Rollins et al. proposed V_S prediction equations for Holocene and Pleistocene gravels based on SPT N_{60} with and without stress terms. Rollins et al. found better correlation when including effective stress in the regression analyses, as indicated by higher coefficients of determination (r^2).

Table 4.8 SPT–V_S correlation equations for gravels: Equations (4.80) through (4.91).

Study	Soil Type	Geology Age[a]	Geology Deposition[b]	V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
Imai & Tonouchi (1982)	Sand & Gravel	H	F	$91.7\ N^{0.26}$	81	0.42	67[c]	$89.1\ N_{60}^{0.26}$	(4.80)
Ohta & Goto (1978)	Sand & Gravel	Q	A	$89.7\ N^{0.34}$	----	0.53	67[c]	$86.4\ N_{60}^{0.34}$	(4.81)
Ohta & Goto (1978)	Sand & Gravel	H	A	$99.5\ N^{0.25}$	----	0.62	67[c]	$96.8\ N_{60}^{0.25}$	(4.82)
Ohta & Goto (1978)	Sand & Gravel	P	A	$144.1\ N^{0.25}$	----	0.62	67[c]	$140.2\ N_{60}^{0.25}$	(4.83)
Ohta & Goto (1978)	Gravel	Q	A	$104.6\ N^{0.34}$	----	0.53	67[c]	$100.8\ N_{60}^{0.34}$	(4.84)
Ohta & Goto (1978)	Gravel	H	A	$113.7\ N^{0.25}$	----	0.62	67[c]	$110.6\ N_{60}^{0.25}$	(4.85)
Ohta & Goto (1978)	Gravel	P	A	$164.6\ N^{0.25}$	----	0.62	67[c]	$160.1\ N_{60}^{0.25}$	(4.86)
Imai & Tonouchi (1982)	Gravel	H	A	$75.4\ N^{0.35}$	28	0.62	67[c]	$72.5\ N_{60}^{0.35}$	(4.87)
Imai & Tonouchi (1982)	Gravel	P	A	$136.0\ N^{0.25}$	114	0.30	67[c]	$132.4\ N_{60}^{0.25}$	(4.88)
Lum & Yan (1994)	Gravel	----	Fl, G	$116.0\ N_{60}^{0.27}$	----	0.38	BPT[d]	$116.0\ N_{60}^{0.27}$	(4.89)
Rollins et al. (1998)	Gravel	H	----	$63.0\ N_{60}^{0.43}$	186	0.59	BPT[d]	$63.0\ N_{60}^{0.43}$	(4.90)
Rollins et al. (1998)	Gravel	P	----	$132.0\ N_{60}^{0.32}$	105	0.48	BPT[d]	$132.0\ N_{60}^{0.32}$	(4.91)

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary

[b]Geologic Deposition: F = Fill, A = Alluvium, Fl = Fluvium, G = Glaciofluvium

[c]SPT energy ratio assumed to be 67% for Japanese practices.

[d]Equivalent SPT N_{60} interpreted from BPTs.

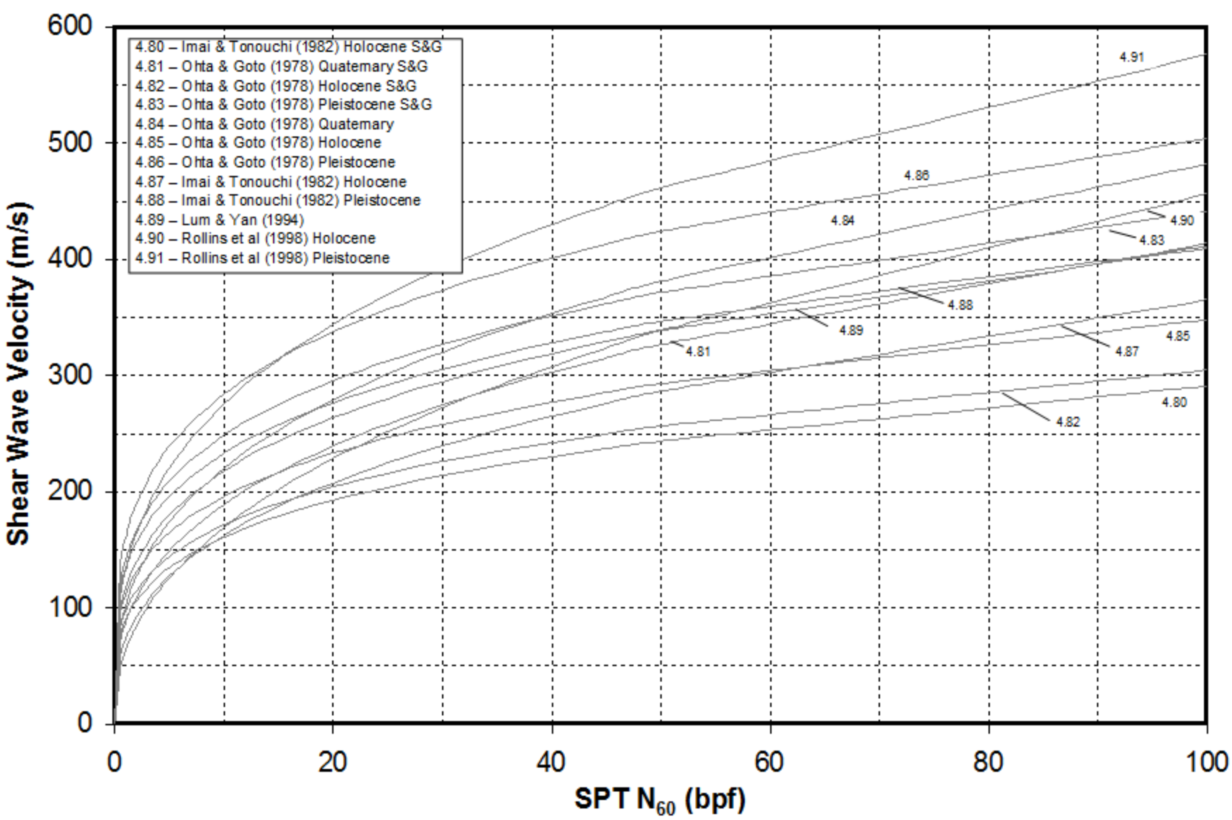


Figure 4.16 SPT N_{60}–V_S correlation equations for gravels.

Table 4.9 SPT–stress–V_S Correlation equations for gravels: Equations (4.92) through (4.102).

Study	Soil Type	Geology Age[a]	Geology Deposition[b]	V_S based on Uncorrected N-value (m/s)	Number of Data Pairs	r^2	Estimated SPT Energy	V_S based on N_{60} (m/s)	(Eq #)
Ohta & Goto (1978)	Sand & Gravel	Q	A	$71.5\ N^{0.22}\ D^{0.23}$	----	0.69	67[c]	$69.8\ N_{60}^{0.22}\ D^{0.23}$	(4.92)
Ohta & Goto (1978)	Gravel	Q	A	$92.3\ N^{0.22}\ D^{0.23}$	----	0.69	67[c]	$90.1\ N_{60}^{0.22}\ D^{0.23}$	(4.93)
Yoshida et al. (1988)	Gravelly Sand	----	F	$60.0\ N^{0.25}\ \sigma'_v{}^{0.14}$	----	----	60[d]	$60.0\ N_{60}^{0.25}\ \sigma'_v{}^{0.14}$	(4.94)
Ohta & Goto (1978)	Sand & Gravel	H	A	$79.3\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$77.8\ N_{60}^{0.17}\ D^{0.20}$	(4.95)
Andrus (1994)	Sandy Gravel	H	Fl	$68.0\ N^{0.17}\ D^{0.20}$	----	----	60[d]	$68.0\ N_{60}^{0.17}\ D^{0.20}$	(4.96)
Ohta & Goto (1978)	Gravel	H	A	$99.6\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$97.7\ N_{60}^{0.17}\ D^{0.20}$	(4.97)
Rollins et al. (1998)	Gravel	H	----	$53.0\ N_{60}^{0.19}\ \sigma'_v{}^{0.18}$	186	0.66	BPT[e]	$53.0\ N_{60}^{0.19}\ \sigma'_v{}^{0.18}$	(4.98)
Ohta & Goto (1978)	Sand & Gravel	P	A	$103.3\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$101.4\ N_{60}^{0.17}\ D^{0.20}$	(4.99)
Andrus (1994)	Sandy Gravel	P	Fl	$109.0\ N^{0.17}\ D^{0.20}$	----	----	60[d]	$109.0\ N_{60}^{0.17}\ D^{0.20}$	(4.100)
Ohta & Goto (1978)	Gravel	P	A	$129.8\ N^{0.17}\ D^{0.20}$	----	0.73	67[c]	$127.4\ N_{60}^{0.17}\ D^{0.20}$	(4.101)
Rollins et al. (1998)	Gravel	P	----	$115.0\ N_{60}^{0.17}\ \sigma'_v{}^{0.12}$	105	0.58	BPT[e]	$115.0\ N_{60}^{0.17}\ \sigma'_v{}^{0.12}$	(4.102)

D measured in m; σ'_v measured in kPa

[a]Geologic Age: H = Holocene, P = Pleistocene, Q = Quaternary

[b]Geologic Deposition: F = Fill, A = Alluvium, Fl = Fluvium

[c]SPT energy ratio assumed to be 67% for Japanese practices.

[d]SPT energy ratio unknown. Assumed to be 60%.

[e]Equivalent SPT N_{60} interpreted from BPTs.

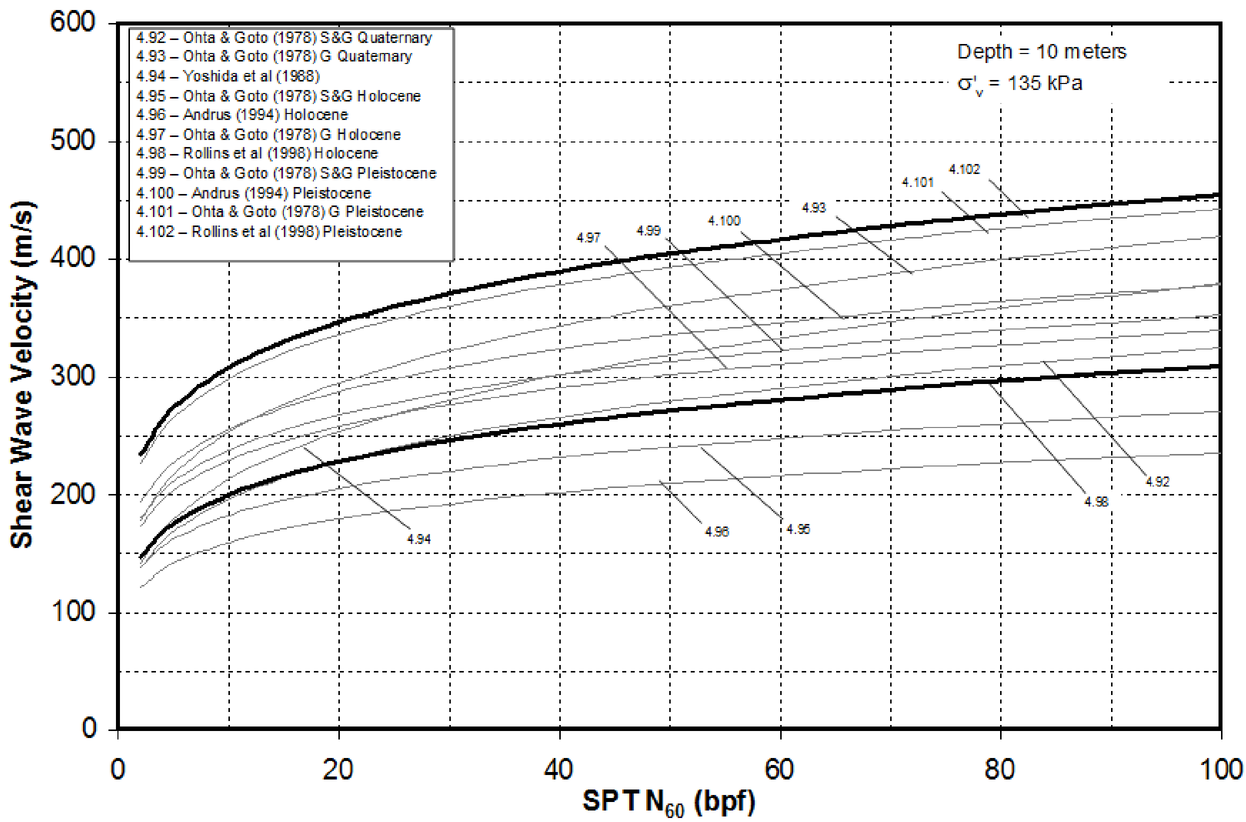


Figure 4.17 SPT N_{60}–stress–V_S correlation equations for gravels.

4.3 AGE SCALING FACTORS

Table 4.10 presents ASFs derived from the equations presented in the previous sections. Columns 3 through 5 present the ratio of the younger soil to older soil (i.e., Holocene divided by Quaternary). Columns 6 through 8 present the inverse ratio, older soil to younger soil.

For example, the ASFs for Holocene and Quaternary clays by Ohta and Goto were calculated by dividing the results of Equation (4.35) by Equation (4.34). A range is reported due to the varying exponents for both the N and depth terms.

As discussed in the previous sections, sets of equations were developed for All Soils, clays and silts, and sands, of Quaternary, Holocene, and Pleistocene age. Table 4.11 presents the recommended equations for Quaternary soils, as well as, ASFs for Holocene and Pleistocene soils. The recommended ASFs range from of 0.87 to 0.9 for Holocene soils and 1.12 to 1.17 for Pleistocene soils.

Table 4.10 Age scaling factors for SPT–V_S correlation equations.

Soil Type	Study	Holocene / Quaternary	Holocene / Pleistocene	Quaternary / Pleistocene	Quaternary / Holocene	Pleistocene / Holocene	Pleistocene / Quaternary
All Soils	Ohta & Goto (1978)	0.8 to 0.9	0.7	0.75 to 0.9	1.1 to 1.3	1.45	1.15 to 1.3
Clays & Silts	Ohta & Goto (1978)	0.75 to 0.9	0.7	0.8 to 0.9	1.15 to 1.3	1.45	1.1 to 1.3
	Imai & Tonouchi (1982)	----	0.85 to 0.9	----	----	1.1 to 1.15	----
Sands	Ohta & Goto (1978)	0.8 to 0.95	0.70	0.7 to 0.85	1.05 to 1.25	1.45	1.15 to 1.45
	Imai & Tonouchi (1982)	----	0.80	----	----	1.2 to 1.25	----
Gravels	Ohta & Goto (1978)	0.8 to 0.9	0.70	0.75 to 0.9	1.1 to 1.3	1.45	1.15 to 1.3
	Imai & Tonouchi (1982)	----	0.7 to 0.85	----	----	1.2 to 1.45	----
	Andrus (1994)	----	0.65	----	----	1.60	----
	Rollins (1998)	----	0.6 to 0.75	----	----	1.35 to 1.65	----

4.4 SITE-SPECIFIC CORRELATIONS

Site-specific correlations between V_S and SPT data can be developed in two ways: modifying existing correlations equations and development of new correlations based on site-specific data.

If limited V_S and SPT data are available at a site, the recommended equations (Table 4.11, presented in subsequent section) may be modified by adjusting the coefficients and exponents to match site-specific data. If sufficient site-specific V_S and SPT data is available it is possible to develop new site-specific correlation equations.

The strongest correlation equations include SPT N_{60}-value, effective stress, soil type, and geologic age. The same functional form as Equation (4.103) below is recommended.

$$V_S = a \cdot N_{60}^{\,b} \cdot \sigma'^{\,c}_v \tag{4.103}$$

To develop a site specific correlation a regression analysis can be performed using Microsoft Excel using the "LINEST" function. LINEST performs linear regression in the form shown in Equation (4.104):

$$y = b + m\,x \tag{4.104}$$

or for multiple x variables as shown in Equation (4.105):

$$y = b + m_1\, x_1 + m_2\, x_2 + m_n\, x_n \qquad (4.105)$$

To utilize the LINEST function, Equation (4.103) can be re-written to Equation (4.106):

$$\log V_S = \log a + b{\cdot}\log N_{60} + c{\cdot}\log \sigma'_v \qquad (4.106)$$

An example is presented in Figure 4.18. The LINEST function requires that the results area be defined as an array. The results area has the LINEST function in the upper left corner (Cell D23 in this example), columns equal to the number of variables (three in this example), and five rows. The area is can be defined as an array by highlighting the cells, then hitting Control-Alt-Enter.

The function returns coefficients b, m_1, and m_2. The coefficients m_1 and m_2 can be used in Equations (4.103) and (4.106) for *b* and *c*, respectively. Excel coefficient b can be inserted into Equation (4.106) as the "log *a*" term, or 10^b can be used in Equation (4.103) as the *a* coefficient.

	A	B	C	D	E	F
1	LINEST Example					
2						
3	V_S	N_{60}	σ'_v	Log V_S	Log N_{60}	Log σ'_v
4	(m/s)	(bpf)	(kPa)	(m/s)	(bpf)	(kPa)
5	100	2	95	2.000	0.301	1.978
6	152	11	99	2.182	1.041	1.996
7	164	15	110	2.215	1.176	2.041
8	182	23	110	2.260	1.362	2.041
9	189	30	115	2.276	1.477	2.061
10	205	25	130	2.312	1.398	2.114
11	212	30	140	2.326	1.477	2.146
12	219	35	145	2.340	1.544	2.161
13	236	50	150	2.373	1.699	2.176
14	210	16	240	2.322	1.204	2.380
15	220	20	245	2.342	1.301	2.389
16	239	30	250	2.378	1.477	2.398
17	265	50	240	2.423	1.699	2.380
18	287	75	250	2.458	1.875	2.398
19	247	25	320	2.393	1.398	2.505
20	256	30	330	2.408	1.477	2.519
21	277	45	340	2.442	1.653	2.531
22	326	100	340	2.513	2.000	2.531
23				0.250	0.221	1.451
24				0.015	0.008	0.030
25				0.993	0.011	#N/A
26				1069.8	15.000	#N/A
27				0.236	0.002	#N/A
28						

Results Format

	A	B	C	D	E	F
1	m_n	$m_{n\text{-}1}$	. . .	m_2	m_1	b
2	se_n	$se_{n\text{-}1}$	. . .	se_2	se_1	se_b
3	r_2	se_y				
4	F	d_f				
5	ss_{reg}	ss_{resid}				

Row 1 - Coefficients (Example Row 23)

b =	1.451	(Cell F23)
m_1 =	0.221	(Cell E23)
m_2 =	0.25	(Cell D23)

Row 2 - Standard Errors (Example Row 24)

S.E. b =	0.030	(Cell F24)
S.E. m_1 =	0.008	(Cell E24)
S.E. m_2 =	0.015	(Cell D24)

Row 3 - Additional Statistics (Example Row 25)

S.E. y =	0.011	(Cell E25)
r^2 =	0.993	(Cell D25)

Figure 4.18 Regression analysis example.

4.5 RECOMMENDATIONS

Recommended V_S–SPT correlation equations are presented in Table 4.11 for All Soils, clays and silts, sands, and gravels. For use in the recommended equations, field N-values should be corrected for variations from the standard, such as non-standard sampler type, borehole diameter, rod length, and normalized to the reference energy ratio of 60%. As discussed in Chapters 3 and 4, it is not appropriate to normalize penetration resistance for overburden stress for use with these equations.

The recommended equations may be considered valid for N_{60}-values of up to approximately 100 bpf. Limiting blow counts to 100 bpf is consistent with the data that was used to formulate most of the original equations and with BSSC guidelines for site classification, which limits N-values to 100 bpf for any given layer of the soil profile [BSSC 2003]. The recommended equations were developed for Quaternary soils and are appropriate for use if the thicknesses of Holocene and Pleistocene soils are not known. If the age of the soil is known, ASFs may improve the accuracy of correlation equations. The ASFs are presented in Columns 3 and 4 of Table 4.11.

Site-specific correlations between V_S and SPT N-values may be developed by either adjusting the coefficients and exponents for the equations presented in Table 4.11 to match site-specific data, or if sufficient V_S and SPT data is available, site-specific correlation equations can be developed based on the regression procedure presented in Section 4.4.

Table 4.11 Recommended SPT–stress–V_S correlation equations.

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

σ'_v measured in kPa

5 Cone Penetration Test Correlations

The CPT involves advancing an instrumented cone penetrometer into the ground and measuring the cone tip resistance (q_c) and sleeve friction (f_s) at selected intervals (typically 1 to 5 cm). The three most common commercially available CPT systems used for geotechnical site investigation are the conventional CPT, the Piezo-CPT (CPTu), and the Seismic CPT (SCPT or SCPTu).

The piezocone or CPTu incorporates a pore pressure transducer to measure the dynamic pore water pressure. The pore water pressure transducer is typically located behind the cone tip in the "u_2" position, as shown in Figure 5.1.

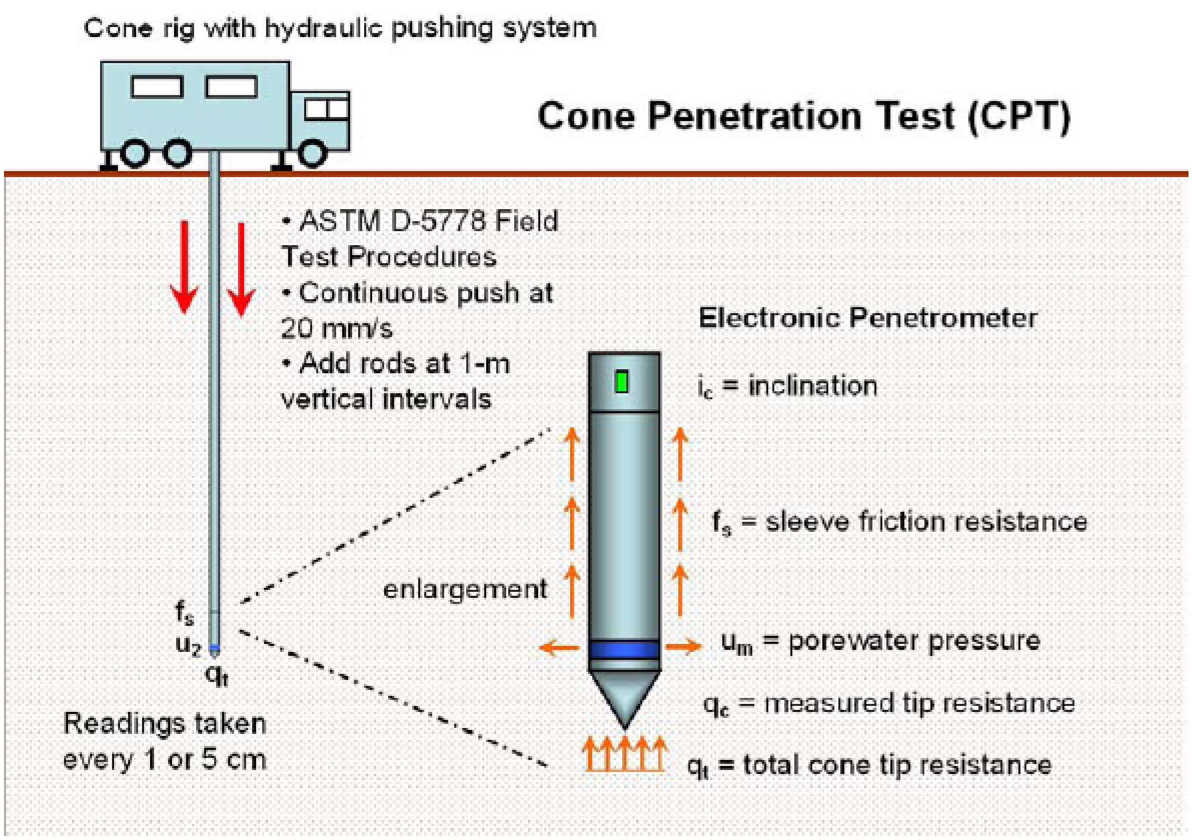


Figure 5.1 CPTu schematic [Mayne 2007].

The CPTu allows for correction of the tip resistance due to pore pressures acting on unequal areas of the cone. The corrected tip resistance or the total tip resistance (q_t) can be calculated by Equation (5.1):

$$q_t = q_c + (1-a_n) \cdot u_2 \qquad (5.1)$$

where q_c is the measured tip resistance and a_n is the net area ratio. The net area ratio is a property of the cone, which is determined by calibration tests, and can be obtained from the CPT contractor. Typical values of a_n range from 0.5 to 1.0 [Lunne et al. 1986].

The SCPT or $SCPT_u$ is performed in the same manner as the CPT or CPT_u with the addition of a geophone or accelerometer located in the CPT tip. Measurement of V_S is performed at selected intervals (typically 1 to 2 m) by striking a steel or wood beam pressed firmly against the ground. The V_S is calculated based on the difference in travel time of the shear wave between the source and the geophone at two consecutive depth positions.

5.1 SOIL BEHAVIOR TYPE

The CPT does not retrieve actual soil samples for classification. Soil classification estimation is typically based in interpreted Soil Behavior Type (SBT). Figure 5.2 presents the normalized classification system proposed by Robertson (1990), which consists of nine SBTs. The Robertson (1990) classification system is based on the normalized tip resistance (Q) and normalized friction ratio (F). Q is calculated by Equation (5.2):

$$Q = [(q_t - \sigma_v)/p_a] \cdot [p_a/\sigma'_v]^n \qquad (5.2)$$

where σ_v and σ'_v are the total and effective stress, and p_a is atmospheric pressure in the same units as q_c and σ_v. The exponent "n" varies from 0.5 for clays to 1.0 for sands [Olsen 1997; Robertson and Wride 1998]. An iterative method for determination of the exponent n is given in Youd et al. (2001). Robertson (2009) proposed a continuous function for n based on the SBT index (I_C), which is defined in Equation (5.3) below:

$$n = 0.381 (I_C) + 0.05 (\sigma'_v / p_a) - 0.15 \qquad (5.3)$$

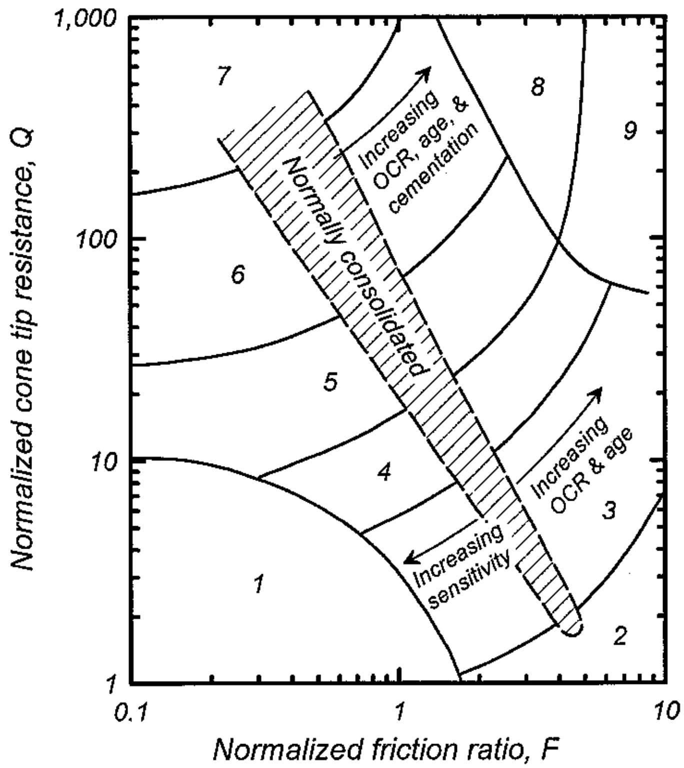
The normalized friction ratio, F, is defined as:

$$F = [f_s / (q_t - \sigma_v)] \cdot 100\% \qquad (5.4)$$

Jefferies and Davies (1993) proposed I_C to aid in classification of SBT. I_C is essentially the radius of concentric circles that define the boundaries on the Q-F chart. Robertson and Wride (1998) modified the definition of I_C to apply to the Robertson (1990) Q-F chart:

$$I_C = [(3.47 - \log Q)^2 + (\log F + 1.22)^2]^{0.5} \qquad (5.5)$$

The relationship between I_C and SBT developed by Robertson and Wride is presented in Table 5.1.



1. *Sensitive, fine grained*
2. *Organic soils - peats*
3. *Clays - silty clay to clay*
4. *Silt mixtures - clayey silt to silty clay*
5. *Sand mixtures - silty sand to sandy silt*
6. *Sands - clean sand to silty sand*
7. *Gravelly sand to dense sand*
8. *Very stiff sand to clayey sand **
9. *Very stiff, fine grained **

** Heavily overconsidated or cemented*

Figure 5.2 SBT chart [Robertson 1990].

Table 5.1 CPT soil behavior types.

Soil Behavior Type Index	Zone	Soil Behavior Type
$I_C < 1.31$	7	Gravelly Sand and Dense Sand
$1.31 < I_C < 2.05$	6	Sands: Clean Sand to Silty Sand
$2.05 < I_C < 2.60$	5	Sand Mixtures: Silty Sand and Sandy Silt
$2.60 < I_C < 2.95$	4	Silt Mixture: Clayey Silt to Silty Clay
$2.95 < I_C < 3.60$	3	Clays: Silty Clays to Clay
$I_C > 3.60$	2	Organic Soils: Peats

5.2 PREVIOUS STUDIES

Various researchers have studied relationships between CPT resistance and V_S. Table 5.2 summarizes the pertinent details of the previous studies, including: location, number of sites, geologic age, depositional environment, and method of V_S measurement. The studies explored correlation relationships between V_S and various parameters, including: CPT tip (q_c), f_s, I_C, effective stress (σ'_v), depth (D), and the *in situ* void ratio (e).

Published CPT–V_S correlation equations were generally developed for specific soils types (i.e., "Sand" or "Clay") or grouped together as All Soils. Correlation equations that were reviewed for this study are listed in Table 5.3.

5.2.1 Sykora and Stokoe [1983]

Sykora and Stoke [1983] developed a relationship between q_c and V_S based on 256 data points from 9 sites. The V_S was measured using cross-hole logging. The dataset included tip resistances ranging from approximately 1 to 70 MPa (10 to 730 tsf) and V_S ranging from approximately 120 to 500 m/sec. A plot of Sykora and Stoke's data and best-fit relationship are shown in Figure 5.3 with V_S in ft/sec and q_c in kg/cm^2. Sykora and Stokoe found a linear relationship between q_c and V_S, as opposed to nonlinear relationships proposed by other researchers for CPT and SPT resistance values [Sykora 1987].

Table 5.2 Studies between the Cone Penetration Test and V_S.

Study	Location	# Sites	Geologic Age	Deposition	Method of V_S Measurement
Sykora (1983)	United States	9	----	----	Crosshole
Baldi et al. (1989)	Italy	2	Holocene	----	----
Hegazy & Mayne (1995)	Worldwide	61	Quaternary	Glacial, Marine, Deltaic,	Crosshole, Downhole, SCPT, SASW
Mayne & Rix (1995)	Worldwide	31	Quaternary	Glacial, Marine, Deltaic,	Crosshole, Downhole, SCPT, SASW
Piratheepan (2002)	California, Japan, Canada,	----	Holocene, Pleistocene	----	----
Mayne (2006)	Worldwide	----	Quaternary	Glacial, Marine, Deltaic,	Crosshole, Downhole, SCPT, SASW
Andrus et al. (2007)	California, Japan, South Carolina	----	Holocene, Pleistocene, Tertiary	----	SCPT, Downhole, Suspension
Robertson (2009)	Worldwide	----	Quaternary	-----	SCPT

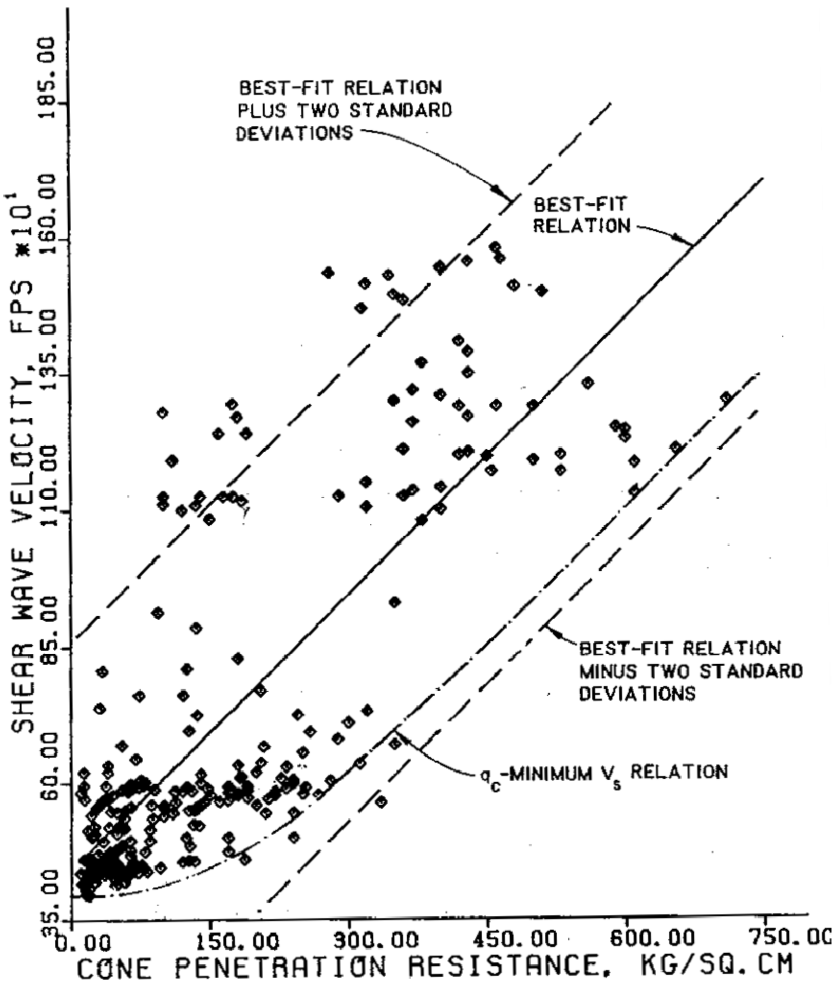


Figure 5.3 V_S versus q_c [Sykora and Stokoe 1983].

5.2.2 Baldi et al. [1989]

Baldi et al. [1989] proposed a relation between V_S and q_c for uncemented, unaged silica sands. Baldi et al. developed the relationship based on laboratory resonant column tests and CPTs and dilatometer calibration chamber tests. As shown in Figure 5.4, the regression equation compared well to SCPT data collected in Holocene sands at three sites in Italy Holocene [Piratheepan, 2002].

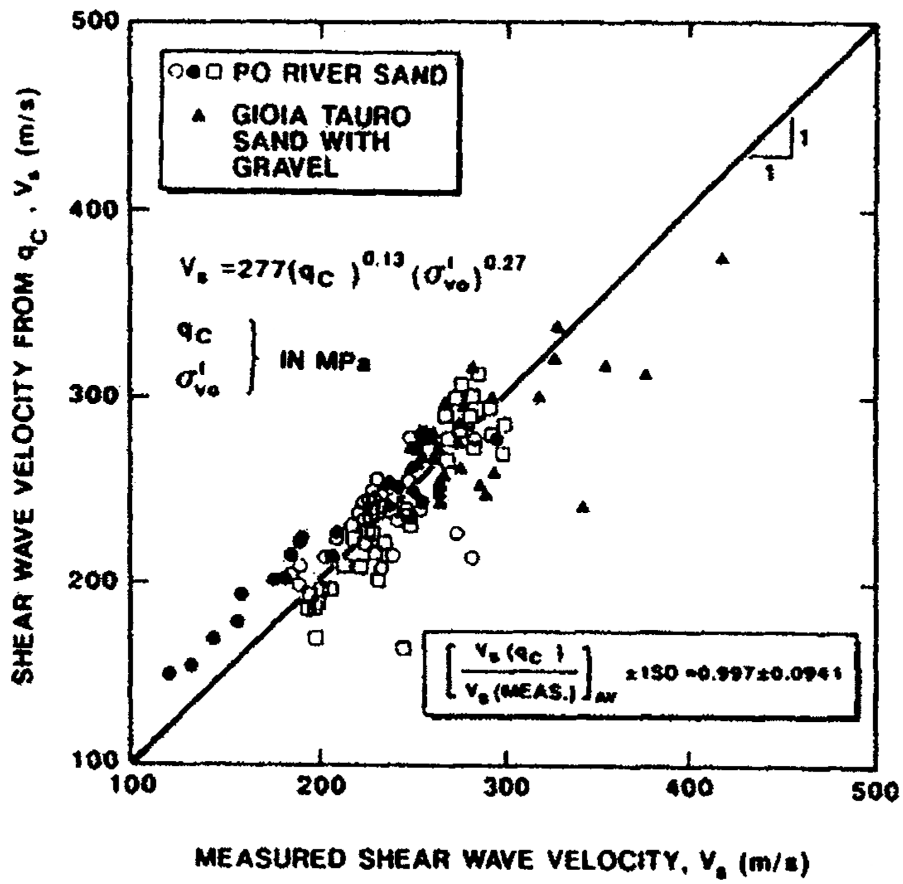


Figure 5.4 Estimated V_S versus measured V_S [Baldi et al. 1989].

5.2.3 Hegazy and Mayne [1995]

Hegazy and Mayne [1995] studied the relationship between V_S and four independent parameters: q_c, f_s, vertical effective stress, and *in situ* void ratio (e). The dataset included CPT measurements in clays, sands, intermediate soils, and mine tailings collected at 61 sites worldwide. Hegazy and Mayne proposed correlation equations for clays, sands, and All Soils. They proposed two correlation equations for clayey soils; one with an e_0 term and one without. They note that the correlation equation that includes an e_0 term provides a better fit for the data (as indicated by a higher r^2 value), but that e_0 is normally not known for CPT profiles. A comparison of measured and predicted V_S for the All Soils correlation is presented in Figure 5.5.

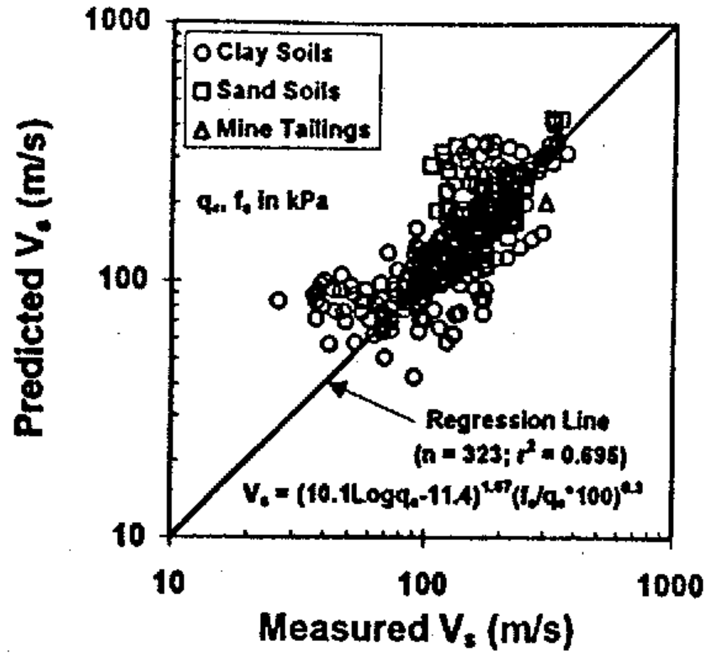


Figure 5.5 Estimated V_S versus measured V_S [Hegazy and Mayne 1995].

5.2.4 Mayne and Rix [1995]

Mayne and Rix [1995] studied the relationship between V_S and clayey soils based on data collected at 31 sites worldwide. The dataset included both intact and fissured clays with a wide range of plasticity characteristics ($8 < PI < 300$), sensitivities ($2 < S_t < 200+$), and overconsolidation ratios ($1 < OCR < 100+$). Similar to Hegazy and Mayne [1995], Mayne and Rix [1995] proposed V_S correlation equations with and without a void ratio term. This study also showed that correlation equations that include the void ratio provide a better fit for the measured V_S data. Figure 5.6 shows the relationship between V_S and q_c.

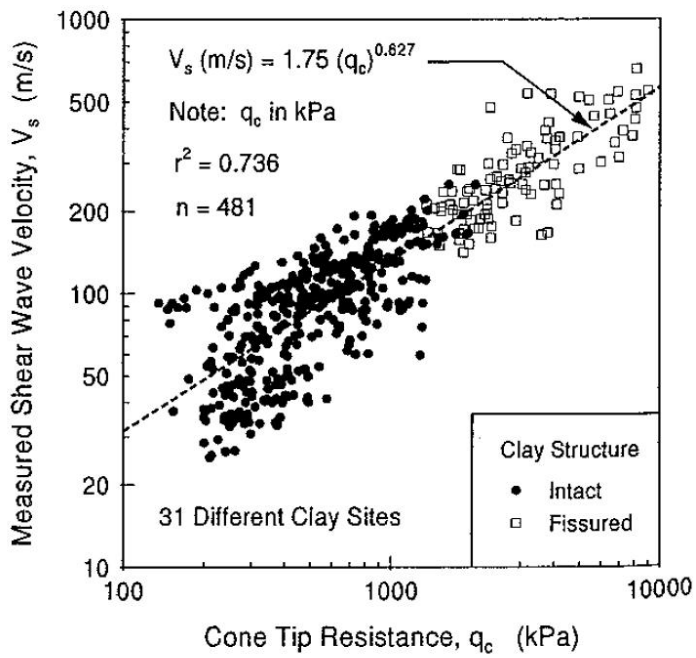


Figure 5.6 V_S versus q_c [Mayne and Rix 1995].

5.2.5 Piratheepan [2002]

Piratheepan [2002] proposed V_S correlation equations based on CPT data from the United States, Canada, and Japan. Piratheepan evaluated V_S correlations using combinations of q_c and f_s, as well as vertical effective stress, and CPT I_C. Figures 5.7, 5.8, and 5.9 present comparisons between measured and predicted V_S for Holocene All Soils, sands, and clays, respectively.

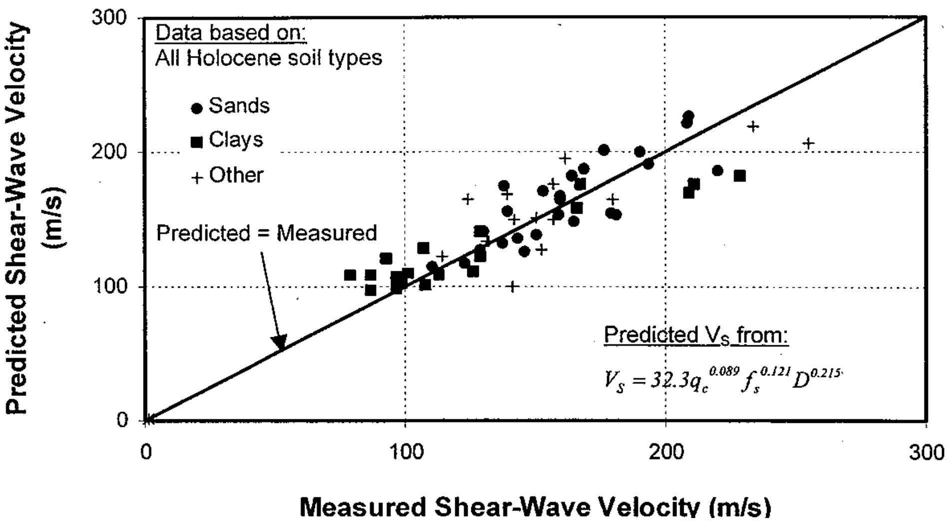


Figure 5.7 Predicted versus measured V_S for all soils [Piratheepan 2002].

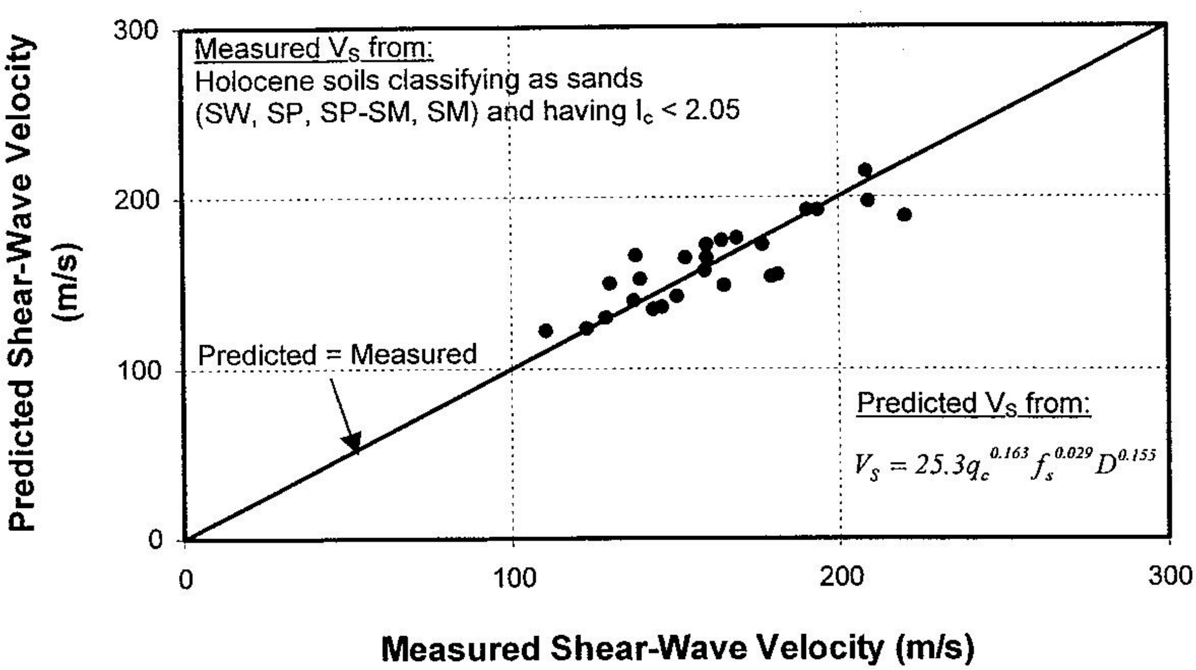


Figure 5.8 Predicted versus measured V_S for sands [Piratheepan 2002].

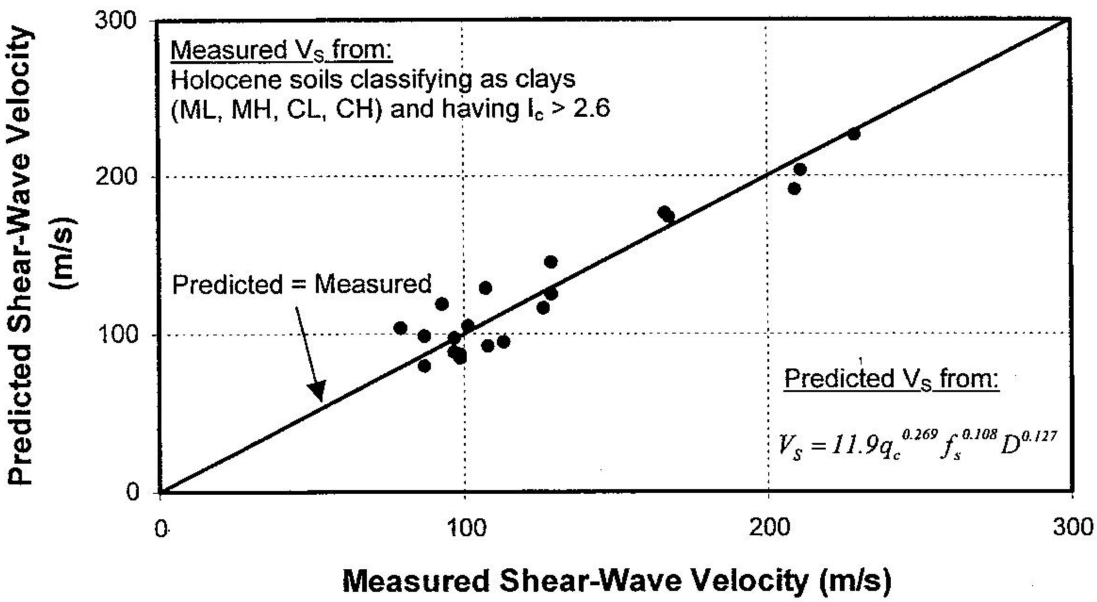


Figure 5.9 Predicted versus measured V_S for clays and silts [Piratheepan 2002].

5.2.6 Mayne [2006]

Mayne [2006] proposed an All Soils correlation between V_S and CPT f_s based on regression of a large dataset from various sites worldwide. A plot of the data and regression equation are presented in Figure 5.10. Equation (5.8) is presented in the form recommended by Mayne [2007] with V_S as a function of the logarithm of f_s, rather than the natural logarithm as originally proposed in Mayne [2006].

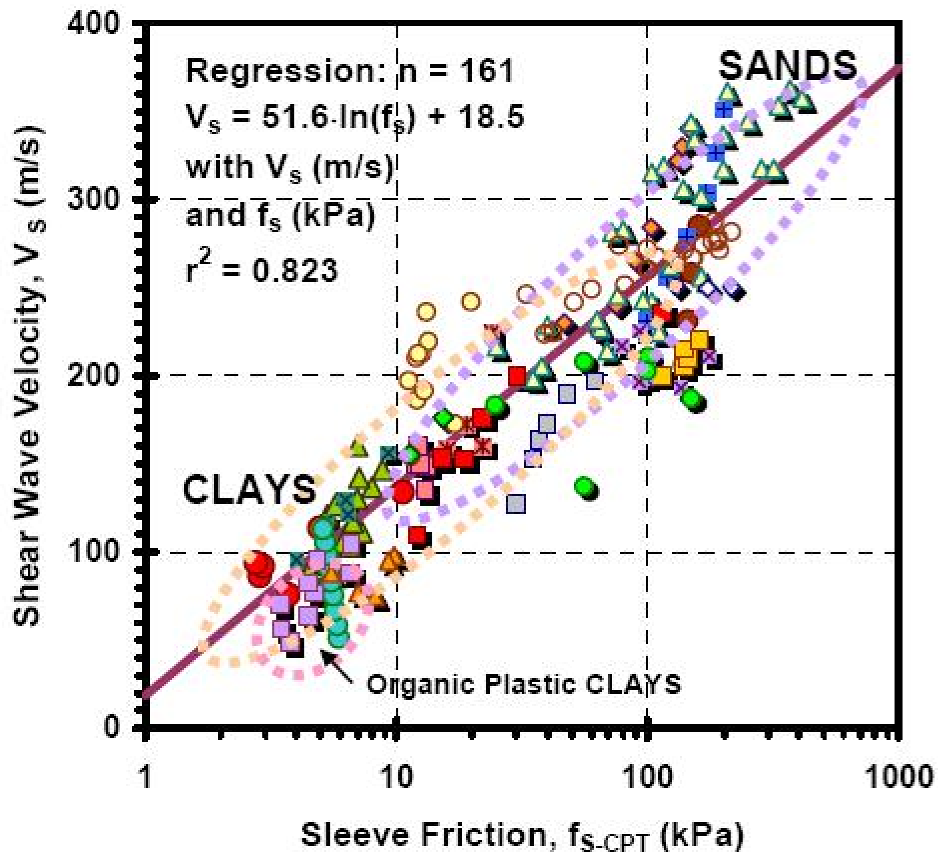


Figure 5.10 V_S versus CPT f_s [Mayne 2006].

5.2.7 Andrus et al. [2007]

Andrus et al. [2007] proposed All Soils correlations based on a dataset of 229 CPT and V_S measurements from sites in South Carolina (143 data pairs), California (80), and Japan (6). The dataset included soils of varying geologic age: 72 data pairs Holocene, 113 Pleistocene, and 44 tertiary. All Tertiary data was taken from the Cooper Marl in South Carolina. The majority of the V_S measurements were performed using the seismic CPT (209 data pairs); the remainder were performed using cross-hole (14) and P-S suspension logging (6) techniques.

5.2.8 Robertson [2009]

Robertson [2009] developed an All Soils relationship between CPT and V_S based on a database of approximately 1035 data pairs from sites throughout the world.

5.3 CORRELATION EQUATIONS

Table 5.3 summarizes the V_S prediction equations from the above referenced studies. For consistency, the equations have been modified to use consistent units: q_c, f_s, and σ'_v are presented in kPa and depth is presented in meters. The number of data points used to develop each correlation equation is presented in Column 5.

Coefficients of determination (r^2) for each equation are presented in Column 6. The scatter in data for CPT-based correlations is due in part to the variation in depth interval over which readings were taken. Typically, CPT measurements are taken every 5 cm, whereas V_S measurements are taken every 1 to 1.5 m [Robertson, 2009].

Table 5.3 CPT–V_S Correlation equations: Equations (5.6) through (5.20).

Soil Type	Study	Geologic Age	Number of Data Pairs	r^2	V_S (m/s)	(Eq #)
All Soils	Hegazy & Mayne (1995)	Quaternary	323	0.70	$(10.1 \log(q_c) - 11.4)^{1.67} (100 f_s/q_c)^{0.3}$	(5.6)
	Mayne (2006)	Quaternary	161	0.82	$118.8 \log(f_s) + 18.5$	(5.7)
	Piratheepan (2002)	Holocene	60	0.73	$32.3\, q_c^{0.089}\, f_s^{0.121}\, D^{0.215}$	(5.8)
	Andrus et al. (2007)	Holocene & Pleistocene	185	(H) 0.71 (P) 0.43	$2.62\, q_t^{0.395}\, I_C^{0.912}\, D^{0.124}\, SF^{a}$	(5.9)
	Robertson (2009)	Quaternary	1,035	----	$[(10^{(0.55Ic+1.68)})(q_t - \sigma_v)/p_a]^{0.5}$	(5.10)
Sand	Sykora & Stokoe (1983)	----	256	0.61	$134.1 + 0.0052\, q_c$	(5.11)
	Baldi et al. (1989)	Holocene	----	----	$17.48\, q_c^{0.13}\, \sigma'^{0.27}_v$	(5.12)
	Hegazy & Mayne (1995)	Quaternary	133	0.68	$13.18\, q_c^{0.192}\, \sigma'^{0.179}_v$	(5.13)
	Hegazy & Mayne (1995)	Quaternary	92	0.57	$12.02\, q_c^{0.319}\, f_s^{-0.0466}$	(5.14)
	Piratheepan (2002)	Holocene	25	0.74	$25.3\, q_c^{0.163}\, f_s^{0.029}\, D^{0.155}$	(5.15)
Clay	Hegazy & Mayne (1995)	Quaternary	406	0.89	$14.13\, q_c^{0.359}\, e_0^{-0.473}$	(5.16)
	Hegazy & Mayne (1995)	Quaternary	229	0.78	$3.18\, q_c^{0.549}\, f_s^{0.025}$	(5.17)
	Mayne & Rix (1995)	Quaternary	339	0.83	$9.44\, q_c^{0.435} e_0^{-0.532}$	(5.18)
	Mayne & Rix (1995)	Quaternary	481	0.74	$1.75\, q_c^{0.627}$	(5.19)
	Piratheepan (2002)	Holocene	20	0.91	$11.9\, q_c^{0.269}\, f_s^{0.108}\, D^{0.127}$	(5.20)

Units: q_c, q_t, f_s, σ_v, and σ'_v are measured in kilopascals (kPa), and depth (D) is measured in meters (m). p_a = 100 kPa.
[a]SF = 0.92 for Holocene and 1.12 for Pleistocene

5.4 USE OF CORRECTED TIP RESISTANCE IN CORRELATION EQUATIONS

Many government agencies perform conventional CPTs without pore pressure measurement. In the absence of pore pressure measurement, the interpretations of soil parameters and application of direct CPT methodologies may be less reliable. The correction is relatively insignificant for sands (less than 10% error), as q_c is generally large relative to the water pressure u_2, which is usually close to u_0; hence, $q_t \sim q_c$ in coarse-grained soils. The unequal end-area correction can be significant in soft fine-grained soil where q_c is low relative to water pressure around the cone due to the undrained penetration condition. The correlation equations in Table 5.3 are presented in their original form. If pore pressure measurements are available, correlations presented herein should use the corrected cone resistance q_t.

5.5 AGE SCALING FACTORS

The correlation equations presented in Table 5.3 were generally developed for Holocene or Quaternary soils. The age of soil deposits is often not known. Equations developed for Holocene and Quaternary soils may slightly underestimate V_S for Pleistocene soils, but are generally valid for all Quaternary soils [Robertson 2009].

If the thicknesses of Holocene and/or Pleistocene soils are known, ASFs may improve the accuracy of the predicted V_S. Andrus et al. [2007] reported ASFs of 0.92 and 1.12 for Holocene and Pleistocene soils, respectively.

5.6 SELECTION OF CORRELATION EQUATIONS

The published CPT–V_S correlation equations presented in Table 5.3 were generally developed for specific soils types (i.e., "Sand" or "Clay") or for more general All Soils. Two methods were evaluated for selecting which correlation equations to use for design. The first method involved using All Soils equations for the entire soil profile. The second method involved selection of soil-type dependent correlation equations based on the CPT SBT. The two methods were used to estimate V_{S30} for 34 CPTs from the USGS database listed in Section 2.4.2.

The All Soils method used an average of three equations: Equation (5.7) [Mayne 2006], Equation (5.9) [Andrus et al. 2007], and Equation (5.10) [Robertson 2009]. The ASF was set at 1.0 for the Andrus et al. (2007) to represent all Quaternary soil. The Piratheepan [2002] All Soils equation and the Andrus et al. equation were based on a similar dataset. The Andrus et al. equation was selected over the Piratheepan because it was newer and relied on an expanded dataset.

The soil type-specific method developed used an average of three or four of the published correlations for each soil type. For sandy soils ($I_C < 2.05$), V_S was estimated using the average result from Equation (5.11) [Sykora and Stokoe 1983], Equation 5.12 [Baldi et al. 1989], Equation 5.13 [Hegazy and Mayne 1995], and Equation 5.15 [Piratheepan 2002].

For intermediate soils ($2.05 < I_C < 2.60$), V_S was estimated using the average result from the three All Soils equations.

For clayey soils ($I_C > 2.60$), V_S was estimated using the average result from Equation (5.17) [Hegazy and Mayne 1995], Equation (5.19) [Mayne and Rix 1995], and Equation (5.20) [Piratheepan 2002].

Statistically, the two methods performed similarly. On average, the soil type-specific method under-predicted by V_{S30} by approximately 8%, and the All Soils method under-predicted V_{S30} by approximately 3%.

The soil type-specific method produced spikes (high and low) in the predicted V_S profile at material transitions where difference equations were used for adjacent CPT sub-layers. For this reason, as well as, ease of implementation, the All Soils method was considered to be more desirable.

5.7 SITE-SPECIFIC CORRELATION EQUATIONS

Site-specific correlations between V_S and CPT data can be developed based on regression analysis following the same procedure presented in Section 4.4 for SPT data. The functional form shown in Equation (5.21) is recommended:

$$V_S = a \cdot q_t^{\,b} \cdot f_s^{\,c} \cdot \sigma'^{\,d}_v \tag{5.21}$$

5.8 RECOMMENDATIONS

V_S for Quaternary soils may be estimated using the average of value calculated by Equation (5.7) [Mayne 2006], Equation 5.9 [Andrus et al. 2007], and Equation 5.10 [Robertson 2009]. If the thicknesses of Holocene and/or Pleistocene soils are known, ASFs may improve the accuracy of the predicted V_S (Section 5.4).

Site-specific correlations between V_S and CPT data may be developed using functional form of Equation (5.21) and the regression procedure presented in Section 4.4.

6 Undrained Shear Strength Correlations

As discussed in Chapter 1, G_{max} and V_S of cohesive soils primarily depend on void ratio, effective stress, and stress history. Similar to penetration-based correlations, relationships between V_S and undrained shear strength for cohesive soils can be made since both properties depend on common parameters. Equation (6.1) presents a common relationship for normalized undrained shear strength.

$$S_u / \sigma'_{vo} = (S_u / \sigma'_{vo})_{NC} \, (OCR)^m \tag{6.1}$$

where S_u is the undrained shear strength, σ'_{vo} is the effective stress, $(S_u /\sigma'_{vo})_{NC}$ is the normally consolidated strength ratio, OCR is the over-consolidation ratio, and m is an exponent ranging from 0.75 to 1.0 (with a typical value of 0.8).

Dickenson [1994] proposed the following relationship [Equation (6.2)] between V_S and S_u for cohesive soils in the San Francisco Bay Area:

$$V_S \text{ (fps)} = 18 \, S_u^{0.475} \tag{6.2}$$

where V_S is measured in ft/sec and S_u is measured in psf. Equation (6.3) is a variation of Equation (6.2) with different units of V_S and S_u:

$$V_S \text{ (m/sec)} = 23 \, S_u^{0.475} \tag{6.3}$$

where V_S is measured in m/sec and S_u is measured in kPa.

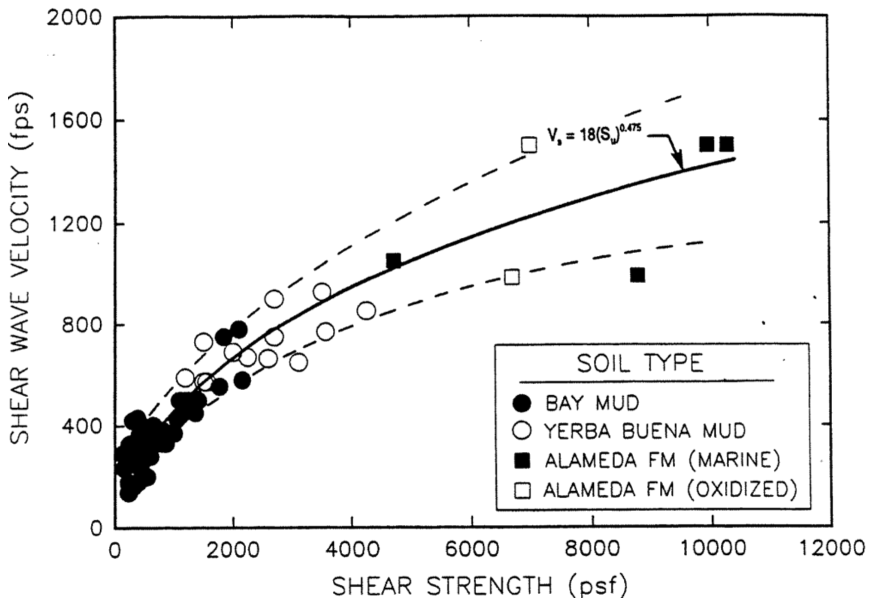


Figure 6.1 V_S versus S_u [Dickenson 1994].

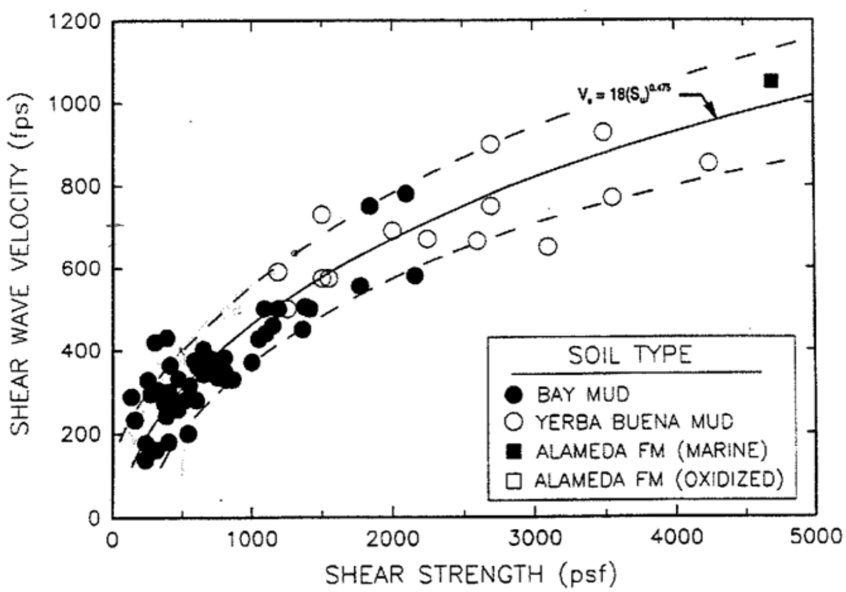


Figure 6.2 V_S versus S_u – reduced scale [Dickenson 1994].

Two plots of Dickenson's V_S data versus S_u are presented in Figures 6.1 and 6.2. This relationship was developed specifically for four cohesive soil units in the San Francisco Bay Area: Bay Mud, Yerba Buena Mud, and Alameda Formation (marine and oxidized). The above relationships may not be appropriate for use in other regions or soils of different depositional environment. Similar to both the SPT and CPT, site-specific correlations may be developed based on a limited number of site-specific V_S measurements and using a similar functional form as Equation (6.2) above.

7. Shallow Velocity Profiles and Intermediate Sites

In many cases, V_S data (either measured or estimated from geotechnical data) does not extend to a depth of 30 m. In these cases, extrapolation of shallow velocity data is required to estimate the V_{S30}. Boore (2004) proposed an extrapolation method based on statistical analysis of borehole data in California, which is discussed in Section 7.1. A method is introduced in Section 7.2 to utilize the Boore regression analysis to calculate V_{S30} for “intermediate” sites (sites containing both soil and rock within the top 30 m of the soil profile).

7.1 STATISTICAL EXTRAPOLATION

Boore [2004] proposed a method for extrapolation based on regression analysis of 135 boreholes in California that extended to depth of at least 30 m. Boore’s model involves a statistical correlation between V_{S30} and the time-averaged V_S to the terminal depth of measurement (V_{Sd}). Boore proposed the following equation [Equation 7.1)]:

$$\log V_{S30} = a + b \cdot \log V_{Sd} \qquad (7.1)$$

Regression coefficients are presented in Table 7.1 for depths ranging from 10 to 29 m. Correlation coefficients (r) between V_{Sd} and V_{S30} for the dataset are presented in Boore et al. (2011) for the depths of 5 m (r = 0.75), 10 m (r = 0.92), 15 m (r = 0.97), and 20 m (r = 0.99). As expected, correlation becomes stronger as the depth of measurement approaches 30 m. This fact is also presented graphically in Figure 7.1; the scatter in the measured V_{Sd} and V_{S30} decreases as depth (d) approaches 30 m.

Table 7.1 Boore [2004] regression coefficients.

Depth (m)	Regression Coefficients a	b
10	0.042062	1.0292
11	0.022140	1.0341
12	0.012571	1.0352
13	0.014186	1.0318
14	0.012300	1.0290
15	0.013795	1.0263
16	0.013893	1.0237
17	0.019565	1.0190
18	0.024879	1.0144
19	0.025614	1.0117
20	0.025439	1.0095
21	0.025311	1.0072
22	0.026900	1.0044
23	0.022207	1.0042
24	0.016891	1.0043
25	0.011483	1.0045
26	0.006565	1.0045
27	0.002519	1.0043
28	0.000773	1.0031
29	0.000431	1.0015

As an example calculation for the of the extrapolation equation, consider a site with an average V_S for the top 15 m of the profile (V_{Sd} or V_{S15}) of 210 m/sec. V_{S30} could be calculated using Boore's equation and the regression coefficients in Table 7.1 as:

$$\log V_{S30} = 0.013795 + 1.0263 \log (210)$$

$$V_{S30} = 250 \text{ m/sec}$$

Extrapolating shallow velocity data to calculate V_{S30} may be appropriate for most sites with relatively uniform soil conditions. This method could lead to errors for sites with a velocity contrast within the top 30 m, such as soft soil over stiff soil or soil over bedrock (as discussed in Section 7.2).

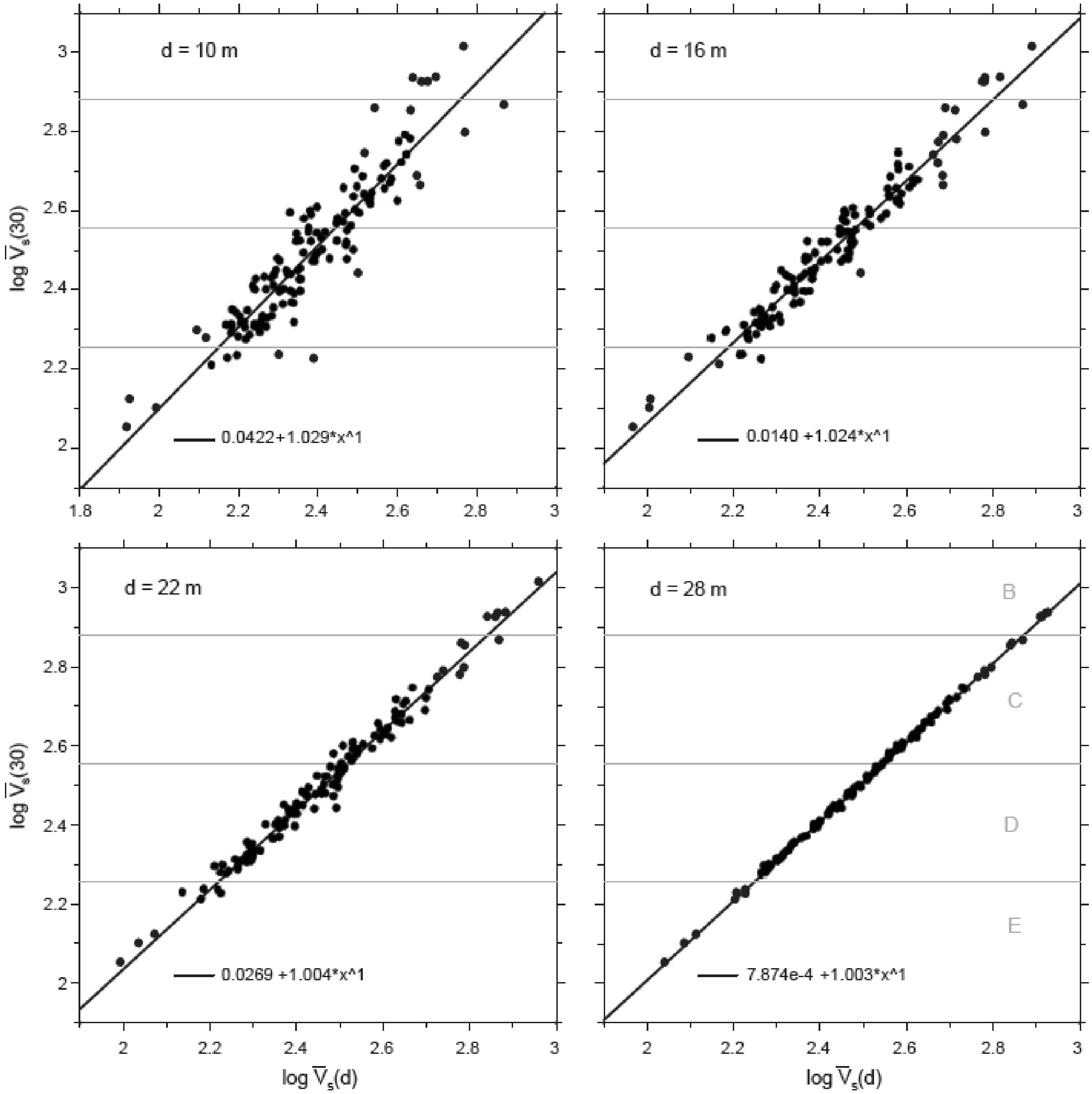


Figure 7.1 log V_{S30} versus log V_{Sd} for Varying Depths [Boore 2004].

7.2 INTERMEDIATE SITES

Intermediate sites have both soil and rock strata within the top 30 m of the profile. The V_S of the soil and rock portions may be estimated separately. The composite V_{S30} may then be calculated using Equation (1.2).

The V_S of the soil portion can be estimated based on geologic and/or geotechnical data as discussed in Chapters 2 through 5 and summarized in Section 8.2. In the absence of measured V_S of the rock portion of the profile (either at the site or within the same geologic unit), the V_S for the rock portion of the profile may be estimated based on published correlations between V_{S30} on surficial geology, such as those discussed in Section 2.3. Since the rock portion of intermediate sites will be less than 30 m, published V_{S30} values must be reduced to represent only the portion of the rock within 30 m of the ground surface.

8 Conclusions

The purpose of this study was to generate guidelines to assist Caltrans engineers in estimating the V_S of the top 30 m of the soil profile (V_{S30}) in the absence of site-specific data or when explorations do not extend to a depth of 30 m. In general, it is recommended that engineers consider all available data including site geology, available measured profiles, and site-specific geotechnical data. The use of correlations in geotechnical engineering should be limited to the conditions for which they were developed and calibrated. The recommendations presented in this paper should be used in conjunction with the engineer's own experience and engineering judgment. Consideration should be given dynamic properties of the structure and the sensitivity of the design ground motion and structural design to shear wave velocity (V_S) or V_{S30}.

Specific recommendations for "Rock," "Soil," and "Intermediate" sites are provided in the following sections. Following the procedures and recommendations provided in this report should provide an estimated V_{S30} within 30% of the actual value, which is the threshold deemed appropriate for use with the Next Generation Attenuation (NGA) ground motion prediction equations. If the resulting V_{S30} values differ from each other by more than 30%, consideration should be given to performing site-specific measurements, or a range of V_{S30} should be considered for design.

8.1 ROCK SITES

Rock sites are considered to be any site with bedrock within approximately 3 m of the ground surface. V_{S30} for rock sites may be estimated based on V_S measurements at the site or, in the absence of site-specific V_S measurements, based on measurements from nearby sites within the same geologic unit with an equal or greater degree of weathering and fracturing. Sources of publicly available data are discussed in Section 2.4. V_{S30} can be estimated from the published values, such as those listed in Table 2.2 or another of the studies referenced in Section 2.3. For fresh, intact bedrock with wide fracture spacing, it may be appropriate to select a mean (or mean plus one standard deviation) V_{S30} for design. For highly fractured or deeply weathered rock, it may be appropriate to select a value of one to two standard deviations below the mean.

8.2 SOIL SITES

Chapters 3 through 6 present recommendations for estimating V_S based on geotechnical properties. Recommendations for V_S estimation based on SPT and CPT data are provided in Chapters 4 and 5. The recommended equations for both SPT and CPT are appropriate for Quaternary soils. If the thicknesses of Holocene and/or Pleistocene soils are known, ASFs may improve the accuracy of the predicted V_S.

Recommendations for development of site-specific V_S correlations are provided in Sections 4.4 and 5.7 for SPT and CPT.

Chapter 6 presents a relationship between V_S and undrained shear strength (S_u). The referenced relationship was developed specifically for four cohesive marine soils in the San Francisco Bay Area. Site-specific correlations may be developed based on a limited number of site-specific V_S measurements and using a similar functional form.

Extrapolating shallow velocity data to calculate V_{S30} may be appropriate for most sites with relatively uniform soil conditions. This method could lead to errors for sites with a velocity contrast within the top 30 m, such as soft soil over stiff soil or soil over bedrock.

V_{S30} values predicted by the methods above should be compared to measured values from nearby sites and published values based on surficial geology to confirm that the predicted values are reasonable.

8.3 INTERMEDIATE SITES

Intermediate sites are considered to be sites containing both soil and rock strata within the top 30 m of the profile. Sites with less than approximately 3 m of soil over bedrock may be considered rock sites. For intermediate sites, the V_S of the soil and rock portions may be estimated separately following the recommendations provided in the two previous sections. The composite V_{S30} may then be calculated using Equation (1.2). As discussed in Section 8.1, in the absence of measured V_S of the rock portion of the profile (either at the site or within the same geologic unit), the V_S for the rock portion of the profile may be estimated based on published correlations between V_{S30} on surficial geology, such as those discussed in Section 2.3. Since the rock portion of Intermediate sites will be less than 30 m, it may be appropriate to reduce published V_{S30} values to represent only the portion of the rock within 30 m of the ground surface.

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