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EXAMINATION OF EXISTING SHEAR WAVE VELOCITY AND SHEAR MODULUS CORRELATIONS IN SOILS

by

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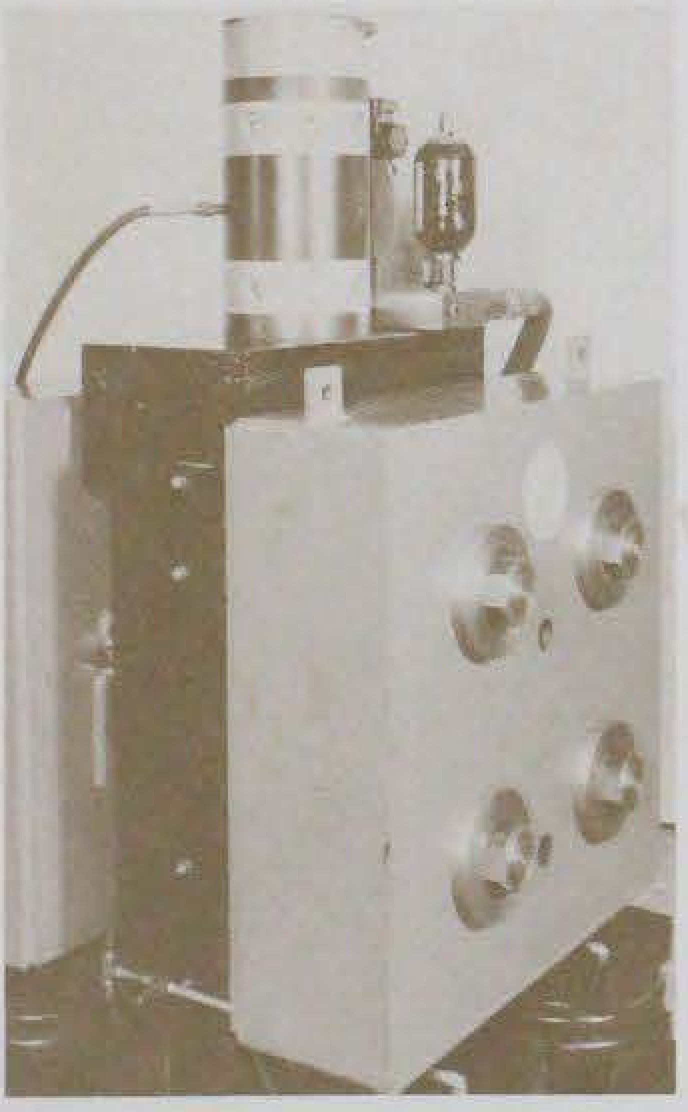

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Dynamic soil stiffness, as indicated by either shear modulus or shear wave velocity, is a prerequisite parameter for the dynamic analysis of earthen structures, foundations for superstructures, and free-field seismic response. Dynamic soil stiffness is an expensive parameter to determine in situ and in the laboratory.

Numerous researchers and practitioners have examined the viability of correlations between dynamic soil stiffness and basic, more common engineering parameters. These correlations appear to have evolved because of the expense of active measurement to augment (in some cases, replace) designated testing. Later studies seem to capitalize on a rapidly expanding data base of measured values that was nonexistent even a decade ago.

This study presents, discusses, and compares a majority of correlations involving shear modulus and shear wave velocity to date in the United States and Japan. The

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objective of this presentation is to provide the reader with a comprehensive understanding of the nature of the correlations in that they may appreciate their evolution and use the technology appropriately in everyday practice.

PREFACE

This study was conducted by the US Army Engineer Waterways Experiment Station (WES) for the Assistant Secretary of the Army (R&D), Project Number 4A161101A91D, as an In-House Laboratory Independent Research (ILIR) Program during FY 86 and FY 87. Initial appropriation was received in January 1986. The title of the overall study was "Evaluation of Dynamic Soil Stiffness Based on Correlations with Other Geotechnical Parameters."

This ILIR study was proposed and performed by Mr. David W. Sykora of the Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL), WES. The report was prepared by Mr. Sykora. It is intended to be one of three reports published under the overall ILIR study topic. The other two reports will describe the creation of a data base of seismic information at WES and the results of correlative analyses using this data base.

Some information contained herein was used by Mr. Sykora in a thesis presented to the University of Texas at Austin in partial fulfillment of the degree of Master of Science in Engineering. That work was performed under the direction of Dr. Kenneth H. Stokoe II, Department of Civil Engineering, and published as an engineering report. However, the material has been updated, rewritten, and reorganized in a manner not only to examine shear wave velocity correlations in more detail but also to allow practitioners to apply the results of various studies appropriately.

Assistance was provided by Mr. William Hanks, Soil Mechanics Division, in drafting figures. Messrs. Umehara, Yamamoto, and Inove of the University of Texas at Austin translated technical articles written in Japanese. The report was edited by Mrs. Joyce H. Walker, Information Products Division, Information Technology Laboratory, WES. Mr. Joseph P. Koester, EEGD, provided technical assistance.

Supervision at WES was provided by Dr. A. G. Franklin, Chief, EEGD. The project was conducted under the general supervision of Dr. William F. Marcuson III, Chief, GL.

COL Dwayne G. Lee, CE, is the Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (force) per square foot	47.88026	pascals
pounds per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
tons per square foot	95.76052	kilopascals

EXAMINATION OF EXISTING SHEAR WAVE VELOCITY AND SHEAR MODULUS CORRELATIONS IN SOILS

PART I: INTRODUCTION

1. The dynamic response of a soil mass subjected to excitation is the focus of much attention among engineers both in research studies and in application of state-of-the-art technology to practical problems. A key property necessary to properly evaluate dynamic response of soil is dynamic shear modulus (modulus of rigidity), G . Shear modulus is necessary to evaluate geotechnical engineering problems both quantitatively and qualitatively, including earthen structures (e.g., Makdisi and Seed 1977), foundations for superstructures (e.g., Franklin 1979), deep foundation systems (e.g., Randolph 1980), soil-structure interaction (e.g., Lysmer et al. 1975), machine foundations (Richart, Hall, and Woods 1970), and free-field response (e.g., Chen, Lysmer, and Seed 1981 and Schnabel, Lysmer, and Seed 1972). Shear modulus is also used to evaluate susceptibility of soils to liquefaction (Dobry et al. 1981) and to predict the ground surface and subsurface motions from outrunning ground shock produced by the detonation of high or nuclear explosives (Hadala 1973).

2. Values of G are determined either by measurement in the laboratory on "undisturbed" soil samples or by calculations using shear wave velocity V_s measured in situ, and the mass density of the soil. Mass density ρ may be determined using "undisturbed" soil samples or in situ density tests. Shear modulus measured at small shear strain (less than 10^{-5} in./in.*) referred to as G_{max} , ultimately is the desired initial design parameter (Hardin and Drnevich 1972b). Using elastic theory which is approximately valid at these small strains, G_{max} is calculated from V_s using the following equation:

$$G_{max} = \rho \cdot V_s^2 \qquad (1)$$

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* A table of factors for converting US customary units of measurement to metric (SI) units is presented on page 5.

3. In situ measurement of V_s provides the most accurate means to determine G_{max} (i.e., from V_s) (Woods 1986). Shear modulus measured in the laboratory via devices such as the resonant column test device are subject to empirical corrections and rely heavily on the assumption that samples are undisturbed (in particular, have not undergone alterations in fabric or cementation) and are representative. Anderson, Espana, and McLamore (1978) and Arango, Moriwaki, and Brown (1978) independently used the results of field and laboratory test measurements to determine that laboratory-derived values of G_{max} were as low as 50 percent of in-situ-derived values, even after empirical corrections were included.

4. Investigators have been attempting to develop correlations between the low-amplitude shear modulus and shear wave velocity and various soil properties for the last two decades. These correlations have evolved from measurements made in both the field and laboratory, although the accuracy and applicability of such correlations developed in these two environments differ. Under controlled laboratory conditions, precise and detailed analyses of factors affecting G and V_s have been performed. Laboratory studies have been very useful in determining soil properties and test conditions upon which G and V_s are most dependent. However, laboratory-prepared samples which offer consistency to the investigator cannot be conditioned to simulated age and cementation effects which occur after tens of thousands of years in situ. These effects are known to significantly affect the magnitude of G (and V_s). Conversely, field correlations involving V_s have been crude with considerable scatter of the data because of limited availability of measured soil properties. Field correlations to date have proved to be functional only to a limited extent in geotechnical engineering practice.

5. The intention of this review is to communicate important ideas and findings which have evolved throughout the past 25 years. Numerous studies have examined shear wave velocity correlations, both in the field and laboratory. The number of these studies included in this study is not exhaustive, nor are the correlations mentioned superior to others not mentioned. Few comparisons have been performed among the various studies available. This may, in part, be due to a language barrier between authors of the greatest number of studies (i.e., English and Japanese). A few technical articles were translated for the purpose of comparisons reported herein.

6. This report begins with an examination of laboratory studies because of the wide use of their results in dynamic analyses. Then, field studies conveniently are compared with laboratory studies. After the various field studies have been presented and discussed, they will be compared with other studies which use the same correlative parameters. This comparison will allow the readers to understand the nature of these correlations and determine which, if any, of the correlations available are most appropriate. Specific recommendations to assist the practitioner are included at the end of this report.

PART II: CORRELATIONS BASED ON LABORATORY MEASUREMENTS

7\. Laboratory studies that address parameters which affect V_s have been more precise, comprehensive, and conclusive than have field studies. Extensive laboratory work has been performed with both sands and clays to investigate such variables as void ratio, effective states of stress, strain amplitude, time of confinement, and degree of saturation. Rather than completely review the history of the numerous laboratory studies conducted to date, only a few of the more prominent studies will be examined in this section to reveal the most important factors.

Initial Study

8\. Hardin and Richart (1963) performed one of the first comprehensive laboratory investigations of variables affecting V_s in soils. A resonant column testing device was used to apply cyclic loads to laboratory-prepared samples of Ottawa sand, crushed quartz sand, and crushed quartz silt. Variables considered were confining pressure, void ratio, moisture content, grain-size distribution, and grain characteristics. The effect of shear strain amplitude was not investigated as peak-to-peak shear strains were kept consistently low (less than 10^{-5} in./in.).

9\. Variations in confining pressure and void ratio were found to have the greatest effect on V_s of the variables studies by Hardin and Richart (1963). Samples of Ottawa sand (with four different gradations) tested at confining pressures between 2,000 and 8,000 psf indicated that V_s is a function of the one-fourth power of the effective confining pressure. Values of V_s measured in samples tested at confining pressures less than 2,000 psf were a function of slightly larger exponential values (>0.25) and were influenced somewhat by moisture content. Shear wave velocity was found to decrease linearly with increasing void ratio and to be independent of relative grain size, gradation, and relative density.

10\. Hardin and Richart (1963) concluded that the V_s of different soils at the same relative density and confining pressure may be quite different, but that different soils at the same void ratio have essentially the same V_s. Hence, the major effect of grain size and gradation was to change the range of possible void ratios which in turn had a significant effect on V_s.

In general, soils with finer relative grain-size distributions have a larger void ratio, and, therefore, a lower V_s. Hardin and Richart also found that given two sands at similar void ratios, one with angular grains and another with rounded grains, V_s in the soil with angular grains is larger. This observation is more pronounced at low confining pressures.

11. The empirical equations developed by Hardin and Richart (1963) with a reported accuracy within ±10 percent are:

for $\bar{\sigma}_o < 2{,}000$ psf:

$$V_s = (119 - 56.0e)\, \bar{\sigma}_o^{0.30} \quad \text{(fps)} \tag{2}$$

for $\bar{\sigma}_o > 2{,}000$ psf:

$$V_s = (170 - 78.2e)\, \bar{\sigma}_o^{0.25} \quad \text{(fps)} \tag{3}$$

where e = void ratio

$\bar{\sigma}_o$ = effective confining pressure (psf).

12. Effects of load history on sands preloaded to simulate the history of field loading conditions were found to be minimal by Hardin and Richart (1963). Shear wave velocity decreased 1 to 4 percent when dry Ottawa sand was preloaded from 16 to 50 psi and then unloaded and retested at 16 psi (producing an overconsolidation ratio of slightly greater than three). The authors attributed this behavior in part to the roundness of the sand grains.

Comprehensive Study

13. Hardin and Drnevich (1972a,b) conducted one of the first comprehensive investigation of parameters affecting the stress-strain relations in soils in the strain range of 0.1 percent or less using results of resonant column and simple shear testing. Shear modulus and damping ratio of both clean sands and cohesive soils were considered. Hardin and Drnevich concluded that strain amplitude, effective mean principal stress, and void ratio are very important parameters that affect the shear modulus of both clean sands and clays. In addition, degree of saturation is very important for clays.

Parameters of lesser importance on the value of G in clean sands are the effective strength envelope and octahedral shear stress. The parameters examined by Hardin and Drnevich (1972a) along with their corresponding importance on shear modulus and damping ratio are summarized in Table 1.

14. Parameters which were reported to be relatively unimportant in directly determining G (and V_s) are also of importance to this study. Hardin and Drnevich showed that for clean sands, the number of low-amplitude cycles of loading, degree of saturation, overconsolidation ratio, frequency of loading, thixotropy, soil structure, and grain characteristics (size, shape, gradation, and mineralogy) have relatively little influence on G. The authors note that although these parameters are listed as being relatively unimportant in directly affecting G, they may have an effect on void ratio, shear strain amplitude, and effective mean principal stress.

15. Hardin and Drnevich (1972a) discuss the results of parametric studies which examined the effects of numerous factors on G. Shear strain amplitude has no effect on G at magnitudes less than 0.25×10^{-2} percent (representing G_{max}). At larger amplitudes, G decreases with increasing amplitude. At lower amplitudes, G_{max} varies with the square root of the effective mean principal stress $\bar{\sigma}_m$ with G increasing with increased $\bar{\sigma}_m$. The authors reference a study by Hardin and Black (1968) who developed an expression relating void ratio e to G. This function, as determined from laboratory tests on undisturbed cohesive soils, is:

$$G = f\left[\frac{(2.973 - e)^2}{1 + e}\right] \tag{4}$$

Using Equation 1, a function for V_s can be determined to be:

$$V_s = f\left[\frac{(2.973 - e)^2}{1 + e}\right]^{1/2} \tag{5}$$

16. Hardin and Drnevich (1972b) developed a particular relationship with G_{max} for an isotropic state of stress:

$$G_{max} = 1230 \cdot \frac{(2.973 - e)^2}{1 + e} \cdot OCR^k \cdot \bar{\sigma}_m^{0.5} \quad \text{(psi)} \tag{6}$$

Table 1

Factors Affecting the Shear Modulus and Damping of Soil as Determined by Laboratory Tests (Hardin and Drnevich 1972a)

	Importance To*			
	Modulus		Damping	
	Clean Sands	Cohesive Soils	Clean Sands	Cohesive Soils
Strain amplitude	V	V	V	V
Effective mean principal stress	V	V	V	V
Void ratio	V	V	V	V
Number of cycles of loading	R**	R	V	V
Degree of saturation	R	V	L	U
Overconsolidation ratio	R	L	R	L
Effective strength envelope	L	L	L	L
Octahedral shear stress	L	L	L	L
Frequency of loading (above 0.1 cycle/sec)	R	R	R	L
Other time effects (thixotropy)	R	L	R	L
Grain characteristics, size, shape, gradation, mineralogy	R	R	R	R
Soil structure	R	R	R	R
Volume change due to shear strain (for strains less than 0.5 percent)	U	R	U	R

---

* V means very important, L means less important, and R means relatively unimportant except that it may affect another parameter; U means relative importance is not clearly known at this time.

** Except for saturated clean sand where the number of cycles of loading is a less important parameter.

where

OCR = overconsolidation ratio

k = dimensionless quantity which is a function of plasticity index (PI)

$\bar{\sigma}_m$ = mean effective stress, psi

Values of k are presented in Table 2. Although developed for cohesive materials, Equation 6 was found to be applicable to cohesionless soils simply by setting k equal to 0 (PI is equal to 0).

Table 2

Empirical Values of Exponential Parameter (k)

Proposed by Hardin and Drnevich (1972b)

PI	k
0 (sands)	0
20	0.18
40	0.30
60	0.41
80	0.48
≥100	0.50

17. Later, Yoshimi et al. (1977) proposed a slightly different function of void ratio to shear modulus. This new function was reported to be more appropriate for rounded-grained soils, whereas, the Hardin-Black function was still applicable for angular grains.

Other Findings

18. Hamilton (1971) presents the results of laboratory pulse measurements of V_s in coarse and fine quartz sands to determine a simple correlation independent of void ratio, a parameter necessarily determined in the laboratory. The intention of the tests was to determine the effect of effective overburden pressure, $\bar{\sigma}_v$, (which can be calculated using moist densities and the location of the phreatic surface) on V_s. The findings were as follows:

For fine sands (grain size ranging from 0.149 to 0.125 mm):

$$1.4 \leq \bar{\sigma}_v \leq 29.0 \quad \text{(tsf)}, \quad V_s = 782\ \bar{\sigma}_v^{\ 0.28} \quad \text{(fps)} \tag{7}$$

For coarse sands (grain size ranging from 0.84 to 0.59 mm):

$$1.4 \leq \bar{\sigma}_v \leq 7.2 \quad \text{(tsf)}, \quad V_s = 846\ \bar{\sigma}_v^{\ 0.31} \quad \text{(fps)} \tag{8}$$

$$7.2 \leq \bar{\sigma}_v \leq 29.0 \quad \text{(tsf)}, \quad V_s = 941\ \bar{\sigma}_v^{\ 0.26} \quad \text{(fps)} \tag{9}$$

19. Lawrence (1965) performed tests using pulse techniques in small cylindrical samples to relate V_s to effective confining stress. Values of V_s were found to be a function of the one-fourth power of $\bar{\sigma}_o$. This value of exponent of $\bar{\sigma}_o$ is consistent with several other laboratory studies.

20. Marcuson and Wahls (1972) used results of numerous tests to determine that G measured in the laboratory varies with time of confinement for laboratory-prepared samples of clay. This finding has since been confirmed for other soil types, including sands. They concluded that time of confinement must be considered when applying results from laboratory samples to field conditions. More important to this study was the noted increase in G with time beyond that associated with a decrease in void ratio, even for sands. This implies that factors such as soil fabric contribute to increases in G with time, even for relatively short periods feasible for laboratory testing. This seems to contradict the conclusion by Hardin and Drnevich (1972a) that soil structure is relatively unimportant to G .

Recent Determinations

21. Knox, Stokoe, and Kopperman (1982) prepared a 7-ft-cubed dry sand sample in a steel-framed structure in which true triaxial stress states could be applied. It was concluded that, for shear waves propagating in a principal stress direction with particle motion also in a principal stress direction, V_s was only dependent on the stress in the direction of particle motion and stress in the direction of shear wave propagation. Shear wave velocity, then, was found to be essentially independent of the state of stress in the third orthogonal direction. Therefore, V_s is not necessarily a function of $\bar{\sigma}_m$.

Other studies (e.g., Lawrence 1965 and Roesler 1979) produced similar results although exponential factors varied slightly, typically with magnitudes less than 0.25.

22. Applying the results of Knox, Stokoe, and Kopperman (1982) to Equation 6, the resulting equation is:

$$G_{max} = 1230 \cdot \frac{(2.973 - e)^2}{1 + e} \cdot OCR^k \cdot \bar{\sigma}_a^{0.25} \cdot \bar{\sigma}_b^{0.25} \cdot \bar{\sigma}_c^{0.0} \quad (10)$$

where

$\bar{\sigma}_a$ = effective stress in direction of shear wave propagation, psi

$\bar{\sigma}_b$ = effective stress in direction of shear wave particle motion (perpendicular to propagation direction), psi

$\bar{\sigma}_c$ = effective stress in third (remaining) orthogonal direction (perpendicular to $\bar{\sigma}_a$ and $\bar{\sigma}_b$), psi

23. Lee and Stokoe (1986) examined, in detail, the effect of anisotropy on measured values of V_s and calculated values of G both theoretically and by using the cube triaxial device reported in Knox, Stokoe, and Kopperman (1982). One excerpt from Lee and Stokoe (1986) is useful to gain insight into the general effect of anisotropy:

> The theory of wave motion in an isotropic space yields one compression wave velocity and one shear wave velocity. Once these wave velocities are measured, values of dynamic constrained modulus (M), shear modulus (G), Young's modulus (E), and Poisson's ratio (ν) can then be determined. However, for nearly all level soil deposits, either inherent or stress-induced anisotropy exists. This anisotropy results in (at least) two compression wave velocities and two shear wave velocities present for wave measurements along principal stress directions. The material model which best describes this condition is known as a cross-anisotropic model. The four wave velocities are related to four of the five independent constants required to describe a cross-anisotropic model... Therefore, any simple equation relating shear modulus or shear wave velocity to the mean effective stress...cannot reflect the anisotropy of the material...
>
> Stress-induced anisotropy may cause an isotropic medium to behave as a cross-anisotropic material. This is one of the main reasons for the discrepancy between measured values of V_s and values predicted by the "mean-effective-stress" method... As such, a "three-individual-stresses" method is employed in this study as compared to the "mean-effective-stress" method or the "average-stress" method...

24. Different nomenclature is used henceforth in this study to simplify describing the anisotropic stress condition which is used to calculate G_{max} . The relationship between G_{max} and effective stress for a cross-anisotropic (biaxial) stress condition is:

$$\left(G_A\right)_{max} = f\left(\bar{\sigma}_A^{\ 0.50}\right) \tag{11}$$

where:

G_A = shear modulus in principle stress plane a-b

$\bar{\sigma}_A$ = cross-anisotropic effective stress = $\left(\bar{\sigma}_a \cdot \bar{\sigma}_b\right)^{0.5}$

25. Seed and Idriss (1970), and later Seed et al. (1984) attempted to simplify the equation proposed by Hardin and Drnevich (1972b) (Equation 6). Seed and Idriss (1970) developed the equation:

$$G = 1000\ K_2 \left(\bar{\sigma}_m\right)^{1/2} \text{ (psf)} \tag{12}$$

where K_2 is a shear modulus coefficient. At low shear strain (less than 10^{-4} percent), K_2 is referred to as $\left(K_2\right)_{max}$ corresponding to G_{max} . Parametric studies indicated that $\left(K_2\right)_{max}$ was a function only of void ratio and typically ranged from 30 (loose sands: $e \approx 0.95$) to 75 (dense sands: $e \approx 0.35$). Select data from six sites in the United States were used to substantiate this range (although values of $\left(K_2\right)_{max}$ of 166 and 119 for slightly cemented and clayey sands, respectively, were ignored).

26. Seed et al. (1984) used the results of laboratory tests on gravels to determine a range in $\left(K_2\right)_{max}$ of 80 to 180 for relatively dense, well-graded gravels. The results were in good agreement with in situ measurements made at four sites, two of which were not in the United States but in Caracas, Venezuela.

Discussion

27. Numerous laboratory studies have been performed to examine parametric effects on G . However, a few studies are conclusive enough to allow premises to be formulated for the remainder of this study. The consensus of studies indicates that void ratio and the effective stress state are the two primary variables which affect V_s measured in situ (small strain). Specifically, the cross-anisotropic effective stress is the parameter which controls V_s in most soil deposits. Overconsolidation ratio is also important for cohesive soils. Shear strain amplitude is not of concern for field studies since seismic methods typically measure V_s at a range of strain below the threshold strain. Time of confinement is also very important when determining field G from laboratory-prepared samples.

PART III: CORRELATIONS BASED ON FIELD MEASUREMENT

28. Published studies which address field correlations involving V_s concentrated initially in Japan and more recently in the United States. Variables associated with soil properties, site location, and soil strata conditions have been studied. Criteria for choosing particular variables used in specific V_s correlations appear to have been:

- a. Availability of information.
- b. Parameters which were thought to be most indicative of V_s.
- c. Modest levels of accuracy.
- d. Simplicity.
- e. Economics.

Consequently, the complexity and accuracy of the correlative studies and subsequent equations vary considerably.

Initial Studies

29. The first few studies performed to determine methods of estimating V_s appear to be well conceived but very indirect. Most initial studies conclude with a relationship between Standard Penetration Test (SPT) N-value and V_s derived from theory and laboratory measurements as opposed to a field-derived data base. The inclusion of these studies in this report is deemed important to understand and appreciate the evolution of V_s correlations.

30. Sakai (1968) investigated the possibility of correlating V_s and N-value to assist in earthquake analyses. Sakai used both the SPT and plate-bearing tests and assumed the soil to be an elastic material to determine the vertical distribution of V_s. The equation ultimately used to calculate V_s was:

$$V_s = \sqrt{\frac{E}{\rho} \frac{1}{2(1 + \nu)}} \qquad (13)$$

where

E = Young's modulus

ρ = mass density

ν = Poisson's ratio

31. Young's modulus was the key parameter necessary to calculate V_s. Sakai attempted to determine E by performing plate-bearing tests and correlating the allowable bearing capacity q_a measured in this test and SPT N-value. Shear wave velocity could then be correlated with N-value.

32. Sakai (1968) presented equations to calculate V_s in sands from N-value that depend on the average strains determined in the plate-bearing test. Average strain $\bar{\varepsilon}$ was used because of the variation in strain with depth. Sakai suggested that $\bar{\varepsilon}$ be determined by averaging the strain over a specific depth-of-influence, usually three to four times the diameter of the circular loading plate. The equations proposed by Sakai (1968) were combined for the complete range in $\bar{\varepsilon}$ from 1/600 to 1/167 (in./in.) and assumed values of ν ranging from 0.2 to 0.5 to produce:

$$V_s = (49 \text{ to } 110)\ N^{0.5} \quad \text{(fps)} \tag{14}$$

33. Sakai (1968) then compared his results with previous correlations by Kanai (1966), and undated work by a researcher named Yoshikawa. Kanai (1966) used the results of over 70 microtremor measurements, mostly in sands, to develop the correlative equation:

$$V_s = 62\ N^{0.6} \quad \text{(fps)} \tag{15}$$

Yoshikawa (date unknown) proposed the correlation:

$$V_s = 3.28 \left(\frac{N + b}{a}\right) \quad \text{(fps)} \tag{16}$$

where $1 \le b \le 3$ and $1/3{,}000 \le a \le 1/1{,}500$ which can be rewritten to produce the following maximum range in V_s:

$$V_s = 127\ (N + 1)^{0.5} \quad \text{to} \quad 178\ (N + 3)^{0.5} \quad \text{(fps)} \tag{17}$$

Sakai claimed that the results of his correlations were more similar to those of Yoshikawa, mostly because of the similarity in the exponential term (0.5).

34. Ohsaki and Iwasaki (1973) modified data reported by Kanai (1966) using typical values of in situ density for sands and clays (115 and 100 pcf,

respectively) to make a comparison between shear modulus of sands and clays, as depicted in Figure 1. Trends shown in this figure suggest that at equal N-values, a clay has a larger shear modulus than a sand.

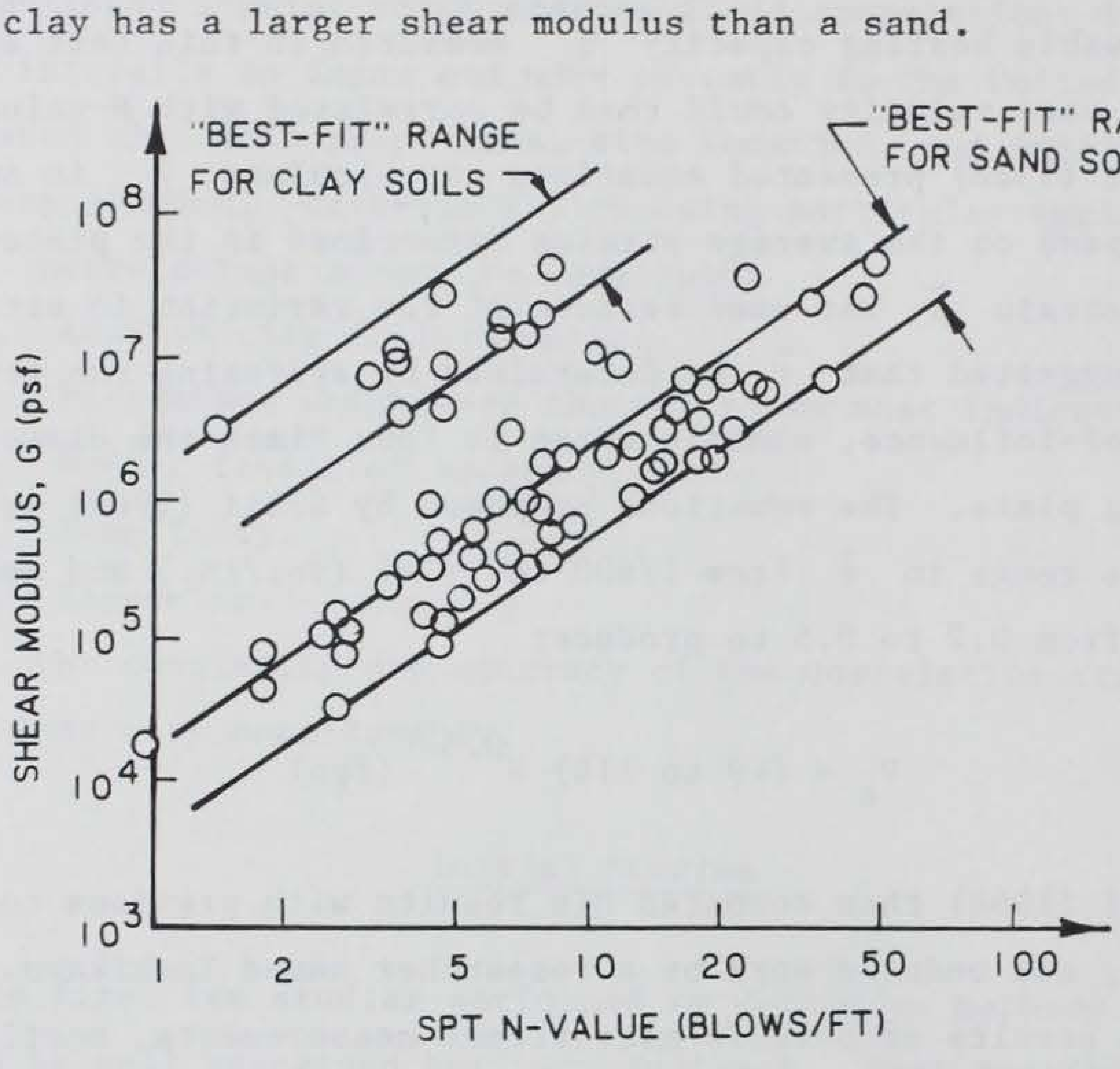

Figure 1. Variation in shear modulus of sands and clays with SPT N-value (Kanai 1966) (as presented in Ohsaki and Iwasaki 1973)

35. Shibata (1970) combined the results of several previous studies on factors affecting V_s to obtain a correlation between V_s and N . His main priority was to account for the fact that both N-value and V_s are functions of density (for sandy soils) and effective overburden pressure.

36. Shibata first considered work performed by Gibbs and Holtz (1957), Schultze and Menzenbach (1961), and Yanase (1968), all of which address the effect of relative density D_r and effective overburden pressure $\bar{\sigma}_v$ on measured N-values. He concluded from the consistency of these three studies that the $\log N - \log \bar{\sigma}_v$ relationship is linear for any particular D_r with a slope of nearly 0.5, and the $\log N - \log D_r$ relationship is linear for any particular effective overburden pressure, with a slope of nearly 2.0.

37. The porosity n of the soil was used to find that N-value was a linear function of $(n_{max} - n)$ for a particular effective overburden pressure. The quantity n_{max} was defined by extrapolating laboratory curves of N versus n to obtain an intercept (a value of n at N equal to 0). An

example of this is given in Figure 2 along with the corresponding linear function of N versus $(n_{max} - n)$. The following relation was then derived:

$$N = A\,(n_{max} - n)\,\bar{\sigma}_v^{\,0.5} \quad \text{(blows/ft)} \tag{18}$$

where

A = constant = 57 to 61

$\bar{\sigma}_v$ = effective overburden pressure, psi

Shibata developed the range in values of A from laboratory studies.

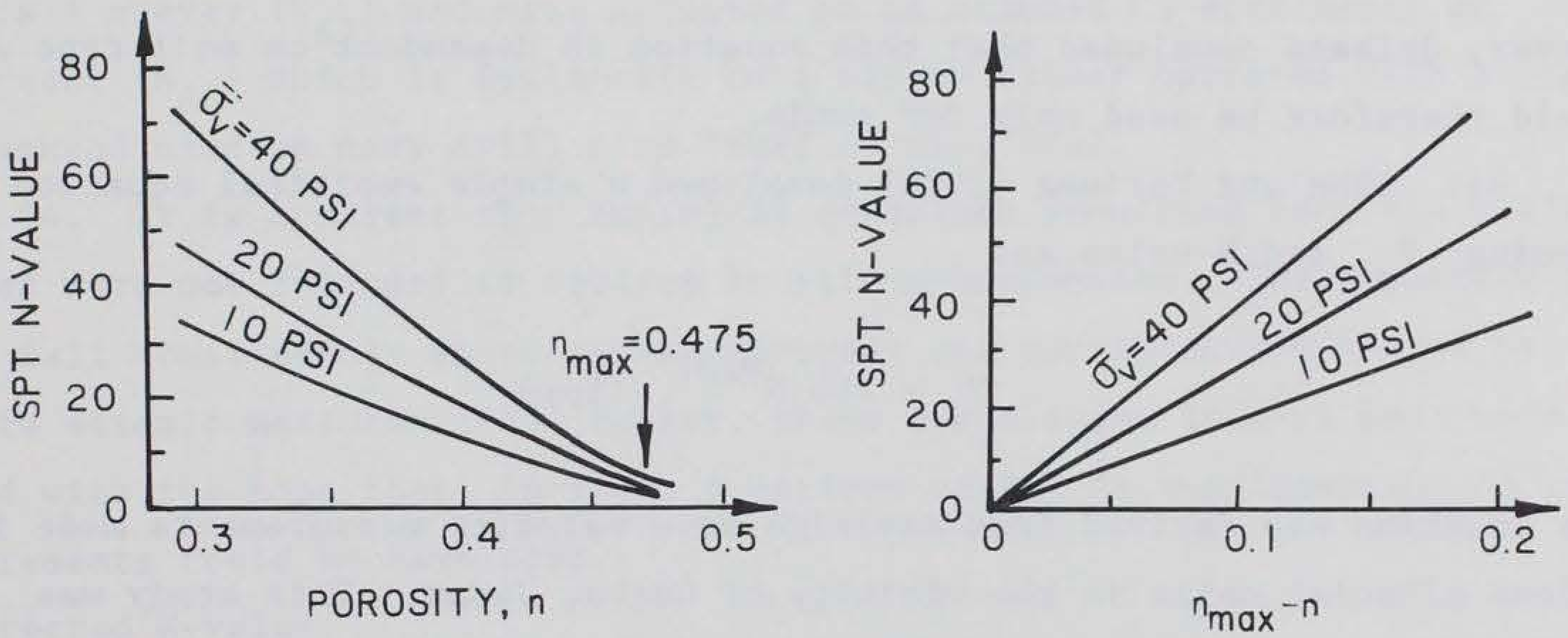

Figure 2. Laboratory results used by Shibata (1970) to develop a correlation between N-value and V_s

38. Next, Shibata considered a study by Toki (1969) that addressed the relationship between V_s, D_r, and $\bar{\sigma}_v$. Toki (1969) made theoretical calculations using porosity, effective overburden stress, and shear wave velocity in sand. His calculations and constant A' were supported by ultrasonic pulse tests performed in a triaxial compression apparatus. Toki thereupon developed the relation:

$$V_s^2 = A'\,(n_{max} - n)\,\bar{\sigma}_v^{\,0.5} \quad (\text{ft}^2/\text{sec}^2) \tag{19}$$

where

A' = constant = 5.70×10^5

$\bar{\sigma}_v$ = effective overburden pressure, psi

39. Shibata used laboratory data presented by Hardin and Richart (1963) to calculate a range of values for A' of (5.65 to 6.00) × 10^5 using Equation 19. The value of A' determined from Toki's data is in the range of values from Hardin and Richart's study.

40. After determining that V_s could be expressed as a function of N-value, porosity, and effective overburden stress, Shibata combined Equations 18 and 19 to produce an equation which is independent of $\bar{\sigma}_v$ and n :

$$V_s = 104\ N^{0.5} \quad \text{(fps)} \tag{20}$$

However, Shibata concluded that this equation is dependent on soil type and should therefore be used only for sands.

41. Ohba and Toriuma (1970) developed a simple empirical equation relating V_s and N-value as:

$$V_s = 280\ N^{0.31} \quad \text{(fps)} \tag{21}$$

This equation was derived from Rayleigh wave velocity measurements made in various alluvial soils in the vicinity of Osaka, Japan. This study was reported by Ohsaki and Iwasaki (1973); no other information was given.

Correlations with SPT N-Value

42. Numerous correlative studies have been conducted to directly examine a relationship between SPT N-value and V_s . Most of these studies were performed in the 1970's in Japan. Since then, a few similar studies have been reported in the United States. Since then, too, careful scrutiny of SPT techniques and procedures have been made in both countries. As a better understanding of the variables affecting N has developed, corrections can be applied to preexisting correlation studies. Specifically, the effect of energy delivered to the drill rod and the effect of the effective overburden stress on N are significant and important to the examination of N versus V_s correlations. Studies incorporating measured N-values (uncorrected) will be reviewed separately from the few studies which examined effective-vertical-stress-corrected N-values N_1 .

43. A recent study by Seed et al. (1985) that compared energy efficiencies and techniques of typical Japanese SPT equipment and procedures with US equipment and procedures indicates that a one-to-one correspondence of N-values between countries is imprecise. Given that techniques for measurement of dynamic properties are equivalent between countries, comparisons between N versus V_s correlations from Japan and the United States must be put on an equivalent basis by adjusting N-values to account for differences. Equations reported in this chapter have not been adjusted to account for differences in energy. However, for graphical comparisons made in Part IV, Japanese N-values were assumed to correspond to an efficiency of 67 percent of free-fall energy (N_{67}) and were adjusted to an assumed US efficiency of 60 percent (N_{60}) which is applicable to a safety hammer operated with a rope and cathead used on many drill rigs (Seed et al. 1985).

44. It is apparent that empirical equations resulting from the various studies were not intended to replace in situ measurements. These correlations would fall considerably short of the accuracy and consistency produced by in situ seismic measurements. Rather, these correlative studies were conducted with the hope that, in time, equations useful in supplementing in situ measurements could be developed.

Uncorrected N-value

45. Ohsaki and Iwasaki (1973) performed simple statistical analyses on over 200 sets of data accumulated from seismic explorations (using predominantly downhole techniques) throughout Japan. The authors were primarily concerned with determining a basic correlation between G and N, but they did analyze the effects of geologic age and soil type.

46. SPT N-values used in the analyses by Ohsaki and Iwasaki (1973) were averaged per soil layer to obtain a "simplified profile," as suggested by Ohsaki and Sakaguchi (1972). This method of averaging is different from the method of using an average N-value per constant shear modulus or shear wave velocity layer which has been predominantly used by other authors. Therefore, the simplified approach results in soil boundaries which do not necessarily coincide with boundaries defining equal values of V_s. It is not known whether values of density used to calculate G from V_s were all measured values or estimated, or a combination of both.

47. Ohsaki and Iwasaki (1973) presented an equation relating G and N for all soils based on data they accumulated. The equation is:

$$G = 124\ N^{0.78} \quad \text{(tsf)} \tag{22}$$

Data used to determine this equation are shown in Figure 3. By assuming a constant value for unit weight of 112.4 pcf, as is common for Japanese sands (Ohsaki 1962), an equation to estimate V_s can be determined:

$$V_s = 267\ N^{0.39} \quad \text{(fps)} \tag{23}$$

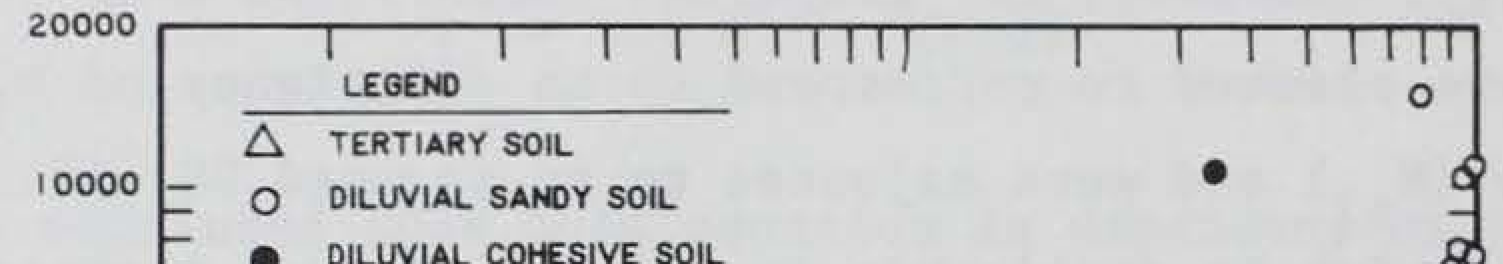

Figure 3. Correlation between SPT N-value and G (performed by Ohsaki and Iwasaki 1973)

48. Ohsaki and Iwasaki performed statistical analyses on subsets of their complete data base. Equations and correlation coefficients were developed and comparisons were made by dividing the data into groups according to soil type and geologic age divisions. Table 3 lists the parameters and correlation coefficients (r) for various divisions as presented by Ohsaki and Iwasaki. The parameters a and b are for use in an equation of the form:

$$G = a \cdot N^{b} \quad \text{(tsf)} \tag{24}$$

Table 3

Regression Parameters Resulting from Correlations Between SPT N-Value and Shear Modulus (Ohsaki and Iwasaki 1973)

Category	Groups	Parameter a	Parameter b	Correlation Coefficient
All data	--	124	0.78	0.886
Geologic age	Tertiary (Pliocene)	57.3	0.97	0.821
	Diluvial (Pleistocene)	110	0.82	0.812
	Alluvial (Holocene)	149	0.64	0.786
Soil type	Cohesionless	66.3	0.94	0.852
	Intermediate	121	0.76	0.742
	Cohesive	143	0.71	0.921
$G/\sqrt{\sigma'_m}$	Sands	--	--	0.742

Also included in Table 3 is the correlation coefficient for the ratio of $G/\sqrt{\sigma'_m}$ (where $\sigma'_m = \bar{\sigma}_m$). This ratio was considered to be proportional by Ohsaki and Iwasaki based on results of laboratory measurements by Hardin and Drnevich (1972b) and Seed and Idriss (1970). The mean effective principal stress was calculated using the coefficient of lateral earth pressure at rest K_o determined from an estimated angle of internal friction ϕ of the soil:

$$K_o = 1 - \sin \phi \tag{25}$$

The estimate of ϕ was derived from the empirical relation (Ohsaki 1962):

$$\phi = \sqrt{20N + 15} \quad \text{(degrees)} \tag{26}$$

This equation produces a minimum value of ϕ equal to 4 deg at N equal to zero.

49. The results of the statistical analyses were interesting partly because of the originality of this approach. The best relation (as determined by correlation coefficients) occurred when incorporating data only from tests in cohesive soils. The second most accurate correlation occurred when including the complete data base. The results would seem to indicate that the most

accurate correlation between G and N is independent of soil type or geologic age divisions. However, only independent use of geologic age or soil type were employed in the analyses.

50. The low correlation coefficient produced for examination of $G\sqrt{\sigma'_m}$ was of particular interest to this study. A possible explanation for this is that a significant amount of near-surface soils were used for this analysis. Relations originally proposed by Hardin and Richart (1963) indicated that V_s was a function of $\bar{\sigma}_o^{0.30}$ at $\bar{\sigma}_o$ less than 1.0 tsf (therefore $G = f\ \bar{\sigma}_o^{0.60}$, not $\bar{\sigma}_o^{0.50}$). Another plausible explanation is that values of σ'_m were estimated using two empirical equations--one to estimate K_o and the other to estimate ϕ. Therefore, values of σ'_m are not expected to be very accurate.

51. Best-fit exponential relations proposed by Ohsaki and Iwasaki (1973) vary in both exponent and linear coefficient for various geologic age and soil-type categories. Tertiary (oldest age group) and cohesionless soil groups exhibit a linear relationship with G. Other data groups incorporate lower exponents progressively with decreasing age and decreasing relative grain-size distribution. As the exponential values decrease, linear coefficients typically increase proportionately. Using the equations for clays and sands at N-values less than 28 (blows/ft), the equation predicts that G of cohesive soils is greater than G of cohesionless soils at the same N-value. At N-values greater than 28 (blows/ft), the opposite is true.

52. Ohta et al. (1970) developed an equation to calculate G from N-value by incorporating 100 data points from 18 sites in Japan:

$$G = 142\ N^{0.72}\quad \text{(tsf)} \tag{27}$$

These data are plotted in Figure 4, as presented by Ohsaki and Iwasaki (1973). By using regression analyses, Ohta et al. (1970) found a slight tendency for sandy soils to have a lower stiffness than cohesive soils at the same N-value, which agrees with findings of Ohsaki and Iwasaki (1973) at N-values less than 20 (blows/ft) and using data from Kanai (1966).

53. Ohta and Goto (1978a,b) used statistical analyses on nearly 300 sets of data from soils in Japan. Each data set consisted of values of V_s, SPT N-value, depth, geologic age, and soil type. The result of the analyses was the evolution of 15 different equations, with varying correlation

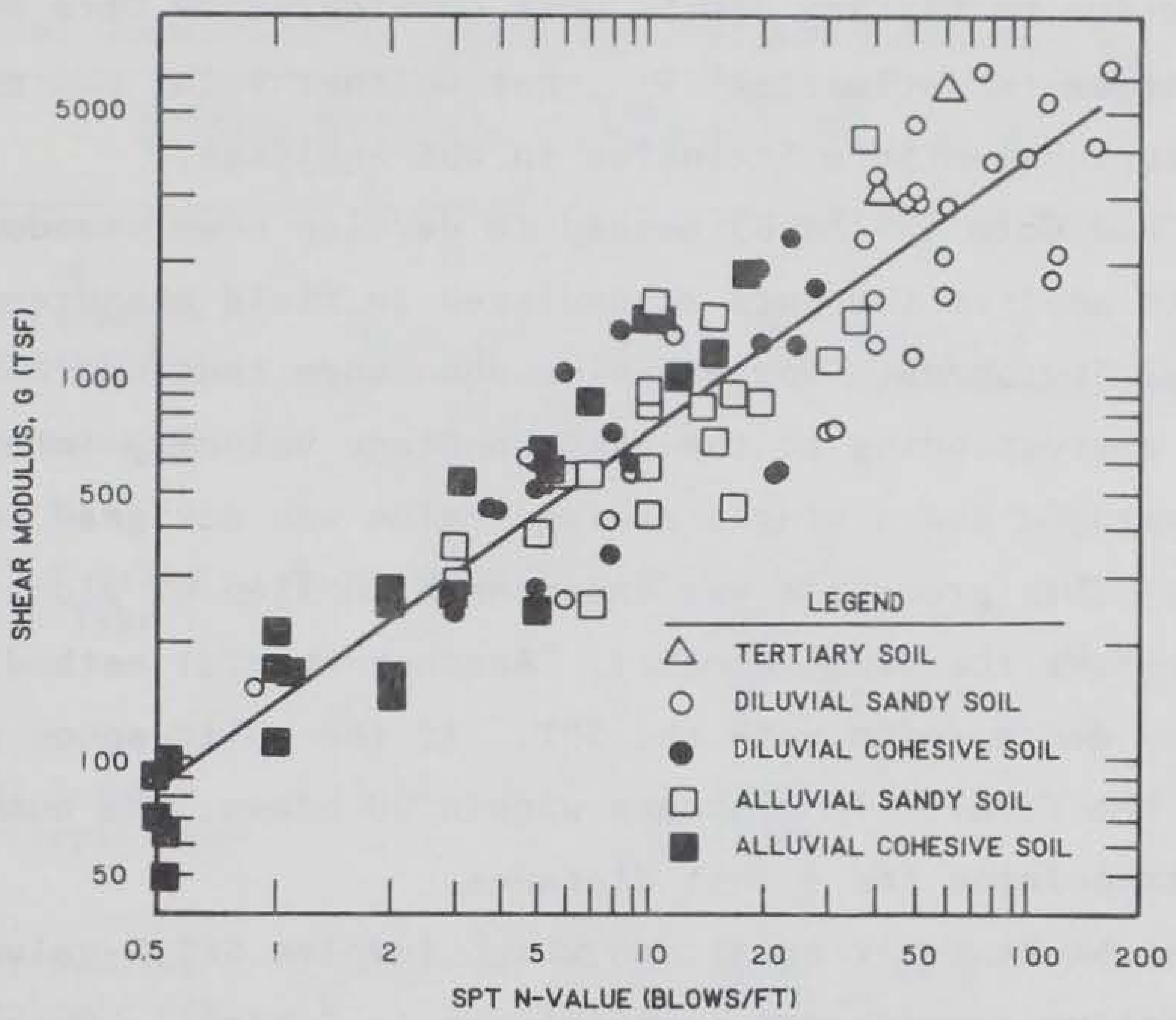

Figure 4. Correlation between SPT N-value and G using data from Ohta et al. (1970) (as presented by Ohsaki and Iwasaki 1973)

coefficients for predicting V_s . In using this approach, variables and combinations of variables were examined to determine their effect on V_s predictions and also to determine which combinations of variables produced the most accurate results (highest correlation coefficients).

54. Correlative variables (SPT N-value, soil type, geologic age, and depth) considered in the analyses were chosen on the basis of ease in determination and use in field investigations. Since these four soil variables consisted of nominal, interval (quantitative), and ordinal (qualitative) values, quantification theory was required to develop the empirical equations (described by Ohta and Goto 1978a). Geologic age, one of the two ordinal variables, was divided into two ranges: Holocene and Pleistocene. The majority of field data accumulated were from alluvial plains of Holocene age. The six divisions of soil type, the other ordinal variable considered in the original regression analyses were clay, fine sand, medium sand, coarse sand, sand and gravel, and gravel (Ohta and Goto 1978a). Later, Ohta and Goto (1978b) narrowed the soil divisions to three groups--clays, sands, and gravels. This simplification produced only slightly lower correlation coefficients for correlations involving soil-type divisions. In situ density and depth of the

water table relative to testing depths were considered by Ohta and Goto to be important quantities in estimating V_s, but neither value was measured frequently enough to substantiate inclusion in the analysis.

55. Ohta and Goto (1978a,b) needed to develop some standard methods of data reduction to analyze the data accumulated in field measurements, particularly for special instances. For example, when more than one N-value was measured at depths corresponding to the same constant velocity interval, those N-values were averaged and a single average value was assigned to the middepth of the interval. This procedure was undertaken in lieu of plotting each individual N-value versus the same velocity. Another special method was necessary when testing very dense soils with the SPT. If the split-spoon sampler had not been driven the final 1-ft distance within 50 blows, the number of blows per foot was extrapolated for a 1-ft distance.

56. The eight best-fit equations which involve SPT N-value are listed along with respective correlation coefficients in Table 4. Ohta and Goto (1978a,b) did the only known studies which examined V_s correlations with both N-value and depth in the same equation. The equation most representative of the data (largest $r = 0.853$) includes all four variables--N-value, soil type, geologic age, and depth (No. 8 in Table 4). From the eight equations presented in Table 4, the equation solely dependent on N-value (Equation 1 of Table 4) is the least accurate ($r = 0.719$). Further examination of results listed in Table 4 indicates that the accuracy of correlations between N and V_s is improved by including depth, geologic age, and soil type, in decreasing influential order. The correlation with N and depth produced only a somewhat better correlation than with N and geologic age and soil type. The influence of soil type (range in ordinal values) ranges from 9 to 20 percent of the estimated values of V_s. The influence of geologic age (range in ordinal values) ranges from 31 to 46 percent of the estimated values of V_s. One of the most noticeable results of correlations summarized in Table 4 is the minor effect that the inclusion of soil type has on the accuracy of equations (average increase in correlation coefficient of less than 0.5 percent). The average increase in accuracy (correlation coefficients) produced by including geologic age divisions into the correlative equation is 6 percent.

57. Fumal (1978) suggested that there seemed to be a maximum V_s for loose sands (which he defined as having an N-value less than 40 blows/ft) in

Table 4

Results of Quantification Regression Analysis Involving V_s and SPT N-Value Performed by Ohta and Goto (1978b)

Equation No.	Combination of Correlative Parameters	Best-Fit Relation (V_s in fps)*	Correlation Coefficient
1	SPT N-value	$V_s = 280\ N^{0.348}$	0.719
2	SPT N-value Soil Type	$V_s = 285\ N^{0.333}\ \begin{vmatrix}1.000\\1.018\\1.086\end{vmatrix}_S^{**}$	0.721
3	SPT N-value Geologic Age	$V_s = 302\ N^{0.265}\ \begin{vmatrix}1.000\\1.456\end{vmatrix}_G^{**}$	0.784
4	SPT N-value Geologic Age Soil Type	$V_s = 306\ N^{0.247}\ \begin{vmatrix}1.000\\1.458\end{vmatrix}_G\ \begin{vmatrix}1.000\\1.045\\1.096\end{vmatrix}_S$	0.786
5	SPT N-value Depth	$V_s = 155\ N^{0.254}\ D^{0.222}$	0.820
6	SPT N-value Depth Soil Type	$V_s = 146\ N^{0.218}\ D^{0.288}\ \begin{vmatrix}1.000\\1.073\\1.199\end{vmatrix}_S$	0.826
7	SPT N-value Depth Geologic Age	$V_s = 180\ N^{0.209}\ D^{0.188}\ \begin{vmatrix}1.000\\1.308\end{vmatrix}_S$	0.848
8	SPT N-value Depth Geologic Age Soil Type	$V_s = 179\ N^{0.173}\ D^{0.195}\ \begin{vmatrix}1.000\\1.306\end{vmatrix}_G\ \begin{vmatrix}1.000\\1.085\\1.189\end{vmatrix}_S$	0.853

* Depth in feet.

** Ordinal numbers shall be interpreted as:

$\begin{vmatrix}Y_1\\Y_2\end{vmatrix}_G$
Y_1 = factor corresponding to Holocene-age soil.
Y_2 = factor corresponding to Pleistocene-age soils.

$\begin{vmatrix}Y_1\\Y_2\\Y_3\end{vmatrix}_S$
Y_1 = factor corresponding to clays.
Y_2 = factor corresponding to sands.
Y_3 = factor corresponding to gravels.

the San Francisco, California bay area of 820 fps and a minimum value of V_s for gravels of 1,180 fps. Fumal found it convenient and worthwhile to separate soils according to soil type. A plot of 38 measurement points of N-value and V_s produced considerable scatter, as shown in Figure 5. Fumal concluded that a correlation between V_s and N-value was not substantiated, but, N-value could be correlated with other indexes which are affected by the same physical properties which influence V_s.

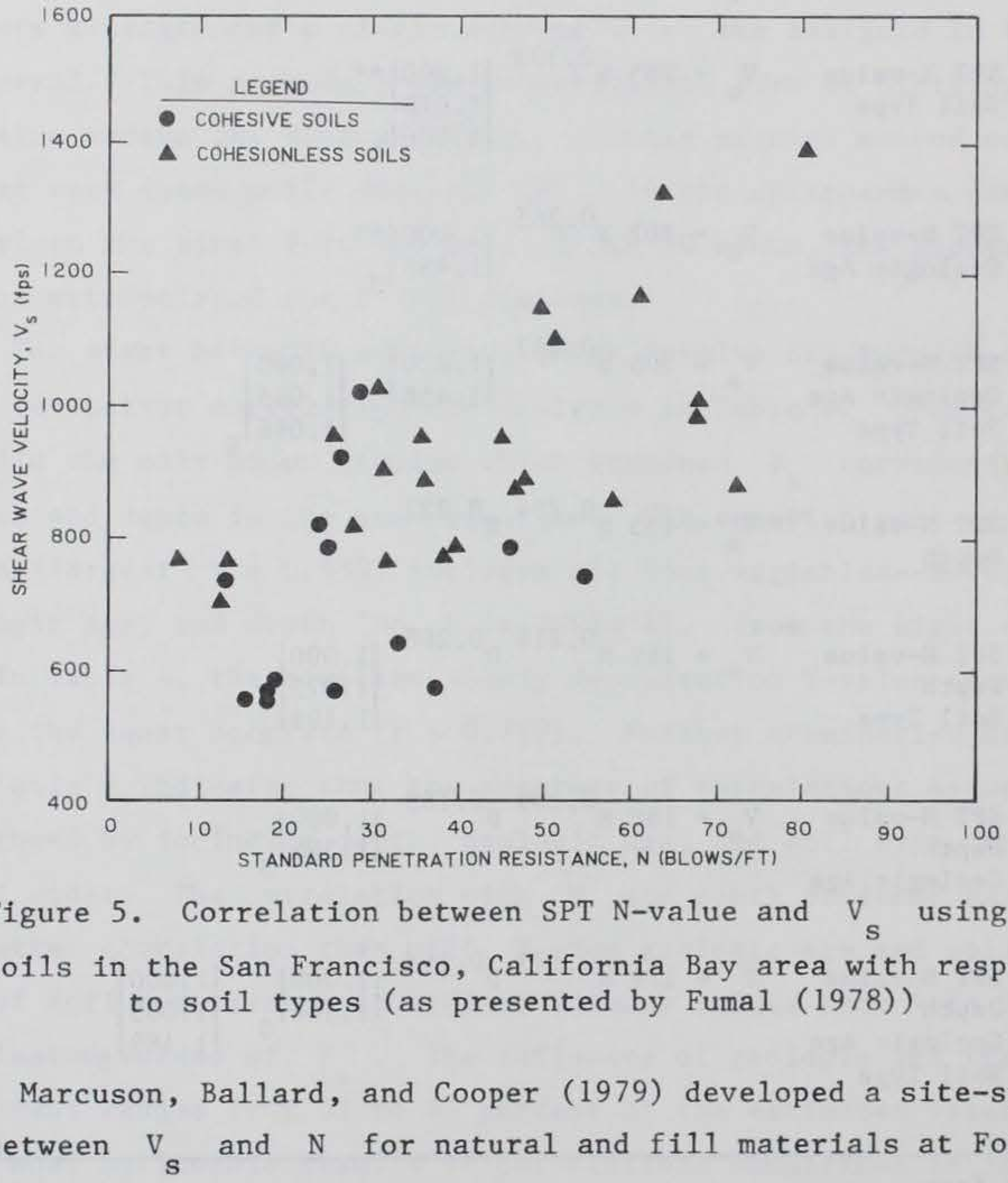

Figure 5. Correlation between SPT N-value and V_s using soils in the San Francisco, California Bay area with respect to soil types (as presented by Fumal (1978))

58. Marcuson, Ballard, and Cooper (1979) developed a site-specific correlation between V_s and N for natural and fill materials at Fort Peck Dam located near Glasgow, Montana. A simple linear relation of the form was determined:

$$V_s = a \cdot N \quad \text{(fps)} \tag{28}$$

where $15 \leq a \leq 40$ (dependent on material). Two of the materials, natural alluvium and rolled fills, had values of "a" equaling 15 and 28, respectively.

Equation 28 was found to predict V_s within 25 percent of the measured value most of the time.

59. Seed, Idriss, and Arango (1983) suggested using the following equation for sands and silty sands to calculate G and V_s using N-value:

$$G_{max} = 65\ N \quad (\text{tsf}) \tag{29}$$

and

$$V_s = 185\ N^{0.5} \quad (\text{fps}) \tag{30}$$

These equations were developed primarily for use in liquefaction analysis of sand deposits.

60. Mr. Imai has been involved in V_s correlations since at least 1970 when he published the results of his initial study (Imai and Yoshimura 1970). Since then, he has coauthored three other papers (Imai and Yoshimura 1975; Imai, Fumoto, and Yokota 1975); and Imai and Tonouchi 1982) which address V_s correlations involving SPT N-value using a progressively larger data base of measurements. All data were collected using measurements made with a downhole borehole receiver at sites throughout Japan. The quantity of data used for each study is summarized in Table 5. It is presumed that later studies incorporated all data from previous studies.

Table 5

Distribution of Data for Studies Reported by Imai and Others

Study	No. of Sites	No. of Boreholes	No. of Data
Imai and Yoshimura (1970)	*	*	26
Imai and Yoshimura (1975)	70	100	192
Imai, Fumoto, and Yokota (1975)	*	200	756
Imai and Tonouchi (1982)	*	400	1,654

* Not reported.

61. In the first three studies, Imai and others found it difficult to distinguish the effect of soil type or geologic age on N versus V_s

correlations. However, differentiation among these data groups indicated that values of V_s tended to fall in specific ranges. Therefore, only general relations were developed in each study. Imai and Yoshimura (1970) proposed the following equation:

$$V_s = 250\ N^{0.39} \quad \text{(fps)} \tag{31}$$

Later, Imai and Yoshimura (1975) proposed:

$$V_s = 302\ N^{0.329} \quad \text{(fps)} \tag{32}$$

Using fill soils and peats for the first time in addition to all other soils, Imai, Fumoto, and Yokota (1975) found that:

$$V_s = 295\ N^{0.341} \quad \text{(fps)} \tag{33}$$

Most recently, with a very large data base, Imai and Tonouchi (1982) determined the following:

$$V_s = 318\ N^{0.314} \quad \text{(fps)} \tag{34}$$

Density measurements made in association with V_s measurements were used to correlate N with G. The relationship they developed is:

$$G = 147\ N^{0.680} \quad \text{(tsf)} \tag{35}$$

62. Data used by Imai and Tonouchi (1982) to determine Equation 34 are reproduced in Figure 6. Many researchers, like Imai, choose to plot N versus V_s data on a log-log scale. However, the narrow range in V_s per N-value on this type of plot can be very misleading. To examine these data from a different perspective, a band corresponding to about 95 percent of the data were plotted on an arithmetic scale as shown in Figure 7. The wide range in data in Figure 7 is unusual. For example, at an N-value of 25 blows/ft, the range in V_s is 600 to 1,520 fps. This range is excessive, probably as a result of combining all possible combinations of soil types (peats and fill

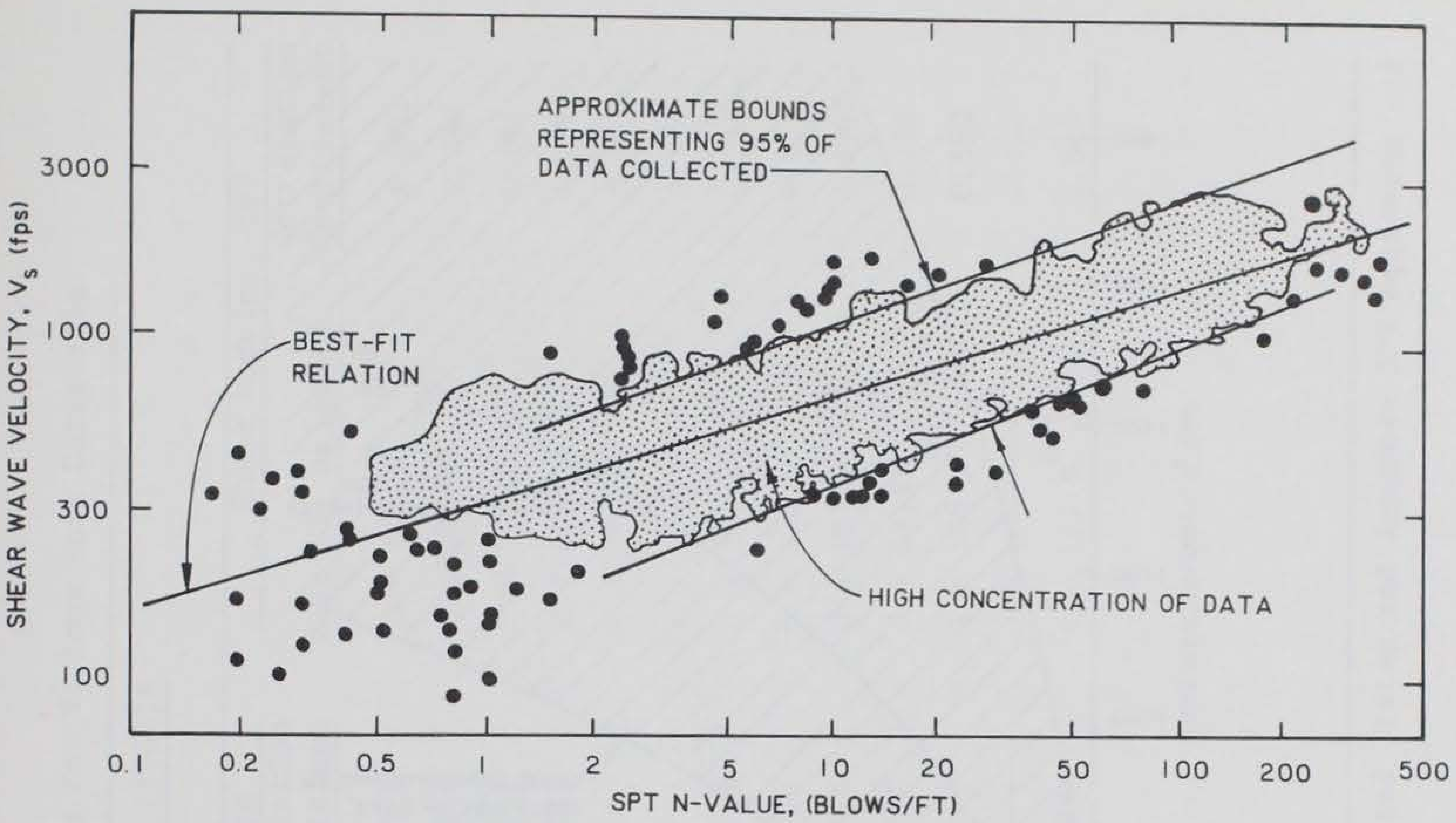

Figure 6. Correlation between SPT N-value and V_s (by Imai and Tonouchi 1982)

materials included) and conditions. It is apparent that this variability must be considered for successful employment of V_s correlations.

63. Imai and Tonouchi (1982) determined that correlations among different soil type and geologic groups were worthy of examination. Best-fit relations to determine both V_s and G for different groups are summarized in Table 6. Best-fit relations proposed indicate that division of data among both soil type and geologic age groups has a significant effect on the relation representative of the data and the corresponding correlation coefficient. For correlations involving V_s, exponential parameters of N-value range from 0.153 (indicative of very little dependence of V_s on N) to 0.453. For equivalent soil groups with different age, the exponent was found to decrease with increased age. This indicates that V_s of older soils is less dependent on N. Linear coefficients range from 209 to 446 (typically higher values associated with lower exponents and vice versa). Therefore, it appears as though soil type and geologic age should be used to estimate V_s. However, correlation coefficients for these subdivisions are lower than that for all data combined. The average correlation coefficient of groups individually is 0.655 as compared to 0.868 for all data. For natural soil deposits only, correlation coefficients average 0.708. Natural clays and peats exhibited

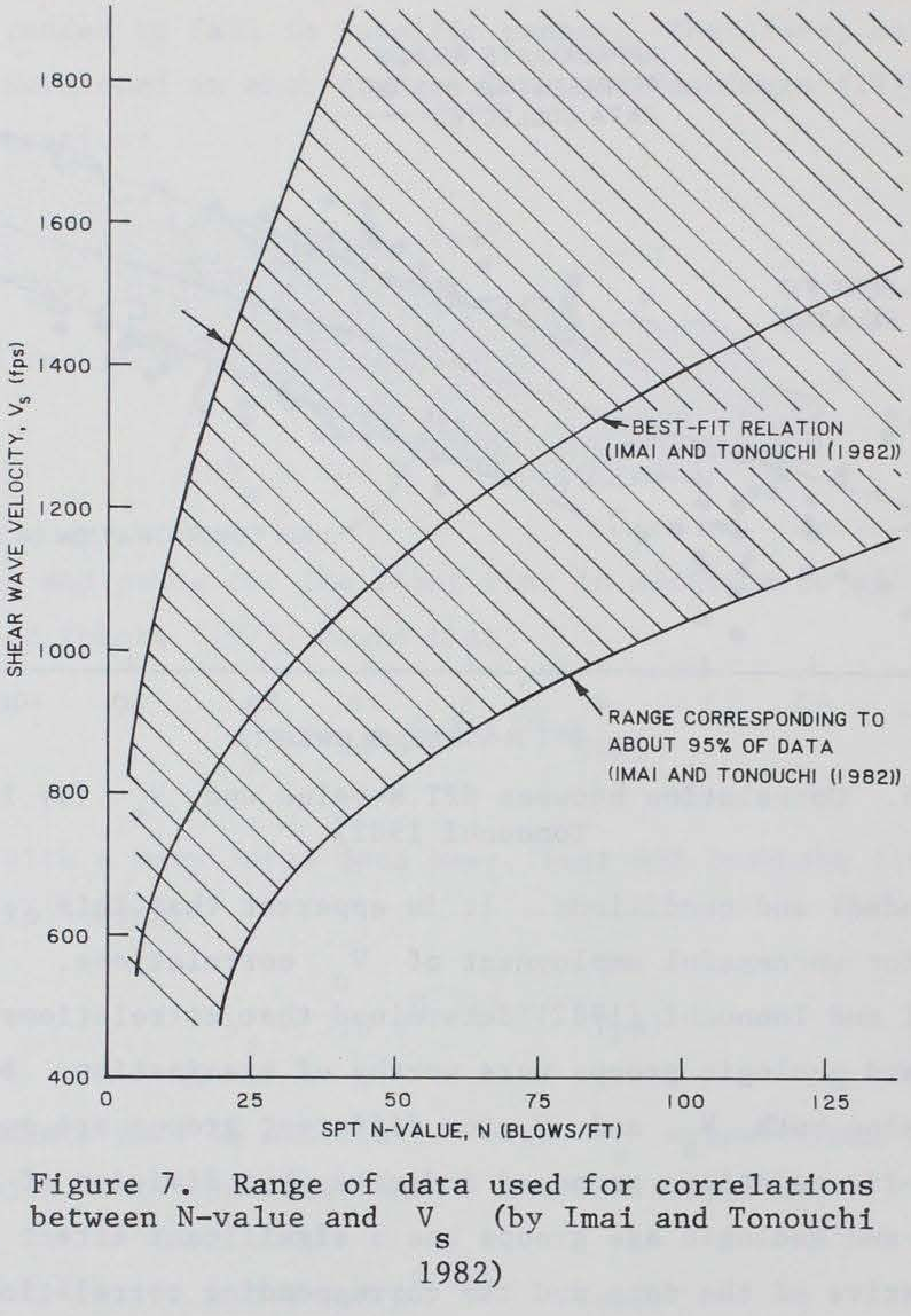

Figure 7. Range of data used for correlations between N-value and V_s (by Imai and Tonouchi 1982)

consistent correlation coefficients (ranging from 0.712 to 0.771); whereas, granular soils have a much larger range (0.550 to 0.791).

64. Correlations performed by Imai and Tonouchi (1982) using G, in general, are more accurate than V_s correlative equations for granular soil categories and less accurate for cohesive soil categories (based strictly on correlation coefficients). There is no apparent explanation for a dichotomy in accuracies between granular and cohesive soil groups. Note that the exponential values typically are greater than double those for corresponding V_s correlations. The range of exponents of N is 0.383 to 1.08. The range of linear coefficients is 55 to 326. Exponential values decreased with increasing age for clay and gravel data groups (contrary to Ohsaki and Iwasaki

Table 6

Best-Fit Relations for V_s and G from SPT N-Value for Various Soil Categories

Proposed by Imai and Tonouchi (1982)*

Category	No. of Data	Shear Wave Velocity, fps		Shear Modulus, tsf	
		Best-Fit Relation	Correlation Coefficient	Best-Fit Relation	Correlation Coefficient
Clay fill	63	$V_s = 323\ N^{0.248}$	0.574	$G = 158\ N^{0.557}$	0.582
Loam	64	$V_s = 430\ N^{0.153}$	0.314	$G = 229\ N^{0.383}$	0.487
Sand fill	81	$V_s = 301\ N^{0.257}$	0.647	$G = 145\ N^{0.500}$	0.606
Tertiary clay and sand	108	$V_s = 358\ N^{0.319}$	0.717	$G = 209\ N^{0.686}$	0.682
Alluvial clay	325	$V_s = 351\ N^{0.274}$	0.721	$G = 180\ N^{0.607}$	0.715
Alluvial peat	17	$V_s = 209\ N^{0.453}$	0.771	$G = 55.0\ N^{1.08}$	0.769
Diluvial clay	222	$V_s = 420\ N^{0.257}$	0.712	$G = 257\ N^{0.555}$	0.712
Alluvial sand	294	$V_s = 288\ N^{0.292}$	0.690	$G = 128\ N^{0.611}$	0.871
Diluvial sand	338	$V_s = 361\ N^{0.285}$	0.714	$G = 181\ N^{0.631}$	0.729
Alluvial gravel	28	$V_s = 247\ N^{0.351}$	0.791	$G = 84.5\ N^{0.787}$	0.798
Diluvial gravel	114	$V_s = 446\ N^{0.246}$	0.550	$G = 326\ N^{0.528}$	0.552
All soils	1,654	$V_s = 318\ N^{0.314}$	0.868	$G = 147\ N^{0.680}$	0.867

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* Not adjusted for differences in energy efficiency between United States and Japanese SPT equipment and procedures.

(1973)) but increased with age for sands. Correlation coefficients of equations for natural soil groups ranged from 0.552 to 0.871 and averaged 0.729 as compared to 0.867 for all data combined.

65. The correlation coefficient for all data used by Imai and Tonouchi (1982) in N versus G correlations is essentially equal to that for N versus V_s correlations. This occurrence may seem trivial but, in actuality, it could be very significant. Shear modulus is usually the required end product. If V_s is used to calculate G , the value of V_s is squared. Any inherent error in the value of V_s consequently is squared resulting in a less-accurate ultimate value of G . If correlations between N and G are of the same accuracy, or even slightly less accurate, the G correlations should be used. This reasoning does not imply necessarily that correlations incorporating G are always to be preferred. Correlations in which G was calculated directly from V_s and only an estimated value of ρ are no better than using G estimated from correlations involving V_s . In other words, values of ρ must be measured also to justify using G correlations.

66. The more prominent soil categories presented by Imai and Tonouchi (1982) were used to quantify ranges in data and corresponding error between best-fit relations and the upper and lower bounds (in velocity). This evaluation is summarized in Table 7. Three values of N were selected for convenience: 10, 30, and 100 blows/ft. The errors estimated appear to be consistent (independent of N) and average about +50 percent (best-fit V_s to upper bound) and -40 percent (best-fit V_s to lower bound).

67. A comparison was made of best-fit relationships determined by Imai and Yoshimura (1970, 1975); Imai, Fumoto, and Yokota (1975); Imai and Tonouchi (1982), and others to examine any potential influence of the number of data on the best-fit relation. The four best-fit relationships are plotted in Figure 8. A summary of data available is contained in Table 5. The studies with the least and most data, Imai and Yoshimura (1970) and Imai and Tonouchi (1982), respectively, represent the upper and lower bounds, respectively. The difference in equations is only noticeable beyond an N-value of about 25 blows/ft. The differences in V_s per N-value are significant only beyond about 50 blows/ft.

Table 7

Typical Values of V_s Measured and Estimated (from Imai and Tonouchi 1982)

	SPT N-Value* = 10 (blows/ft)			SPT N-Value* = 30 (blows/ft)			SPT N-Value* = 100 (blows/ft)		
Category	Estimated V_s, fps	Estimated Range in V_s, fps	+/- Error in Range percent	Estimated V_s, fps	Estimated Range in V_s, fps	+/- Error in Range percent	Estimated V_s, fps	Estimated Range in V_s, fps	+/- Error in Range percent
Alluvial clay	660	440-1,000	+52/-33	890	**		1,240	**	
Diluvial clay	750	360-1,340	+76/-53	1,005	660-1,330	+32/-34	1,370	980-1,840	+34/-28
Alluvial sand	560	330-920	+64/-41	780	360-1,640	+110/-54	1,105	**	
Diluvial sand	695	400-850	+22/-42	950	680-1,370	+44/-28	1,340	750-2,200	+64/-44
Alluvial gravel	555	**		815	590-1,000	+23/-28	1,245	690-1,570	+26/-45
Diluvial gravel	785	**		1,030	625-1,300	+20/-39	1,385	950-2,250	+62/-31
Average errors per N-value			+54/-42			+47/-37			+47/-37

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* Not adjusted for difference in energy efficiency between United States and Japanese SPT equipment and procedures.

** Not enough (or no) data in this range of N-value.

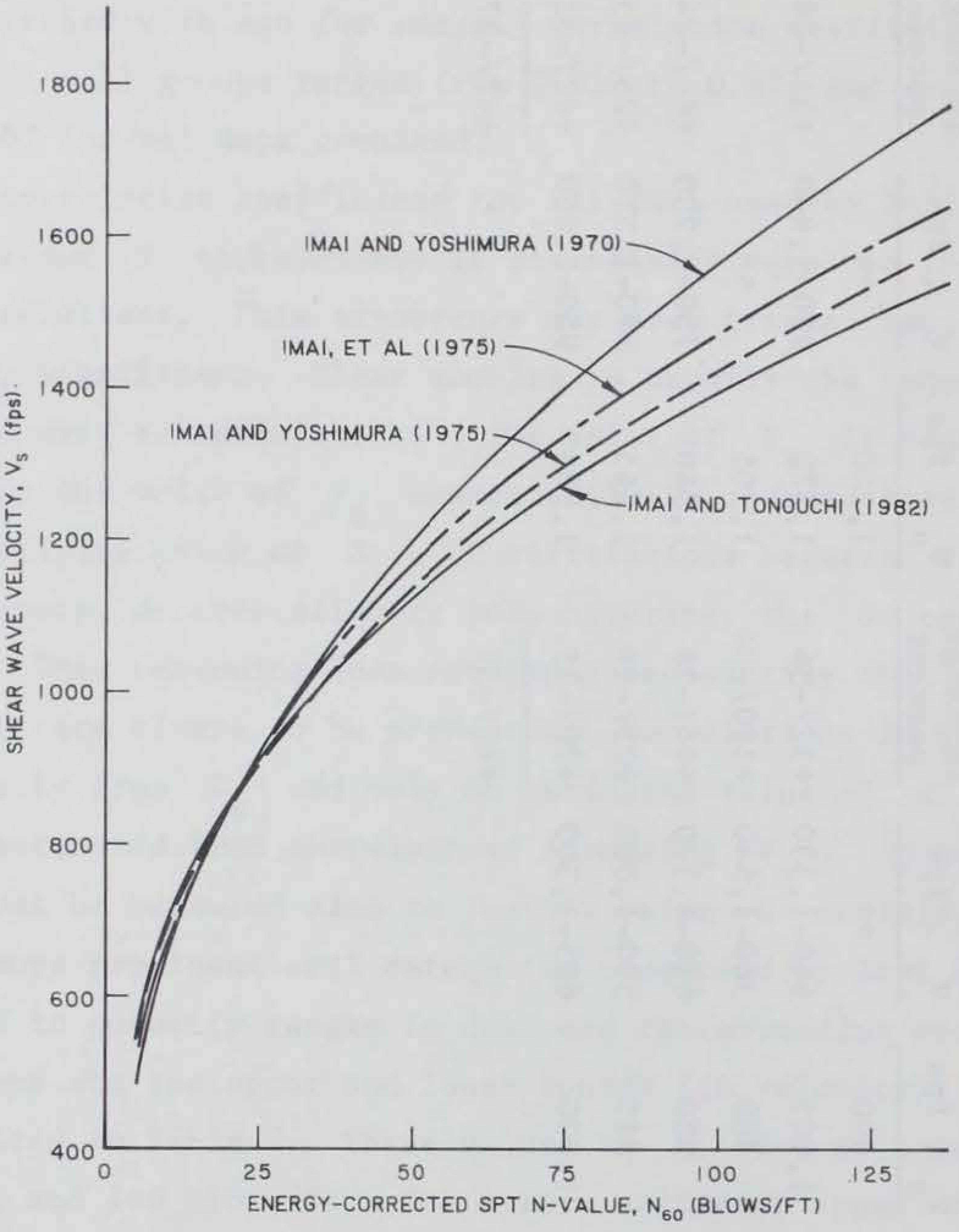

Figure 8. Comparison of results for N versus V_s correlations (proposed by Imai and Yoshimura 1970, 1975; Imai, Fumoto, and Yokota 1975; and Imai and Tonouchi 1982)

68. Sykora and Stokoe (1983) performed correlations with N as the independent variable using data measured only using crosshole geophysical methods. (For reference on different seismic methods and types of techniques (interval and direct), refer to Patel (1981) or Stokoe (1980).) Division of data among the various geophysical techniques indicated that downhole measurements produced very low correlation coefficients (0.56 and 0.67 and direct and interval techniques, respectively) as compared to correlation coefficients resulting from curve-fitting analyses of data from crosshole and interval downhole techniques (correlation coefficient of 0.84). A comparison of best-fit relations for these three data sets is shown in Figure 9. Despite significant differences in accuracy produced using data collected using different

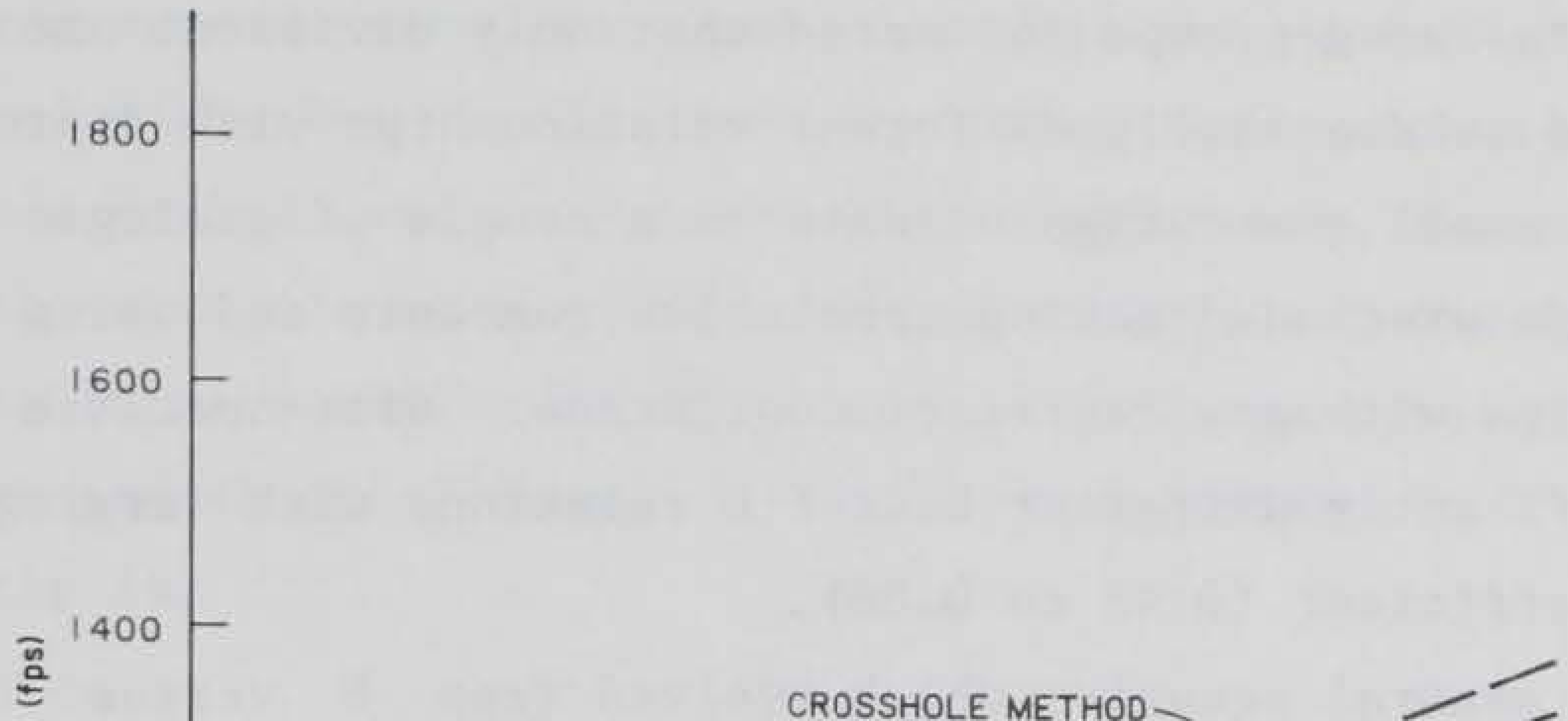

Figure 9. Comparison of best-fit relations for correlations between N-value and V_s for different geophysical methods (by Sykora and Stokoe 1983)

geophysical methods, best-fit relations are very similar, differing primarily in a multiplicative constant. Elimination of all downhole data reduced the number of data points available for analysis from 481 to 229.

69. Sykora and Stokoe (1983) examined the influence of the following variables on N versus V_s correlations:

- Relative location of the phreatic surface.
- Geologic age.
- Soil type.
- Previous seismic history.
- Range of N-values.
- Site specificity.

Analyses of data among groups indicated that only divisions among soil-type groups produced substantially different relationships with improved accuracy. Unfortunately, small quantities of data in a couple of geologic age and soil-type data groups precluded making conclusive comments and using these different relationships with any degree of confidence. Site-specific correlations produced significantly different best-fit relations with varying magnitudes of correlation coefficient (0.45 to 0.86).

70. The general equation which evolved from N versus V_s correlations applicable to granular soils, as plotted in Figure 10, is:

$$V_s = 330\ N^{0.29} \quad \text{(fps)} \tag{36}$$

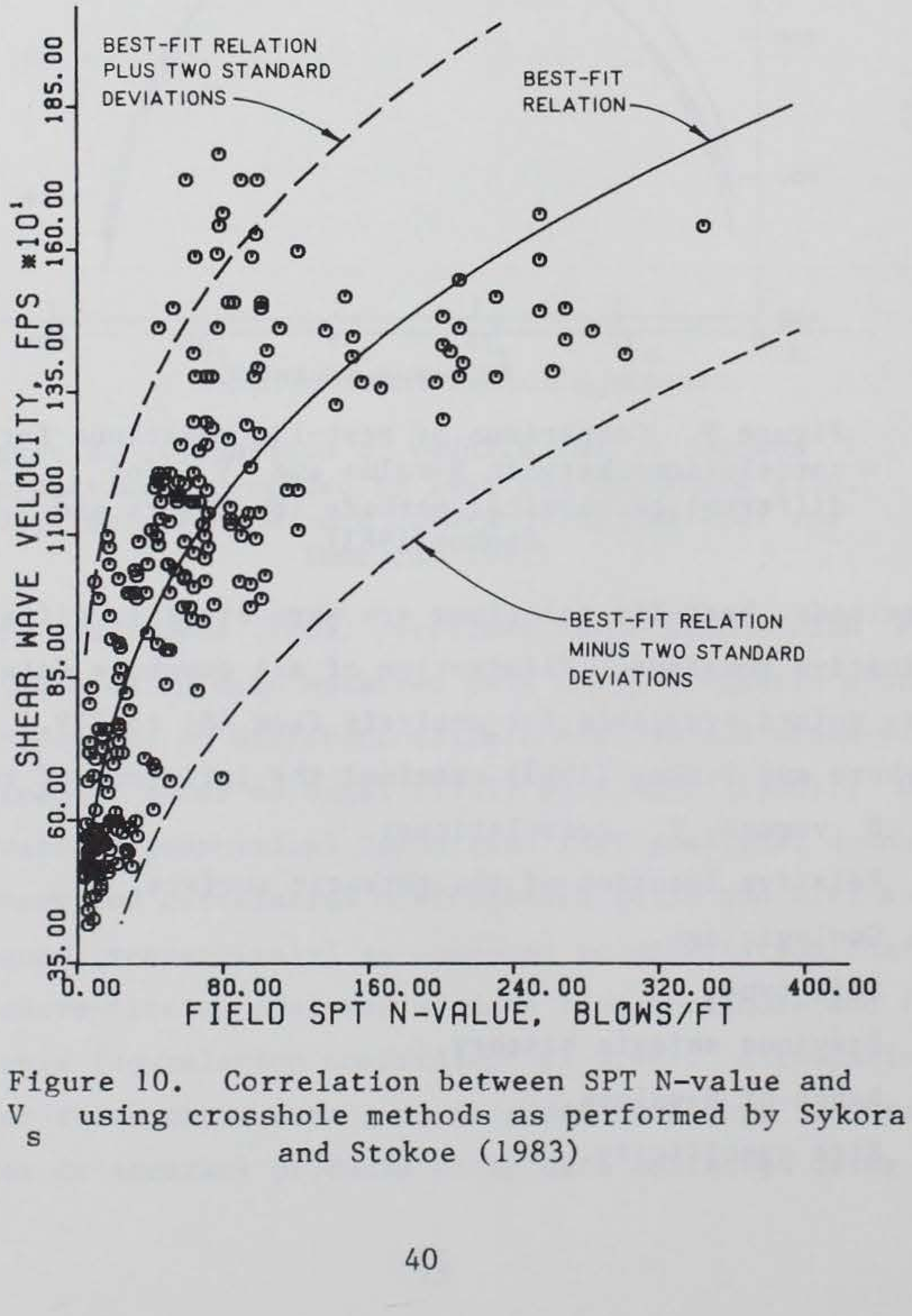

Figure 10. Correlation between SPT N-value and V_s using crosshole methods as performed by Sykora and Stokoe (1983)

This equation corresponds to a correlation coefficient of 0.84. One by-product of correlations between N and V_s using data collected with cross-hole and downhole methods was an interpreted relationship, representing about 95 percent of the data, between minimum values of V_s and N-value. This relationship may be very useful in liquefaction analyses by providing a most-critical (lowest possible) value of V_s given any number of N profiles. This relationship is:

$$(V_s)_{min} = 4N + 375 \quad \text{(fps)} \tag{37}$$

Actual data used to interpret this relationship are plotted in Appendix B.

71. Sykora and Stokoe (1983) compared values of V_s estimated using Equation 34 with the actual data collected to determine the range in maximum error for V_s per N-value. Their summary is provided in Table 8. At larger N-values, the estimated values of V_s correspond to a lower variation in the data.

Table 8

Variation of V_s Estimated from SPT N-Value Using Correlation Best-Fit Relations for Sands (determined by Sykora and Stokoe 1983)

N-Value (blows/foot)	Best-Fit V_s, fps	Range in V_s, fps	Error for Range About Best-Fit Value percent
20	790	360-1,220	±54
50	1,030	600-1,460	±42
125	1,340	910-1,770	±32

72. In general, N versus V_s correlations performed by Sykora and Stokoe (1983) indicated that V_s can be estimated with a limited degree of confidence. More definitive conclusions could only be made using a more extensive data base.

Effective-vertical-stress-corrected N-value

73. Few studies exist that examine correlations between effective-vertical-stress-corrected N-value N_1 and V_s. This may be because of the

relatively recent acceptance of N correction factors. All N-values used in this section correspond to reported values (i.e. not adjusted to correct for energy efficiency).

74. Ohsaki and Iwasaki (1973) provided no details of their analysis of N-values corrected for the "effect of confining pressure." However, they determined that "the correlation between N-values and shear moduli is rather better when the latter values are not manipulated in consideration of effective confining pressure."

75. Seed, Idriss, and Arango (1983) proposed an equation to determine V_s from N_1. Values of N_1 are calculated using a factor C_N which was a simplification from a study by Marcuson and Bieganousky (1977). Use and values of C_N are described in Seed and Idriss (1981). The equation to determine V_s from N_1 was reported to be applicable for sands and silty sands up to a maximum depth of 50 ft. This equation is:

$$V_s = 200\ N_1^{0.5} \quad \text{(fps)} \tag{38}$$

76. Seed et al. (1984) proposed a relationship between N_1 and $\left(K_2\right)_{max}$ for use in Equation 12 to calculate G_{max}. This relationship was initiated using a correlative equation involving N, depth, soil type, and geologic age proposed by Ohta and Goto (1976). Seed et al. (1984) made several assumptions to arrive at the relation, including:

- Data from Japan are applicable to US soils.
- Constant unit weight of 120 pcf.
- Depth = $\bar{\sigma}_o \div 62.5$ (for depths >10 ft).
- Soils are either of Holocene or Pleistocene age.
- Soils range between a fine sand and a sandy gravel.

The relation is:

$$\left(K_2\right)_{max} = 20\left(N_1\right)^{1/3} \tag{39}$$

and was substantiated by results of laboratory tests and a few field data.

77. Sykora and Stokoe (1983) used 229 sets of data measured using the crosshole method to correlate N_1 with V_s. They concluded that the use of

N_1 to correlate with V_s proved to be considerably less accurate and more inconsistent than N versus V_s correlations. The correlation coefficient for the overall best-fit relation was 0.67 as compared to 0.84 for N versus V_s correlations. Using the various data groups, correlation coefficient for N versus V_s correlations averaged 32 percent less than N versus V_s correlations for the same data group. Sykora and Stokoe (1983) concluded that N_1 is not an appropriate correlative variable to use in estimating V_s. This conclusion can be rationalized since effective stress is known to influence both V_s and N. The normalization of N to $\bar{\sigma}_v$ eliminates an independent variable ($\bar{\sigma}_v$) from one dependent variable (N) and not the other (V_s).

Correlations with Overburden Stress

78. Few field studies have been performed which examine correlations between overburden stress and V_s. This is unusual since laboratory studies have determined that effective stress, first $\bar{\sigma}_o$, then $\bar{\sigma}_A$, is the most important parameter to determine. Cross-anisotropic (biaxial) state-of-stress conditions exist for most in situ conditions. However, $\bar{\sigma}_A$ is difficult to determine accurately because of the dependence on K_o. For crosshole tests with vertically-polarized shear waves, which constitute nearly all measurements made with hammer sources, $\bar{\sigma}_A$ is related to $\bar{\sigma}_v$ by:

$$\bar{\sigma}_A = K_o^{0.5} \cdot \bar{\sigma}_v \qquad (40)$$

79. The parameter K_o is a function of soil type, moisture conditions, relative density, and overconsolidation ratio. Because of the difficulty in using K_o, the most logical use of effective stress for field correlations is to use $\bar{\sigma}_v$, which can be calculated easily below the phreatic surface from a density profile. Calculation of $\bar{\sigma}_v$ above the phreatic surface assuming pore pressures equal to zero may be too presumptuous, especially in cohesive and fine sandy soils (Wu, Gray, and Richart 1984).

80. Many more studies have been undertaken which use V_s as a function of depth where depth is presumed to be indicative of magnitude of stress. These studies will be examined in the next section. Given the rather narrow range typically expected in density (moist unit weight) profiles, this would

not be a bad presumption. However, the inconsistent presence and location (depth) of phreatic surfaces can produce errors on the order of 50 percent when using depth or total stress to estimate $\bar{\sigma}_A$. Therefore, correlations involving $\bar{\sigma}_v$ and even total overburden stress $\bar{\sigma}_v$ are expected to be more accurate than correlations involving depth.

Effective vertical stress

81. Sykora and Stokoe (1983) performed correlations incorporating $\bar{\sigma}_v$ as the independent variable using only data measured using crosshole and interval downhole methods (190 data points) in natural granular deposits. Correlations between $\bar{\sigma}_v$ and V_s were performed only for measurements made below the phreatic surface because pore pressure is difficult to determine above the phreatic surface. Measured values of density and depth to the phreatic surface were used to calculate $\bar{\sigma}_v$.

82. Correlative analyses by Sykora and Stokoe (1983) indicate that divisions among soil type and geologic age groups improve the accuracy of $\bar{\sigma}_v$ versus V_s correlations. Only limited quantities of data were available in two groups, tempering this conclusion somewhat.

83. The general equation determined by Sykora and Stokoe (1983) from data plotted in Figure 11 is:

$$V_s = 720\ \bar{\sigma}_v^{\ 0.36} \quad \text{(fps)} \tag{41}$$

where σ_v is in tsf. This equation corresponds to a correlation coefficient of 0.84. A relationship representing about 95 percent of the data between minimum values of V_s and $\bar{\sigma}_v$ was interpreted from data collected using all geophysical methods to be:

$$\left(V_s\right)_{min} = 75\ \bar{\sigma}_v + 375 \quad \text{(fps)} \tag{42}$$

Actual data used to interpret this relationship are plotted in Appendix B.

84. Sykora and Stokoe (1983) compared values of V_s estimated using Equation 41 with actual data collected to determine the variation in V_s at various values of $\bar{\sigma}_v$. A similar summary is provided in Table 9. At larger values of $\bar{\sigma}_v$, the estimated values represent a lower variation in the data.

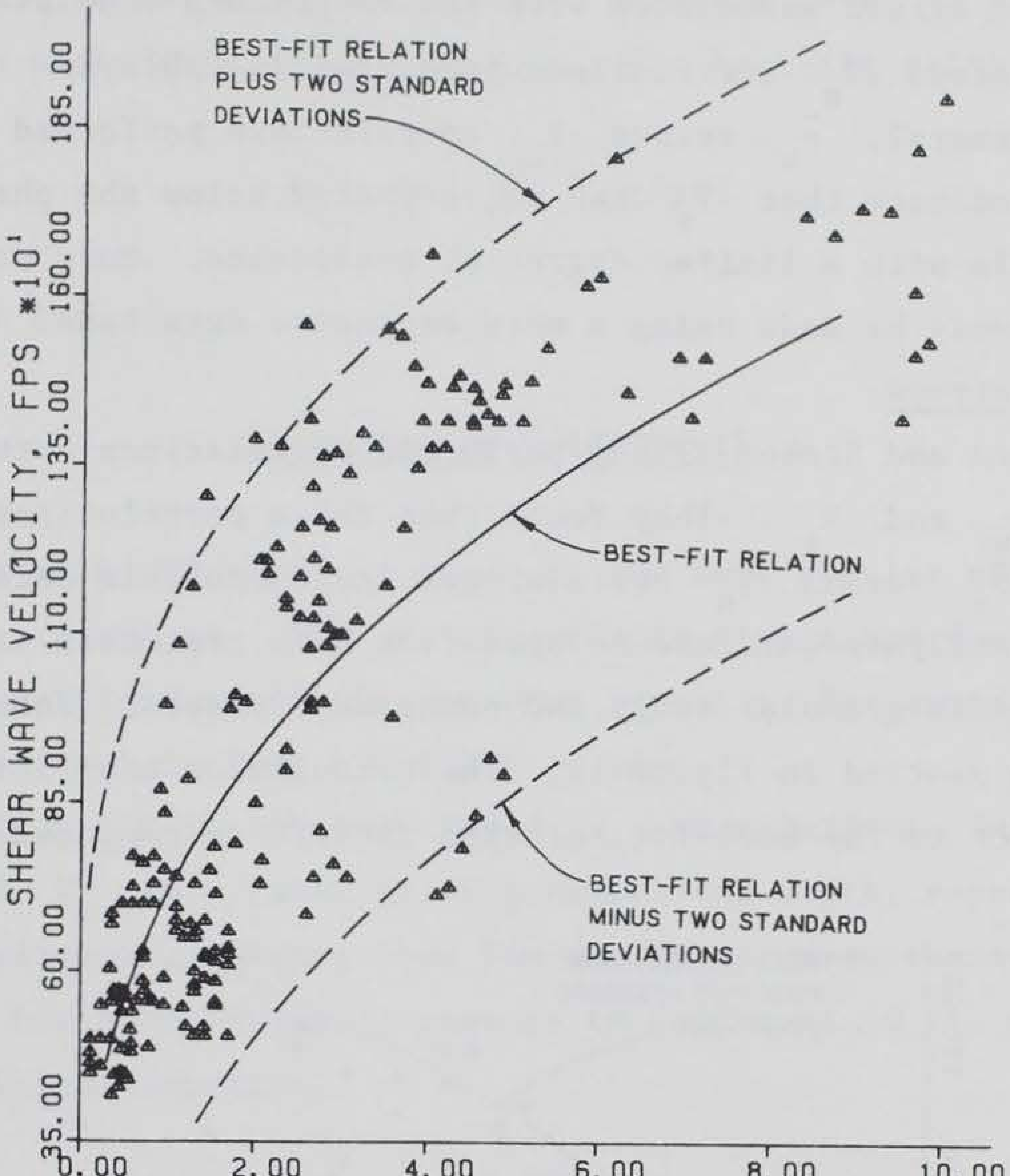

Figure 11. Correlation between $\bar{\sigma}_v$ and V_s using crosshole or interval downhole methods (as performed by Sykora and Stokoe 1983)

Table 9

Variation of V_s Estimated from $\bar{\sigma}_v$ Using Correlation Best-Fit Relations for Sands (determined by Sykora and Stokoe 1983)

Effective Stress, tsf	Best-Fit V_s, fps	Range in V_s, fps	Error for Range About Best-Fit Value, percent
1.0	720	345-1,075	±52
4.0	1,190	815-1,565	±32
8.0	1,520	1,145-1,875	±25

The magnitude of errors associated with the ranges are consistently lower than those for N versus V_s correlations presented in Table 8.

85. In general, $\bar{\sigma}_v$ versus V_s correlations performed by Sykora and Stokoe (1983) indicate that V_s can be estimated below the phreatic surface in granular soils with a limited degree of confidence. More definitive conclusions could only be made using a more extensive data base.

Total vertical stress

86. Sykora and Stokoe (1983) performed correlations between total vertical stress σ_v and V_s. They found that these correlations are less accurate than $\bar{\sigma}_v$ versus V_s correlations for comparable data groups. Data used for their analysis were accumulated from both crosshole and interval downhole methods in granular soils and numbered 328 sets. Total vertical stress data are plotted in Figure 12. The correlation coefficient of this data with respect to the best-fit relation is 0.70 as compared to 0.84 for $\bar{\sigma}_v$

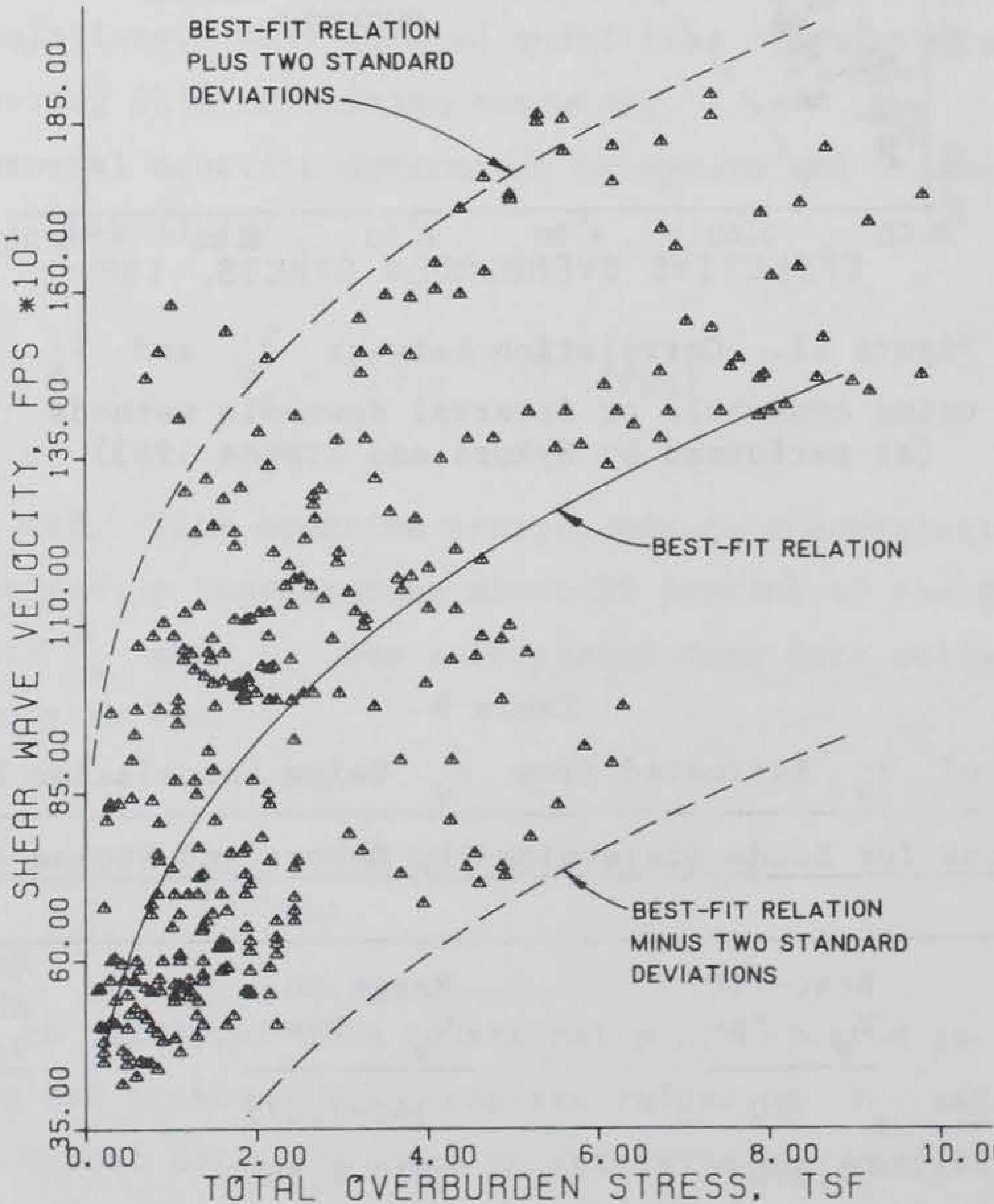

Figure 12. Correlation between σ_v and V_s (as performed by Sykora and Stokoe 1983)

versus V_s data. Correlation coefficients averaged about 13 percent less for σ_v correlations using various data groups. The best-fit relation is:

$$V_s = 750\ \sigma_v^{0.31} \quad \text{(fps)} \tag{43}$$

where σ_v is in tsf.

Correlations with Depth

87. Along with SPT N-value, depth is the most popular correlative variable for V_s correlations. The use of depth is simple and does not require any information on field or laboratory test results. Not surprisingly, the accuracy of these correlations typically is poor.

88. Hamilton (1976) examined field V_s correlations, in particular, the variation of V_s as a function of pressure and depth, especially pertaining to marine sediments. Twenty-nine low-amplitude measurements, consisting of downhole and Rayleigh wave measurements to depths of 40 ft, were used to develop the empirical equation:

$$V_s = 301\ D^{0.28} \quad \text{(fps)} \tag{44}$$

where D is depth, in ft. In the case of downhole measurements, intervals of constant velocity were plotted at depths corresponding to the mid-point of the interval. Hamilton plotted values of V_s derived from Rayleigh wave measurements at a depth corresponding to one-half the wave length.

89. Ohta and Goto (1978a,b) used statistical analysis and quantification theory on nearly 300 sets of data from soils in Japan. Combinations of parameters were used to produce different correlative equations. A more detailed discussion of their studies is contained earlier. The results of correlations performed by Ohta and Goto (1978b) involving depth to estimate V_s are presented in Table 10. Combinations including both depth and SPT N-value were presented previously in Table 4.

90. The results of the analysis are very similar to those for N-value correlations by Ohta and Goto (Table 4). The correlations with depth alone produced the least accurate expression (correlation coefficient, $r = 0.670$). Individual inclusion of soil type and geologic age divisions increased the

Table 10

Results and Quantification Regression Analysis Involving V_s and Depth (performed by Ohta and Goto 1978b)

Equation No.	Combination of Correlative Parameters*	Best-Fit Relation (V_s in fps)**	Correlation Coefficient
1	Depth	$V_s = 202\ D^{0.339}$	0.670
2	Depth Soil Type	$V_s = 181\ D^{0.308} \left\lvert \begin{matrix} 1.000 \\ 1.283 \\ 1.726 \end{matrix} \right\rvert_S$ †	0.757
3	Depth Geologic Age	$V_s = 237\ D^{0.251} \left\lvert \begin{matrix} 1.000 \\ 1.542 \end{matrix} \right\rvert_G$ †	0.767
4	Depth Geologic Age Soil Type	$V_s = 209\ D^{0.241} \left\lvert \begin{matrix} 1.000 \\ 1.434 \end{matrix} \right\rvert_G \left\lvert \begin{matrix} 1.000 \\ 1.240 \\ 1.545 \end{matrix} \right\rvert_S$	0.816

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* Correlations with both depth and N-value are included in Table 4.

** Depth in ft.

† Ordinal numbers shall be interpreted as:

$\left\lvert \begin{matrix} Y_1 \\ Y_2 \end{matrix} \right\rvert_G$

Y_1 = factor corresponding to Holocene-age soil.

Y_2 = factor corresponding to Pleistocene-age soils.

$\left\lvert \begin{matrix} Y_1 \\ Y_2 \\ Y_3 \end{matrix} \right\rvert_S$

Y_1 = factor corresponding to clays.

Y_2 = factor corresponding to sands.

Y_3 = factor corresponding to gravels.

accuracy of correlations. Geologic age typically was more important than soil type. The correlation involving all four parameters produced the most accurate results (r = 0.816). With the assumption that the water table is either significantly below the seismic testing depth or at the ground surface (pore pressures consistent in one of two ways), Ohta and Goto could expect:

$$(\bar{\sigma}_o)^{0.25} \propto (\text{Depth})^{0.25} \tag{45}$$

for homogeneous soil layers (Hardin and Richart 1963). Ohta and Goto (1978b) determined from their data that the exponent for depth was about 0.241 rather than 0.25.

91. The influence of soil type and geologic age delineations on depth versus V_s was greater than that for N versus V_s correlations. The ranges of influence for soil type and geologic age groups were 55 to 73 percent and 43 to 54 percent, respectively.

92. Comparison of depth versus V_s correlations with N versus V_s correlations by Ohta and Goto (1978b) indicates that N-value produces a more accurate relationship (r = 0.719 as compared to 0.670). However, with the inclusion of soil type, geologic age, or both, depth versus V_s correlations are of about equal accuracy. The most accurate correlations incorporate both depth and N-value (refer to Table 4).

93. Fumal (1978) analyzed V_s correlations because of the dependence of the intensity of earthquakes on local geologic conditions. The results of this study were used to microzone the San Francisco, California, bay area, as described by Borcherdt, Gibbs, and Fumal (1978). Downhole seismic data were accumulated from 59 sites in the San Francisco, California, region (as reported by Gibbs, Fumal, and Borcherdt 1975, 1976, and Gibbs et al. 1977) in both cohesive and cohesionless soils.

94. Fumal (1978) desired to identify material properties easily obtainable in the field that exhibit a significant effect on V_s . Variables considered were N-value, depth, soil type, geologic age, and depth of the water table. Fumal concluded that relative grain size had the most significant effect on V_s when examined as a function of depth. At any given depth, V_s was found to increase with increased average grain size. SPT N-value was found to be useful to subdivide soil-type groups that had wide ranges in velocity. Fumal (1978) presented ranges of V_s for these specific soil-type

groups (Table 11). In general, using the groups developed, ranges and deviations in V_s are relatively consistent except for sands and gravels at depth. However, most groups have very small quantities of data to be analyzed.

95. Fumal examined correlations between V_s and depth. There is significant scatter in the data, as is shown in Figure 13. Fumal used data from sandy soils to develop the relation:

$$V_s = 471 D^{0.20} \quad \text{(fps)} \tag{46}$$

and data from cohesive soils to determine:

$$V_s = 462 + 15.4 D \quad \text{(fps)} \tag{47}$$

96. Fumal and Tinsley (1985) considered a data base of information collected in the Los Angeles, California, area to map V_s of surface deposits similar to that reported in Fumal (1978). Data were collected using interval downhole techniques at 84 sites.

97. Most data were presented as a function of depth. However, rather than propose equations for various applications, Fumal and Tinsley (1985) presented a table of statistical results. Separate categories of soil type with subdivisions of range in N-value were presented with corresponding average V_s, standard deviation, and range. Results for late Quaternary deposits are presented in Table 12. Ranges presented in Table 12 for data in Los Angeles have broader ranges and higher standard deviations than those for the San Francisco area. However, that may be attributable primarily to the larger number of data available. Similar to data from Fumal (1978), the ranges and standard deviations for sands ($N > 30$) and gravels are quite high.

98. Contrary to Fumal (1978), Fumal and Tinsley (1985) determined that correlations between N and V_s among data for different soil types can be quite organized with correlation coefficients corresponding to linear regression analysis ranging from 0.62 to 0.97. Geologic age seemed to have little influence on N versus V_s correlations.

99. Campbell and Duke (1976), Campbell et al. (1979), and Lew and Campbell (1985) have been involved with correlations between depth and V_s in

Table 11

Shear Wave Velocities in Sedimentary Deposits of the San Francisco, California, Bay Area (Fumal 1978))

		Shear Wave Velocity, fps			
Physical Proper Unit	Range in Depth, ft	No. of Values Reported	Mean	Standard Deviation	Range
Silty clay and clay--very soft to soft (N < 4)					
Near surface	8 to 39	3	262	62	177 to 331
At depth	39 to 686	2	354	56	331 to 374
Medium to very stiff (4 ≦ N ≦ 20)	0 to 98	7	574	36	525 to 640
Very stiff to hard (N > 20)					
Near surface	8 to 39	3	656	72	574 to 751
At depth	39 to 72	2	886	141	741 to 1,023
Sandy clay and silt loam					
Near surface	8 to 39	3	728	46	666 to 781
At depth	39 to 98	7	951	49	836 to 1,079
Sand					
N ≦ 40	0 to 52	10	676	118	492 to 817
N > 40					
Near surface	0 to 39	11	1,004	131	823 to 1,246
At depth	39 to 98	22	1,305	272	830 to 1,712
Gravel					
Near surface	8 to 33	4	1,381	161	1,181 to 1,630
At depth	33 to 98	8	2,020	371	1,371 to 2,457
Interbedded sediment	8 to 98	5	846	49	764 to 905

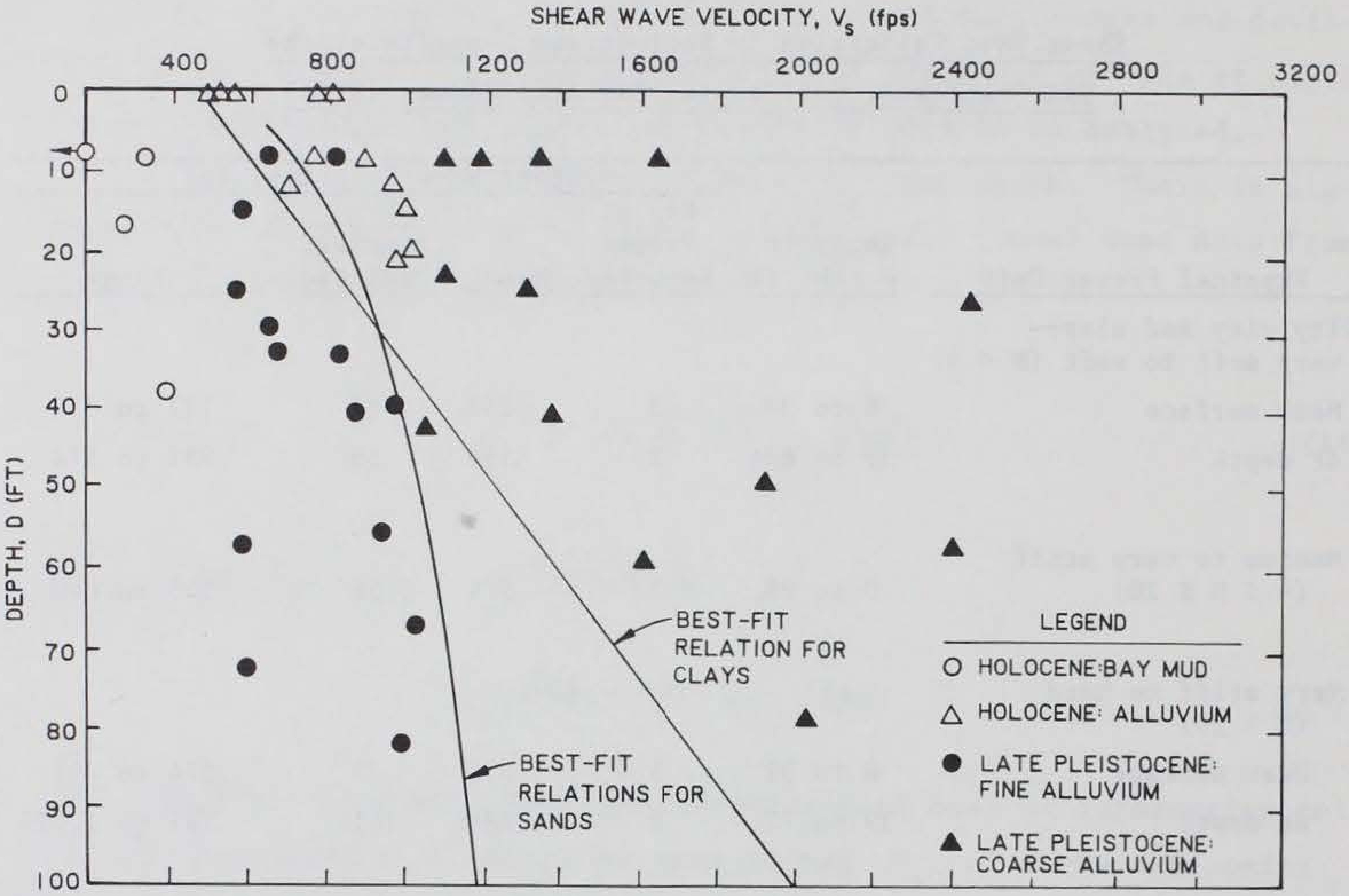

Figure 13. Correlation between depth and V_s using soils in the San Francisco, California, bay area (as presented by Fumal 1978)

the Los Angeles, California, area for over 10 years. Each study has incorporated an expanded data base of V_s data and is presumed to incorporate all data from previous studies. Each of these three studies is discussed herein.

100. Campbell and Duke (1976) made correlations between V_s (as determined mainly by surface seismic refraction testing) and depth. Depths used to correspond with V_s value corresponded to the top of constant-V_s-soil layers. Data were accumulated over a 5-year period from 63 sites in the Los Angeles, California, area. Geotechnical data were obtained from a borehole at each site. The authors used a classification system to separate the soils into five categories: unconsolidated soils, recent alluvium, compacted fill, sand and gravel, and old alluvium. The range of V_s for the two groups recent alluvium and old alluvium were almost mutually exclusive, with the range for recent alluvium being 560 to 790 fps compared with 740 to 1,110 fps for older alluvium. The authors noted that gravel content has a significant effect on the V_s. The ratio of V_s for sands and gravels to alluvium (little or no

Table 12

Shear Wave Velocities in Late Quaternary Sedimentary Deposits in the Los Angeles Region (from Fumal and Tinsley 1985)

Physical Property Unit	No. of Velocity Intervals	Shear-Wave Velocity, fps Mean	Standard Deviation	Range
Clay and silty clay				
Medium to very stiff ($4 \leq N \leq 15$)	8	575	100	460 to 740
Very stiff to hard ($N > 15$)	7	885	164	655 to 1,115
Silt loam and sand clay	29	850	260	525 to 1,180
Sand				
Loose to medium dense ($N \leq 30$)	40	770	115	460 to 935
Dense to very dense ($N > 30$)	55	1,440	360	885 to 2,427
Gravelly sand and gravel	28	1,425	345	950 to 2,230
Cobbles to gravel	8	1,900	605	1,150 to 2,720

gravel), all of the Holocene age, is roughly 1.5. Two of the equations presented by Campbell and Duke (1976) are for:

Recent alluvium:

$$V_s = 319\ D^{0.386} \quad \text{(fps)} \tag{48}$$

Older alluvium:

$$V_s = 491\ D^{0.358} \quad \text{(fps)} \tag{49}$$

101. Campbell et al. (1979) included 48 new velocity measurements in their analysis, all but 3 from southern California. Of the new data added, 10 were determined from surface refraction techniques, 3 from crosshole measurements, and 35 from downhole measurements. Shear wave velocities used were said to correspond to the depth at the top of the measured soil layer. In the

case of surficial layers, the depth was said to be one-third the thickness of the layer.

102. A more extensive and complicated geotechnical classification system was also adopted by the authors with divisions such as soft, intermediate, firm, and very firm soils (all with less than 10 percent gravel) with the modifers saturated and unsaturated. This system does not, however, divide the soils according to geologic ages as before. Again, the influence of gravel on V_s was significant in that the range in V_s for soil with 10 to 50 percent gravel was 805 to 1,150 fps; whereas, for soils with greater than 50 percent gravel, the range in V_s was 1,120 to 1,430 fps.

103. The form of the correlation equation was modified by Campbell et al. (1979) to be applicable for near-surface soil deposits. Three of the equations reported are listed below for:

Soft natural soils:

$$V_s = 170\ (D + 3.9)^{0.456} \quad \text{(fps)} \tag{50}$$

Intermediate soils:

$$V_s = 278\ (D + 2.4)^{0.413} \quad \text{(fps)} \tag{51}$$

Firm natural soils:

$$V_s = 519\ (D + 2.0)^{0.349} \quad \text{(fps)} \tag{52}$$

104. Lew and Campbell (1985) supplemented data presented by Campbell et al. (1979) with data from 159 additional sites (total of 270 sites, most in southern California). Data were collected from measurements made using surface refraction, downhole, and crosshole techniques. The distribution of data among these techniques and the influence of technique on correlations was not reported. The same curve fitting techniques adopted in Campbell et al. (1979) were also used for this update. New soil categories and average values of V_s are provided in Table 13. Standard deviations are relatively low except for gravelly soils.

Table 13

Average Shear Wave Velocities for Soils in the Los Angeles, California, Area (reported by Lew and Campbell 1985)

Soil Description	Shear Wave Velocity, fps Mean	Shear Wave Velocity, fps Standard Deviation
Soft natural soil	528	58
Soft clay (depth < 10 ft)	310	87
Soft clay (10 ft ≦ depth ≦ 100 ft)	630	69
Intermediate natural soil	701	132
Firm natural soil	873	152
Nonengineered fill	518	56
Engineered fill	867	--
10 to 50 percent gravel (depth = 0)	1,040	--
10 to 50 percent gravel (5 ft ≦ depth ≦ 60 ft)	1,305	188
10 to 50 percent gravel with cobbles, 50 percent gravel (5 ft ≦ depth ≦ 50 ft)	1,599	409
Saturated soil	--	--

105. Updated equations presented by Lew and Campbell (1985) differ somewhat from their previous study. Three of the relations representing more common divisions are for:

Soft natural soils:

$$V_s = 220\ (D + 5.33)^{0.385} \tag{53}$$

Intermediate soils:

$$V_s = 262\ (D + 5.24)^{0.402} \tag{54}$$

Firm soils:

$$V_s = 523\ (D + 0.54)^{0.280} \tag{55}$$

where D is depth, ft. Lew and Campbell (1985) presented log-log plots of best-fit relations with corresponding upper and lower limits for each soil category. The upper and lower limit curves for the three categories represented by best-fit relations in Equations 51, 52, and 53 are presented on an arithmetic plot in Figure 14. These three soil categories have significant overlap (roughly one-half of the range) between data ranges. Obviously, a plot of upper and lower limits for all 11 soil categories proposed would be redundant.

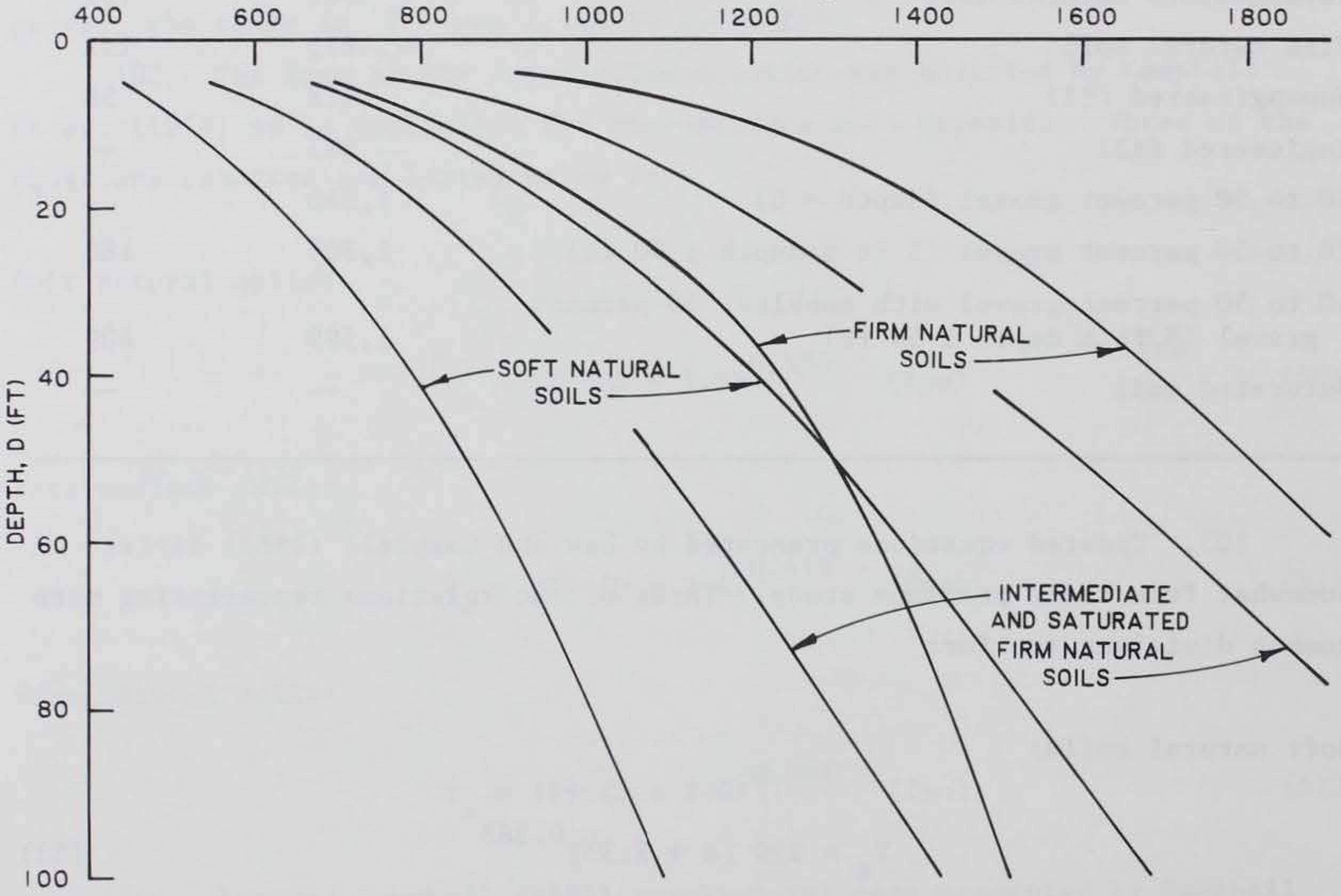

Figure 14. Ranges in data used to correlate depth with V_s for three soil categories, (as performed by Lew and Campbell 1985)

106. Hanna, Ambrosii, and McConnell (1986) conducted a detailed study of thick Pleistocene alluvial terrace gravels for a proposed dam in Argentina. Measurements of V_s in situ were made using crosshole and downhole methods to depths to 65 ft at four locations. Results of gradation tests indicate that the gravels are relatively homogeneous for the fraction greater than 0.75 in. (which corresponds to 58 to 80 percent of the material). Measured values of

V_s were plotted versus depth by Hanna, Ambrosii, and McConnell (1986) and are presented in Figure 15. Depths of the phreatic surface were not reported.

107. Data plotted by Hanna, Ambrosii, and McConnell (1986) define a relatively narrow band which increases only slightly in width (with regard to V_s) with depth. At a depth of 20 ft, the range in V_s for a band wherein most of the data lie is from 800 to 1,200 fps. This range appears to be very low, especially compared with ranges and standard deviations for gravels presented by others, and may be attributable to the site-specific nature of the correlation. The general increase in V_s with depth is associated with the increase with $\bar{\sigma}_A$.

108. Hanna, Ambrosii, and McConnell (1986) also measured V_s in a 23-ft-high test embankment composed of compacted alluvial gravels. Measurements were made at three locations, each representing a different level of compaction effort (function of number of passes (0, 2, 6, or 10) of a vibratory roller). A relation representing average values of V_s for the 6- and 10-pass sections is plotted in Figure 15. This slope of this relation indicates that the natural gravels exhibit a greater increase in V_s with depth that appears to be more than just a function of average void ratio of a soil material. If the phreatic surface exists very near the surface as expected, the increase in V_s as a function of $\bar{\sigma}_v$ and not depth would be even more profound when compared to V_s from the test embankment.

109. Hanna, Ambrosii, and McConnell (1986) also compared correlations between depth and V_s proposed by Ohta and Goto (1978a) for both alluvial (Holocene) and diluvial (Pleistocene) gravels. These relations overestimated V_s at shallow depths and underestimated V_s at greater depths, indicating that V_s tended to increase much more rapidly than suggested by Ohta and Goto (1978a).

Correlations with Other Parameters

110. Other parameters determined either in the field or as a result of a field exploration program have been used at times to correlate with V_s . These include cone penetration (tip) resistance in situ, void ratio, compressive strength, and yield stress of undisturbed samples tested in the laboratory. Correlations with these variables are not common but still are considered in this report. Correlations with variables typically used as supportive information (i.e. soil type and geologic age) also are addressed.

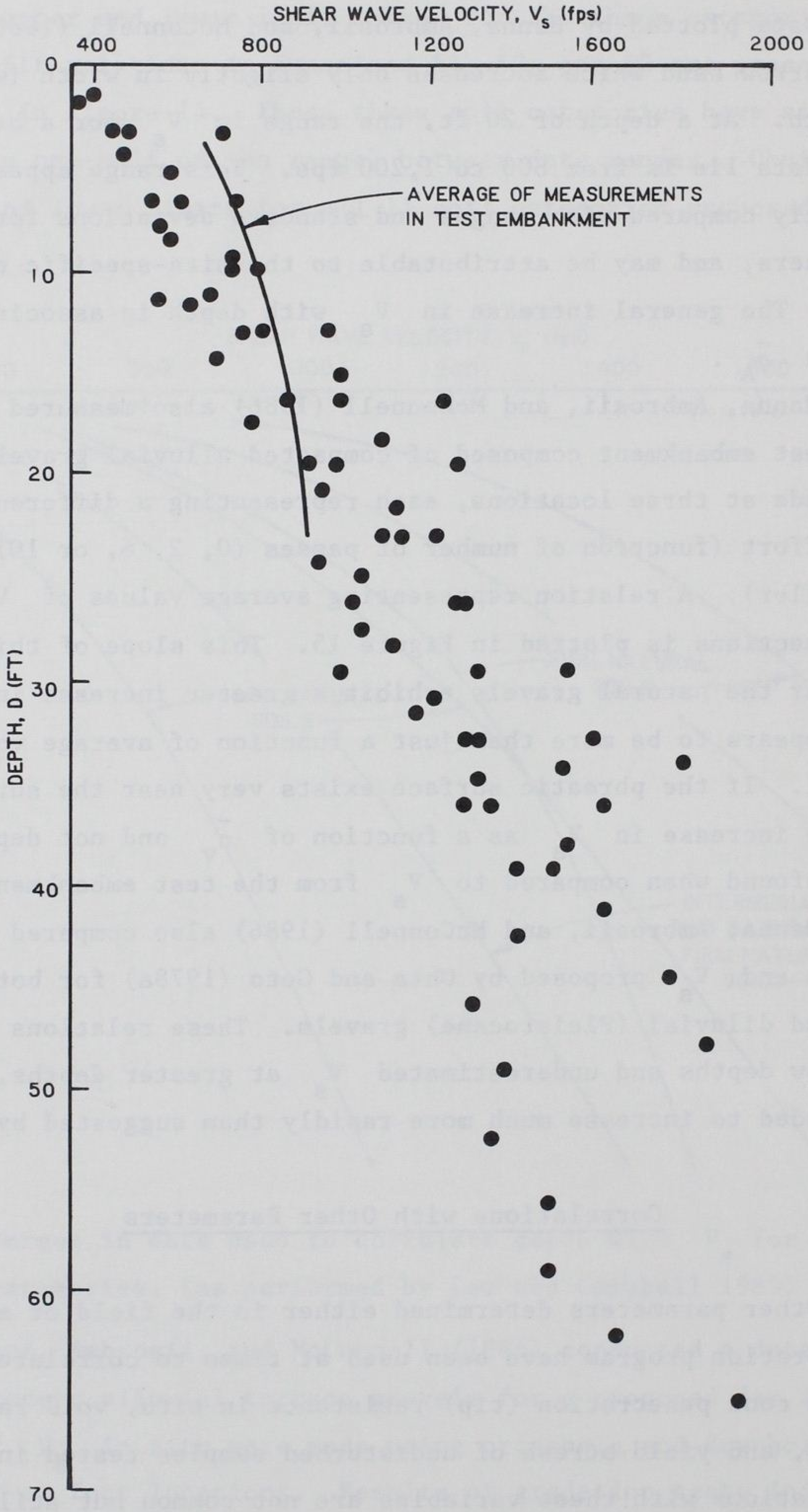

Figure 15. Site-specific correlation between depth and V_s in alluvial gravels (as presented by Hanna, Ambrosii, and McConnell 1986)

Void ratio

111. Tono (1971) presented data that indicates the magnitude of change in void ratio with geologic time, as shown in Figure 16. This data suggests that Holocene-age sands decrease in void ratio slightly with time until a certain point beyond which greater decreases occur. The decrease in void ratio e with time for clays is much greater and constant throughout the time range examined. Data presented in Figure 16 can be interpreted to indicate that the change in e with geologic time is independent of effective stress. This occurrence indicates that definition of geologic age groups may specify a range in void ratio which would be useful for correlations.

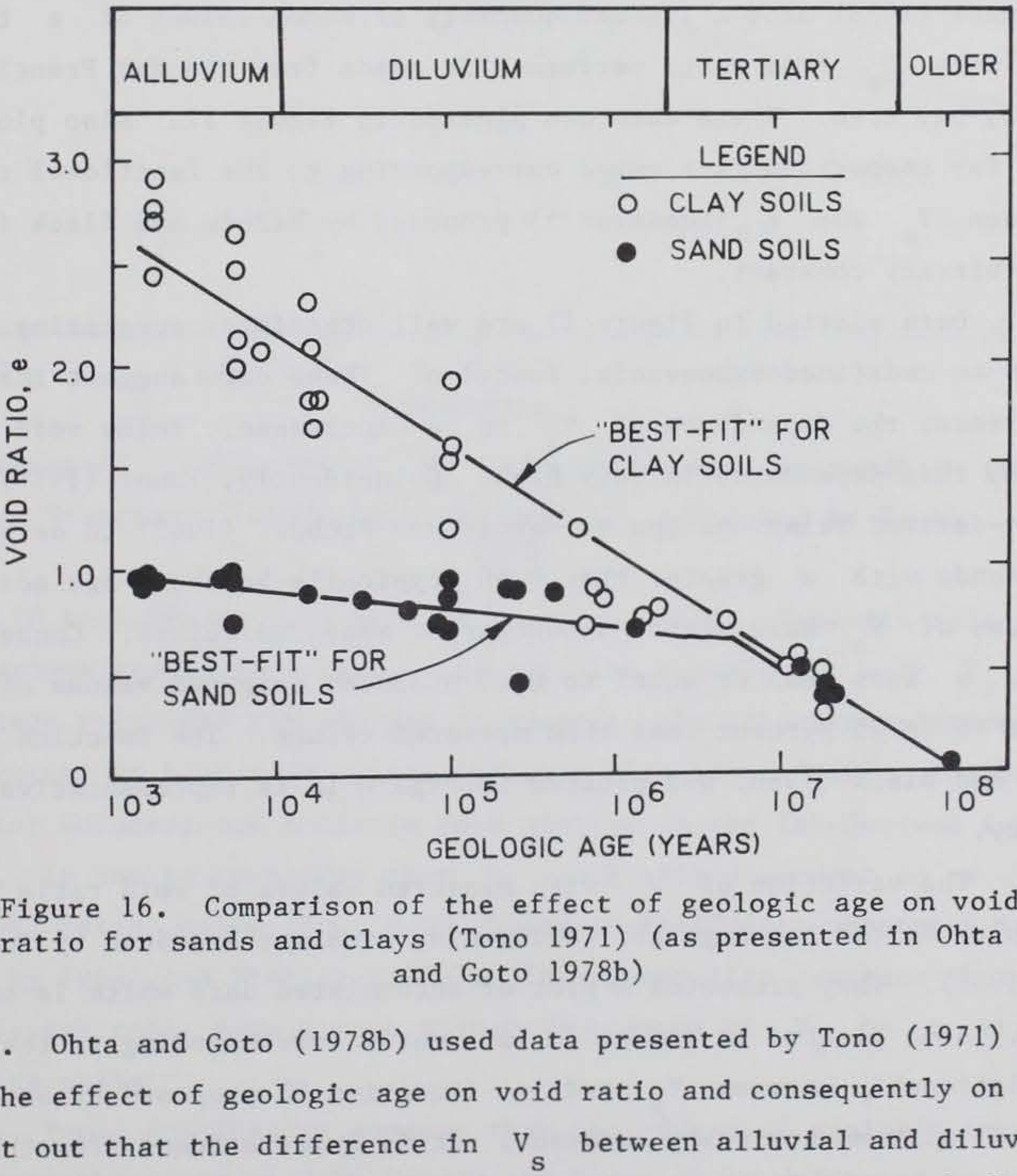

Figure 16. Comparison of the effect of geologic age on void ratio for sands and clays (Tono 1971) (as presented in Ohta and Goto 1978b)

112. Ohta and Goto (1978b) used data presented by Tono (1971) to explain the effect of geologic age on void ratio and consequently on V_s. They point out that the difference in V_s between alluvial and diluvial soils can not be explained merely by void ratio, however. The ratio of V_s of diluvial sands to the V_s of alluvial sands is approximately 1.1 for data

presented by Tono (1971). Ohta and Goto found the ratio to be 1.44 from their statistical results. Ohta and Goto (1978b) found, by using typical values of void ratio for Japanese soils, that Hardin and Richart's equation predicted V_s fairly well for alluvial soils but not for diluvial soils. This may be due, in part, to cementation of the soil grains which diluvial soils would be more likely to have.

113. Fumal (1978) and Fumal and Tinsley (1985) have addressed correlations between V_s measured in situ and e determined from field samples, the few studies available that examined correlations between e and V_s. Many authors have addressed the subject, however, particularly with respect to the association of relative grain size and geologic age to specific ranges in void ratio. Fumal (1978) used a limited quantity of known values of e to correlate with V_s from tests performed in sands from the San Francisco, California, bay area. These data are plotted in Figure 17. Also plotted in Figure 17 for comparison is a curve corresponding to the functional relationship between V_s and e (Equation 5) proposed by Hardin and Black (1968) with an arbitrary constant.

114. Data plotted in Figure 17 are well organized, suggesting a narrow band about an undefined exponential function. These data suggest that as void ratio decreases the dependence of V_s on e increases. Below void ratios of about 0.60, this dependence is very high. Coincidently, Fumal (1978) used laboratory-derived relationships by Hardin and Richart (1963) to determine that for sands with e greater than 0.60 (typically Holocene-age soils), computed values of V_s were within 5 percent of measured values. Conversely, sands with e less than or equal to 0.60 produced computed values of V_s which were 15 to 25 percent less than measured values. The function proposed by Hardin and Black (1968) and plotted in Figure 16 is representative of this discrepancy.

115. The variation of V_s with measured values of void ratio e from field samples in the Los Angeles, California, area was examined by Fumal and Tinsley (1985). They presented a plot of accumulated data which is shown in Figure 18. Also plotted in Figure 18 is a curve corresponding to the functional relationship between V_s and e (Equation 5) proposed by Hardin and Black (1968) with an arbitrary constant. It is quite evident from the data that Holocene-age and Pleistocene-age sediments represent nearly unique ranges in V_s. The range in void ratio for both groups is quite wide and not at all

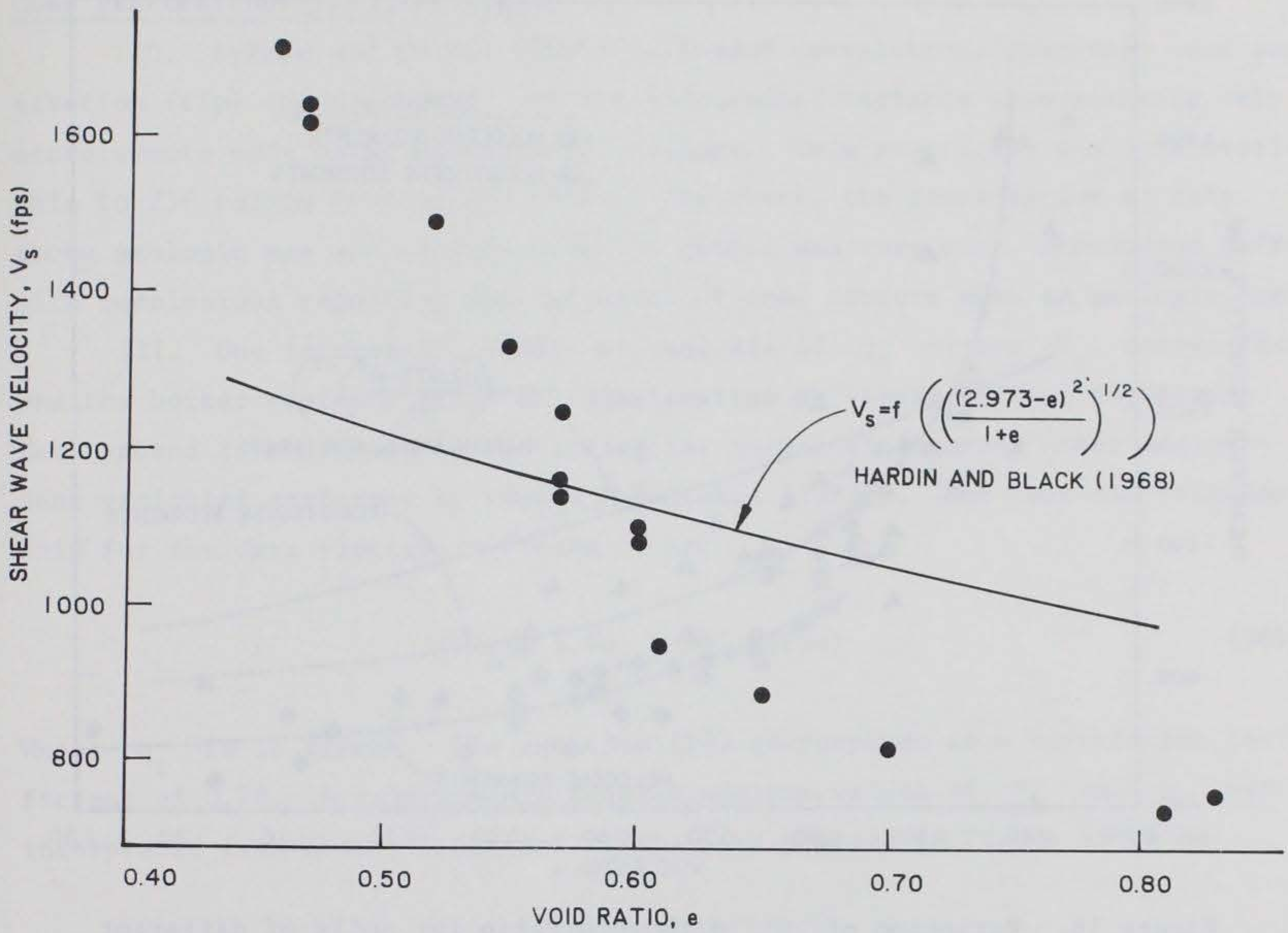

Figure 17. Variation of V_s with void ratio for sands in the San Francisco, California, bay area (as presented by Fumal 1978)

unique (0.58 to 1.28 and 0.37 to 1.18, respectively). Best-fit relations for both age groups are similar with respect to the correlation with V_s. Neither of these relations are similar in slope to the laboratory-derived function except at high void ratios (greater than about 0.80). The best-fit relation for Holocene-age soils is more similar to the lab-derived function.

116. It can be concluded that V_s is highly dependent on e, especially at void ratios below about 0.60, based on field data presented in Figure 18 by Fumal and Tinsley (1985). This generality suggests that Pleistocene-age soils have a much higher dependence of V_s on e than do Holocene-age soils.

117. Fumal and Tinsley suggest that the effect of geologic age may be more profound than suggested by Hardin and Drnevich as evidenced by comparing the best-fit relations with that of the functional curve. However, void ratio

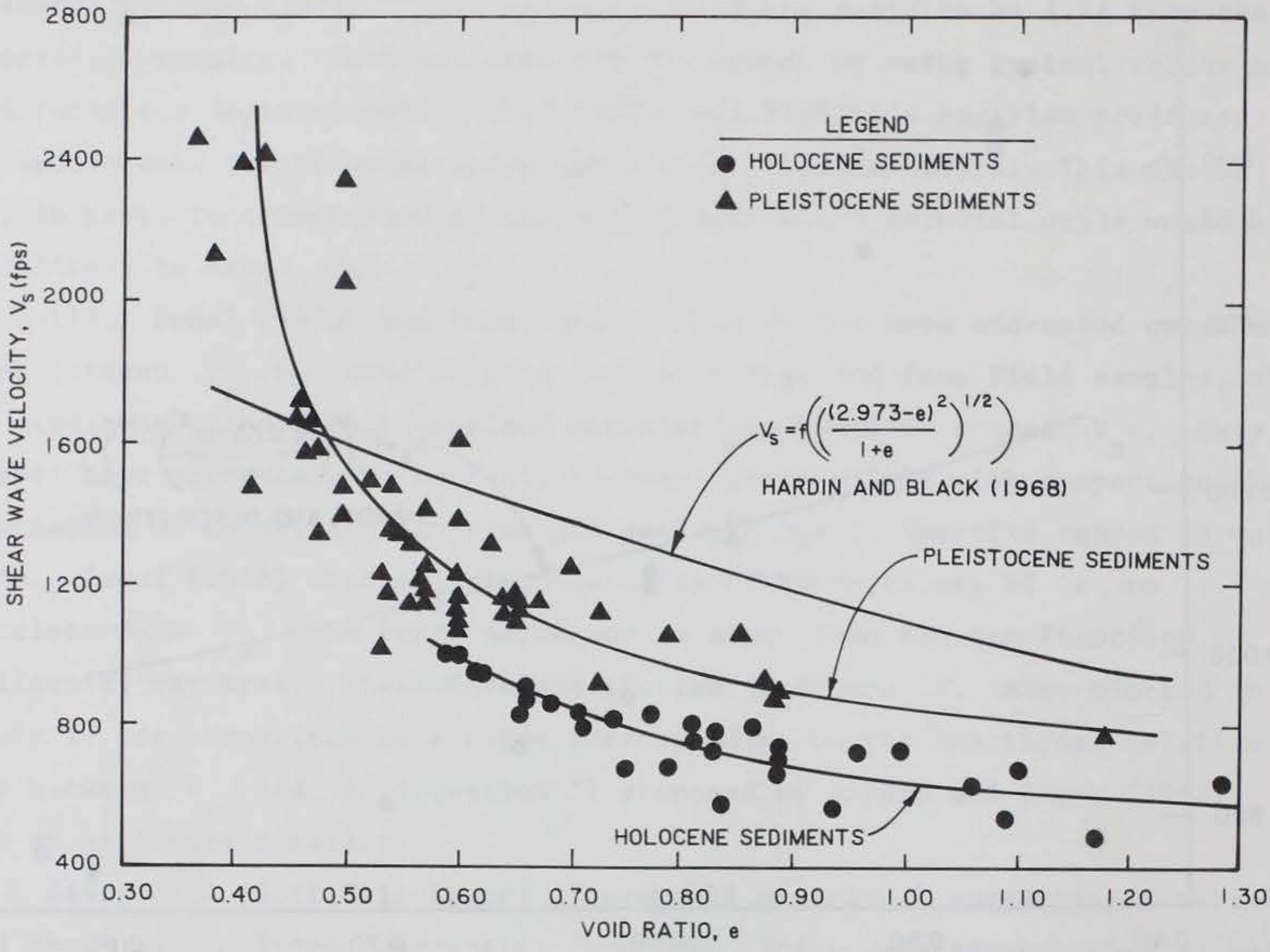

Figure 18. Variation of V_s with void ratio for soils of different geologic age in the Los Angeles, California, area (as presented by Fumal and Tinsley 1985)

was determined on both Pitcher tube (undisturbed) and split spoon (disturbed) samples. The accuracy of e measured on those disturbed samples is highly suspect.

118. Data presented by Fumal (1978) for the San Francisco area (Figure 17) and Fumal and Tinsley (1985) for the Los Angeles area (Figure 18) suggest similar conclusions. The dependence of V_s on e at void ratios lower than 0.60 is consistent. This consistency appears to be more than a coincidence. Although not specifically "correlated" to produce best-fit relations, these data suggest that correlations between e and V_s are very organized.

119. The determination of void ratio is a nontrivial process. Determination of e from field samples is not very accurate even with high-quality "undisturbed" samples. It may be more reasonable to use values of V_s to estimate e in situ.

Cone penetration (tip) resistance

120. Sykora and Stokoe (1983) performed correlations involving cone penetration (tip) resistance q_c as the independent variable incorporating only measurements made using crosshole techniques. This restricted the data available to 256 points from only 9 sites. Therefore, the distribution of data among geologic age and seismic zonation groups was very poor, precluding definite conclusions regarding the influence of some factors such as geologic age.

121. One interesting result of analysis of q_c versus V_s correlations was the better representation of relationships by linear fitting techniques (as opposed to nonlinear curve fitting for correlations using other independent variables performed by Sykora and Stokoe (1983)). The best-fit relationship for the data plotted in Figure 19 is:

$$V_s = 1.7q_c + 440 \quad \text{(fps)} \tag{56}$$

Where q_c is in kg/cm^2. The equation (56) corresponds to a correlation coefficient of 0.78. A relationship between minimum values of V_s and q_c was interpreted from about 95 percent of the data plotted in Figure 19 to be:

$$\left(V_s\right)_{min} = \sqrt{3.0q_c^2 + 140{,}000} \quad \text{(fps)} \tag{57}$$

122. Enough data were available among soil-type groups to determine a significant influence of soil type on q_c versus V_s correlations. Division of data among different soil types improved the accuracy of correlative equations (values of r for different soil-type groups ranged from 0.78 to 0.87). The different relations produced were also markedly different from each other.

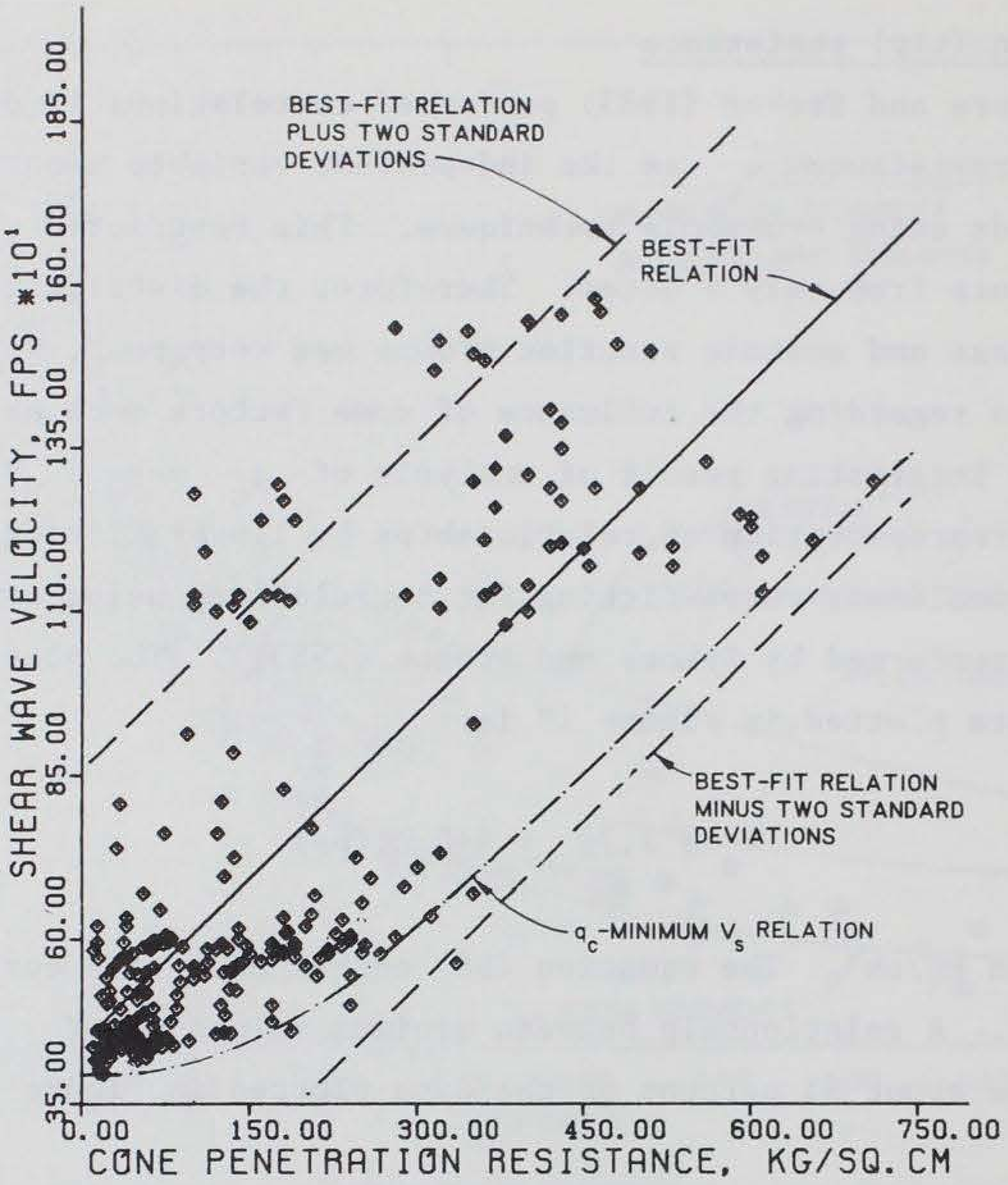

Figure 19. Correlation between cone penetration (tip) resistance and V_s (as performed by Sykora and Stokoe 1983)

Relative density

123. Relative density D_r is a parameter that is applicable to cohesionless soils and is calculated using void ratios:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100 \quad \text{(percent)} \qquad (58)$$

where

e_{max} = maximum index void ratio

e = void ratio of test sample

e_{min} = minimum index void ratio

A close correlation between D_r and V_s is expected based on the reported correlations between e and V_s and the association of D_r to e .

124. Hanna, Ambrosii, and McConnell (1986) compared values of D_r and V_s measured in a 23-ft-high test embankment composed of gravel. A wide range in D_r was achieved by varying compactive effort (function of number of passes (0, 2, 6, or 10) of a vibratory roller) over four separate but contiguous sections. Values of V_s were determined by both crosshole and downhole methods. The results of the comparison along with actual data are shown in Figure 20.

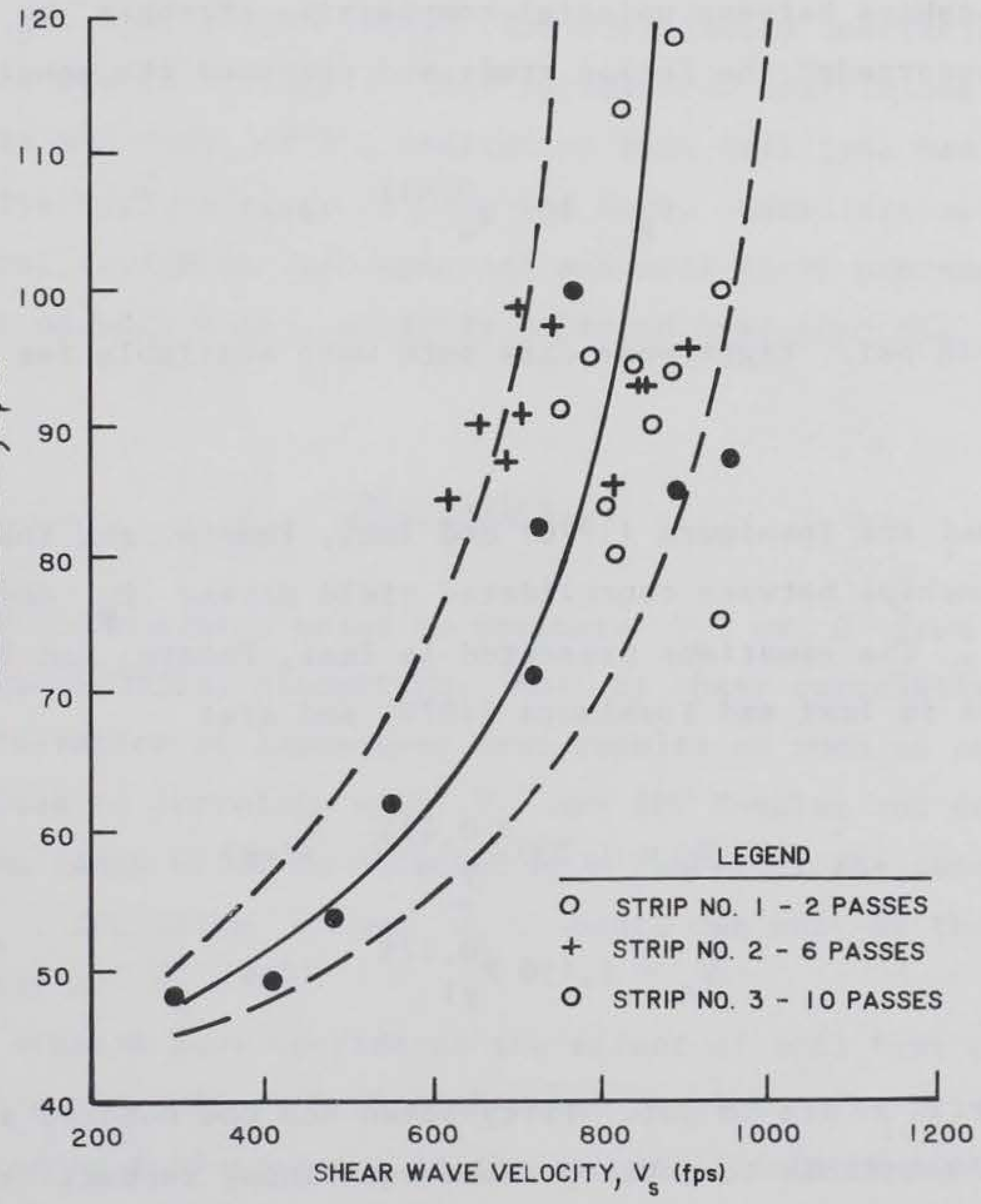

Figure 20. Correlation between relative density and V_s for gravels in a test embankment (as presented by Hanna, Ambrosii, and McConnell 1986)

125. Data plotted in Figure 20 and corresponding relationships indicate that V_s is a function of D_r . However, the dependence of V_s on D_r at

values of D_r greater than about 80 percent is minimal. Correlations between those two parameters appear to be most useful at lower values of D_r.

126. The accuracy of D_r is a function of the accuracy of three measurements of void ratio (refer to Equation 58). Therefore, it could be concluded that correlations might be more advantageous and more accurate if using e directly. Use of D_r may normalize the data and desensitize it as a functional value of V_s.

Compressive strength

127. Imai and Yoshimura (1970) and Imai, Fumoto, and Yokota (1975) presented relationships between uniaxial compressive strength q_u and V_s. The latter study superseded the former study and proposed the equation:

$$V_s = 137\, q_u^{0.417} \quad \text{(fps)} \tag{59}$$

where q_u is in psi. Eighty-one data sets were available for this correlation.

Yield stress

128. Imai and Yoshimura (1970) and Imai, Fumoto, and Yokota (1975) presented relationships between consolidated yield stress P_y and yield pressure P_{y1} with V_s. The equations presented in Imai, Fumoto, and Yokota (1975) supersede those in Imai and Yoshimura (1970) and are:

$$V_s = 1{,}200\, P_y^{0.473} \quad \text{(fps)} \tag{60}$$

$$V_s = 1{,}150\, P_{y1}^{0.375} \quad \text{(fps)} \tag{61}$$

where P_y and P_{y1} are in psi. Fifty-seven and one hundred seventy-five data sets were available to develop these equations, respectively.

Geologic age

129. Geologic age has been used regularly to divide data into different categories. However, only Ohta and Goto (1978a,b) developed a relationship between V_s and geologic age as an ordinal variable. Two age groups were considered: alluvial (Holocene) and diluvial (Pleistocene). Holocene- and Pleistocene-age soils were calculated to be 567 and 1,091 fps, respectively.

The correlation coefficient for this relationship was low (0.621), only somewhat lower than that for correlations between depth and V_s (correlation coefficient = 0.670).

Soil type

130. Soil type, too, has been regularly used to delineate data into different categories. Again, only Ohta and Goto (1978a,b) developed a relationship between V_s and soil type as an ordinal variable. Three soil types eventually were adopted (Ohta and Goto 1978b): clay, sand, and gravel. Clays, sands, and gravels were found to have average values of V_s equaling 557, 766, and 1,121 fps, respectively. The correlation coefficient for this equation was very low (r = 0.458). This correlation coefficient was the lowest found by Ohta and Goto (1978b) indicating that soil type was the poorest single correlative variable used by Ohta and Goto. Correlations which combined both ordinal variables (geologic age and soil type) produced a correlation coefficient of only 0.691, slightly improved over that for geologic age only.

Discussion

131. Field correlations exist to estimate V_s or G from any number or combination of geotechnical parameters. Most of these correlative studies have taken consideration of laboratory test results as much as possible. The most popular values to correlate with V_s are SPT N-value and depth. SPT N-value offers an index which is affected by a number of the same factors which affect V_s, including e and $\bar{\sigma}_A$. Depth can only be thought of as a relative indicator of $\bar{\sigma}_A$.

132. Many studies have considered the effect of soil type and geologic age divisions on correlations, both with mixed results. The primary differences between studies conducted are in the amount of data available and use of statistical analyses. Several of the studies incorporate too few data to be conclusive. Some studies used a moderate amount of data to the maximum extent with statistics.

PART IV: EVALUATION OF FIELD CORRELATIONS AVAILABLE

133. A presentation of existing studies that examine V_s and G correlations has been made previously. Each study has been described in varying amounts of detail, commensurate with usefulness to this study. Juxtaposition of methodologies, velocity ranges, and best-fit relationships are conducted in this part to assist the practitioner in selecting the most appropriate system and set of equations.

Methodologies

134. Studies reviewed in this report are not considered to be on a completely equal basis with each other. Each study represents a unique set of conditions and assumptions incorporating a unique set of data. Therefore, the quality of each is expected to be different. Some of the more important and nonuniform conditions include:

- Type of seismic geophysical method(s) used.
- Method of associating correlative parameters with V or G .
- Method of handling SPT N-values above 50 and below 1.
- Range and distribution of material characteristics, especially V_s (or G), soil types, geologic ages, and correlative variable (e.g., N or D).

Obviously, each of these could significantly affect the adaptation of an existing study to a particular project. More detailed discussion of some of the differences is contained herein.

135. The method of geophysical exploration used can have an effect on correlations due to the nature of different measurements, in particular, averaging effects. Most studies acquired all or a majority of the data using the downhole method. In general, downhole methods provide a profile of V_s with depth which consists of a few averaged uniform values. Layers which exhibit low velocity and are sandwiched between higher velocity layers may go undetected. Selection of depths at which velocity changes is a function of the sampling interval and sometimes the data analyst. Surface refraction methods produce somewhat similar results to downhole tests except that typically only two or three layers of constant V_s can be defined with more averaging and more dependence on the data analyst. Very few studies incorporated

data collected using crosshole methods which unequivocally provides the most detailed profile of V_s with depth (Woods 1986).

136. It seems logical to presume that the sensitivity of measurements will directly affect the sensitivity and accuracy of correlations. If profiles of average V_s are used, the maximum range in V_s is expected to be truncated somewhat as compared with actual in situ conditions. If marginal geophysical techniques are used to measure seismic velocity, the accuracy of V_s can be affected greatly.

137. The use of different geophysical methods also presents a need to decide how to associate correlative parameters with V_s. For instance, with crosshole methods, V_s is associated with the depth of measurement. However, associating N-values with measured V_s involves some interpretation since the two measurements may have been made at different depths. The association of depth or N-value to V_s (or G) is further complicated.

138. Two different methods of data reduction typically were used in N versus V_s studies which used data collected from downhole seismic methods. Although very similar, these two methods of data reduction could produce differences in the number of data points available for analyses and may affect the actual correlative results. Campbell and others chose to use a depth associated with the top of the soil layer for depth versus V_s correlations.

139. Ohsaki and Iwasaki (1973) reduced their data using a simplified-profile approach in which arbitrary layering was based on soil types. First of all, layers were chosen so that each layer consisted of a single soil stratum or a combination of adjacent strata with a similar soil type. Next, N-values corresponding to depths within the range of each layer were averaged. Finally, the depths and thicknesses of the soil layers were compared with the G profile. If the thickness and depth of a specific soil layer matched that of a constant shear modulus interval (within reason), the two were said to correspond with the averaged N-value. If two or more soil layers matched up to one modulus interval, a data point was used for each of the soil layers corresponding to the shear modulus, and the N-value averaged from the soil layer. If one soil layer matched two or more modulus intervals, a data point was used for each modulus interval corresponding to the same soil strata, and the N-value was averaged over the complete soil layer.

140. Ohta and Goto (1978a,b) and Imai and Tonouchi (1982) used a much simpler approach of data reduction by averaging all N-values at depths

corresponding to constant V_s intervals. This method of reduction not only minimizes data available but desensitizes values of N .

141. The method of data reduction, then, should also be considered when comparing various studies. One important consideration of data reduction techniques seems to be consistency. If a particular correlation is being adopted for use in an engineering study, the methods used to associate correlative parameters with V_s should be used to estimate V_s .

142. Each author handled ranges of correlative parameters differently; for instance, Imai and others plotted N-values equal to zero as 0.5 because data were plotted on a log-log scale (no zero). Ohta and Goto (1978a,b) did not use N-values greater than 50 blows/ft. Other authors extrapolated N-values using penetration depths of less than 1 ft (18 in. total). These factors, too, will affect the correlations to varying degrees.

143. Certainly as important as the aforementioned factors is the effect that the range and distribution of material characteristics have on correlations. Each correlative study is not expected to be representative of a wide range of conditions. As a general guideline, the more data available, the more representative the data is expected to be for more conditions.

144. Use of correlations should be tailored to the characteristics of the data base availability. A study incorporating only a few data from Tertiary soils cannot be expected to be representative of Tertiary soils. Also of consideration is the range of N-value or depth used for the correlation analysis. Oddly enough, few authors placed limitations on range for correlative equations.

145. One example of disparity in distribution of data which typically would go unrecognized exists in the papers by Ohta and Goto (1978a,b). Most users of equations by Ohta and Goto would consider best-fit relations for data groups to be of equal value. However, close examination of their reports indicates that only 8 data were used to develop a correlative equation for gravel as compared with 94 data for fine sands. Obviously, the equation by Ohta and Goto for gravels has severe limitations. The inclusion of fill and peat soils in the analysis by Imai and Tonouchi (1982) could also impact the correlations significantly.

146. It is important to consider the source of correlative equations. The geophysical methods used, methods of data reduction, range in correlative variables, and overall character of the data base should be scrutinized. It

is not sufficient to simply select a correlation based on convenience or availability.

Velocity Ranges

147. Ranges in V_s for various geologic age and soil-type divisions were compiled to provide the practitioner a basis for comparison with measured values. Ranges in V_s for soils of different geologic age and for different soil types are presented in Tables 14 and 15, respectively. Unfortunately, few authors reported ranges of values of V_s collected and used in analyses. Values presented for Imai and Tonouchi (1982) were determined from high-resolution histograms (bar width equal 65 fps). Ohta and Goto (1978a,b) also reported ranges in V_s using histograms. However, they used bar widths varying from about 70 to 545 fps which do not allow for very accurate determination of range. Average values of V_s reported by various studies have been documented previously in this report.

148. Ranges in V_s proposed by various studies for different geologic age groups (Table 14) are consistent in a number of ways. In all cases, the lowest value of V_s per age group per study increases with increased age. Almost as consistent is the incremental increase in the upper bound of the range in V_s with increased geologic age. Also very consistent among studies is the increase in overall range as geologic age increases. The primary difference in ranges is the magnitude of the lower bound V_s. Imai and Tonouchi (1982) have data with very low values of V_s, especially for alluvial (Holocene-age) soils. The low value registered by Fumal (1978) corresponds to a recent deposit of San Francisco Bay mud. It is not known what differences exist between Japanese and US soils which might produce this discrepancy.

149. Ranges in V_s proposed by various studies for different soil types (Table 15) are also consistent in a number of ways but are not quite as consistent as geologic age divisions. In general, the upper and lower bounds of V_s per study increase with increase in relative grain size (i.e., clay, sand, gravel, respectively). The range of V_s also increases with increased relative grain size. The magnitudes of lower-bound values of V_s reported by Imai and Tonouchi (1982) are very low. The applicability of these lower-bound values to US studies is, therefore, suspect.

Table 14

Ranges in V_s for Soils of Different Geologic Age Reported by Various Studies

Study	Application	Seismic Measurement Method(s)	Geologic Age	Shear-Wave Velocity, V_s, fps	
				No. of Data	Range
Fumal (1978)	Soils in San Francisco, Calif., Bay area	Downhole	Holocene	22	175-1,080
			Pleistocene	38	560-2,455
Imai and Tonouchi (1982)	Japanese soils	Downhole	Fill	144	100-1,120
			Alluvial*	664	125-1,640
			Diluvial**	674	300-2,460
			Tertiary	108	400-2,260
Sykora and Stokoe (1983)	US soils	Crosshole	Holocene	122	410-1,110
			Pleistocene	166	465-1,575
			Tertiary	40	650-1,890
Fumal and Tinsley (1985)	Soils in Los Angeles, Calif., area	Downhole	Holocene	73	490-1,230
			Pleistocene	172	655-2,720

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* Holocene--does not include peats.

** Pleistocene.

Table 15

Ranges in V_s for Different Soil Types Reported by Various Studies

Study	Application	Seismic Measurement Method(s)	Soil Type	Shear-Wave Velocity, V_s, fps: No. of Data	Shear-Wave Velocity, V_s, fps: Range
Fumal (1978)	Soils in San Francisco, Calif., Bay area	Downhole	Clays*	27	175-1,080
			Sands	41	490-1,710
			Gravels	12	1,180-245
Imai and Tonouchi (1982)	Japanese soils	Downhole	Peats	17	85-690
			Clays**	847	125-1,840
			Sands**	632	235-2,200
			Gravels	142	555-2,460
Sykora and Stokoe (1983)	US soils	Crosshole	Sands	296	410-1,890
			Gravels†	32	510-1,850
Fumal and Tinsley (1985)	Soils in Los Angeles, Calif., area	Downhole	Clays*	44	460-1,180
			Sands	95	460-2,425
			Gravels	28	950-2,230
			Cobbles	8	1,150-2,720

---

* Includes silt loams and sandy clays.

** Does not include fill.

† Includes gravelly sands.

SPT N-Value

Uncorrected N-value

150. Field correlations reviewed involving SPT N-value and V_s are listed in Table 16. Reported equations superseded by later studies were not included in Table 16. Table 16 does include more than one relation for some studies if different equations for different soils were presented. However, only a few select divisions were presented. Correlative equations proposed independent of soil type are plotted in Figures 21 and 22. Japanese studies were adjusted throughout this section, in figures only, to account for differences in energy efficiency between US and Japanese SPT equipment and procedures. SPT energy efficiencies for US and Japanese studies were assumed to equal 60 and 67 percent, respectively (Seed et al. 1985). The ranges suggested by Sakai (1968) and depicted in Figure 22, were separated from the nonlinear relations in Figure 21 for ease in presentation. Recall (see Figure 7) that large bands of scatter may be associated with each relation. The correlations will be examined and compared with this scatter in mind.

151. An appreciable amount of deviation is evident among relations plotted in Figures 21 and 22, especially at large N-values. The relation proposed by Kanai (1966) is the most incongruous, therefore, it is highly suspect. The other four relations are grouped together with relations proposed by Imai and Tonouchi (1982) and Ohta and Goto (1978a) representing an approximate mean.

152. Three of the studies examining N versus V_s correlations for all soils are prominent for different reasons. Imai and Tonouchi (1982) used a very large data base (1,654 sets of data). Ohta and Goto (1978b) performed detailed sensitivity analyses of various factors thought to affect N versus V_s correlations. Ohsaki and Iwasaki (1973) also paid close attention to various parameters and used limited statistical analysis. The general relationships proposed in these three select studies are plotted in Figure 23.

153. The three relationships selected are very similar for a range in N-value from 5 up to about 30 blows/ft; beyond that value, the relationships begin to deviate considerably. Calculated values of V_s at various N-values are tabulated in Table 17 for comparison.

Table 16

Comparison of Previous N-Value Versus V_s Field Correlations Investigated

Equation No.	Author(s)	Data Information	Soil Types Used	Reported Equation: Shear Modulus, G, tsf	Reported Equation: Shear Velocity, V_s, fps
1	Kanai (1966)	Japanese	All	N.R.	$V_s = 62\ N^{0.5}$
2	Yoshikawa (unknown)	Japanese; reported by Sakai (1968)	--	N.R.	$V_s = 178\ (N + 5)$ to $127\ (N + 1)$
3	Sakai (1968)	Japanese		N.R.	$V_s = (49 \text{ to } 110)\ N^{0.5}$
4	Shibata (1970)	Japanese	Sands	N.R.	$V_s = 104\ N^{0.5}$
5	Ohba and Toriuma (1970)	Alluvial soils in Osaka, Japan	All	N.R.	$V_s = 280\ N^{0.31}$
6	Ohsaki and Iwasaki (1973)	200 sites in Japan; 220 sets of data	All	$G = 125 \cdot N^{0.78}$ (0.886)*	
7	Ohsaki and Iwasaki (1973)	200 sites in Japan; 220 sets of data	Sands	$G = 66.5\ N^{0.94}$ (0.852)*	$V_s = 195\ N^{0.47}$**
8	Ohta and Goto (1978a)	289 sets of data; Japanese soils	All	N.R.	$V_s = 280\ N^{0.341}$ (0.719)**

(Continued)

Note: N = Standard Penetration Resistance N-value (blows/ft); not adjusted for differences in energy efficiency. N.R. = Not reported.

* Regression correlation coefficient.

** Assumed $\gamma = 112.4$ pcf, typical for Japanese sands (Ohsaki 1962).

Table 16 (Concluded)

Equation No.	Author(s)	Data Information	Soil Types Used	Reported Equation	
				Shear Modulus, G, tsf	Shear Velocity, V_s, fps
9	Ohta and Goto (1978b)	289 sets of data; Japanese soils	Sands	N.R.	$V_s = 290\ N^{0.340}$
10	Ohta and Goto (1978b)	289 sets of data; Japanese soils	Gravels	N.R.	$V_s = 309\ N^{0.340}$
11	Imai and Tonouchi (1982)	1,654 sets of data; Japanese soils	All	$G = 147\ N^{0.68}$ (0.867)*	$V_s = 318\ N^{0.314}$ (0.868)*
12	Seed, Idriss, and Arango (1983)†	Unknown	All	$G = 65\ N^{1.0}$	$V_s = 185\ N^{0.5}$
13	Sykora and Stokoe (1983)†	Throughout United States	Granular	N.R.	$V_s = 350\ N^{0.27}$ (0.84)*

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* = Regression correlation coefficient.

† = Average SPT energy assumed equal to 60 percent as compared with 67 percent for Japanese SPT equipment and procedures.

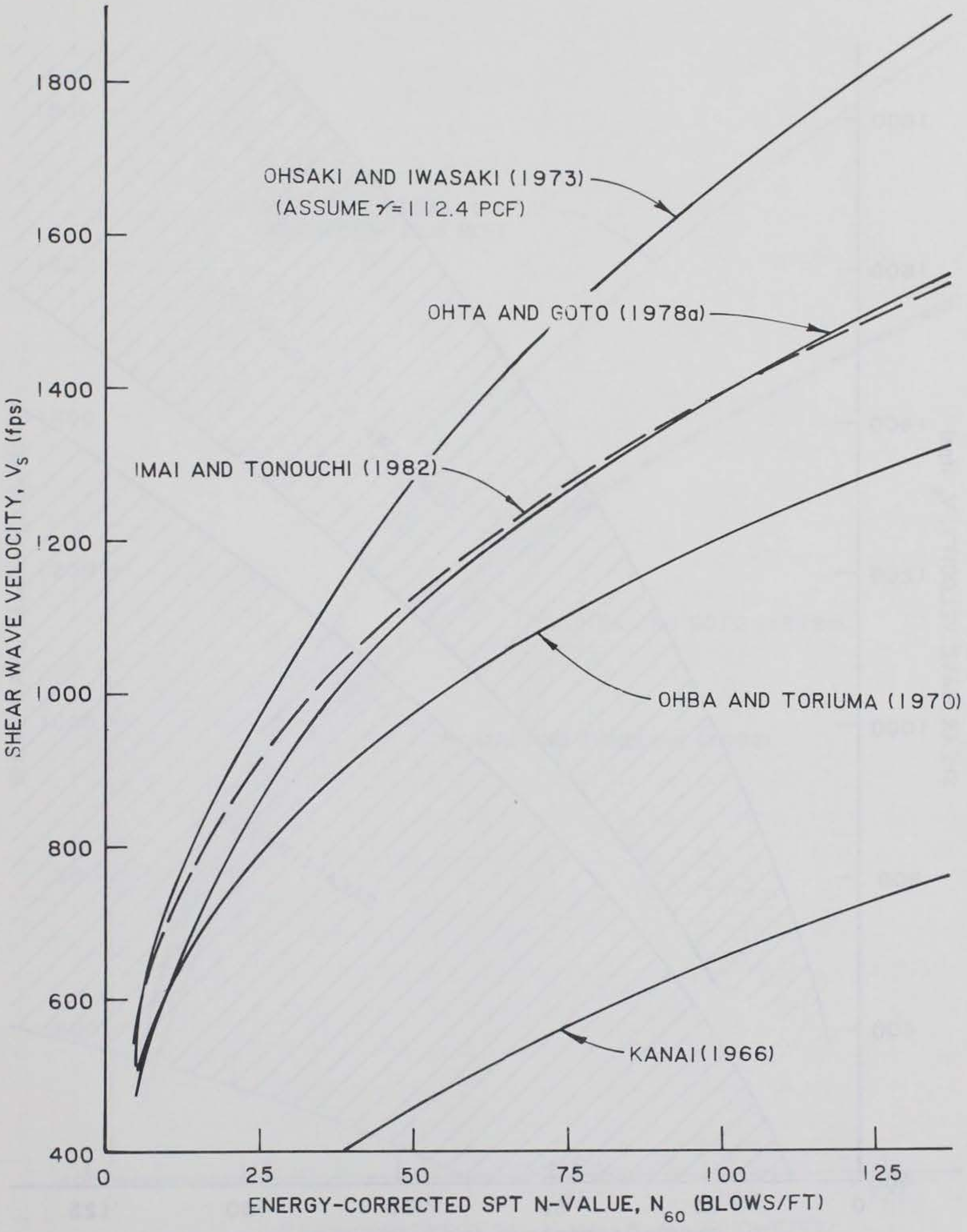

Figure 21. Comparison of results for N versus V_s correlations (proposed by various studies for all soils and geologic conditions)

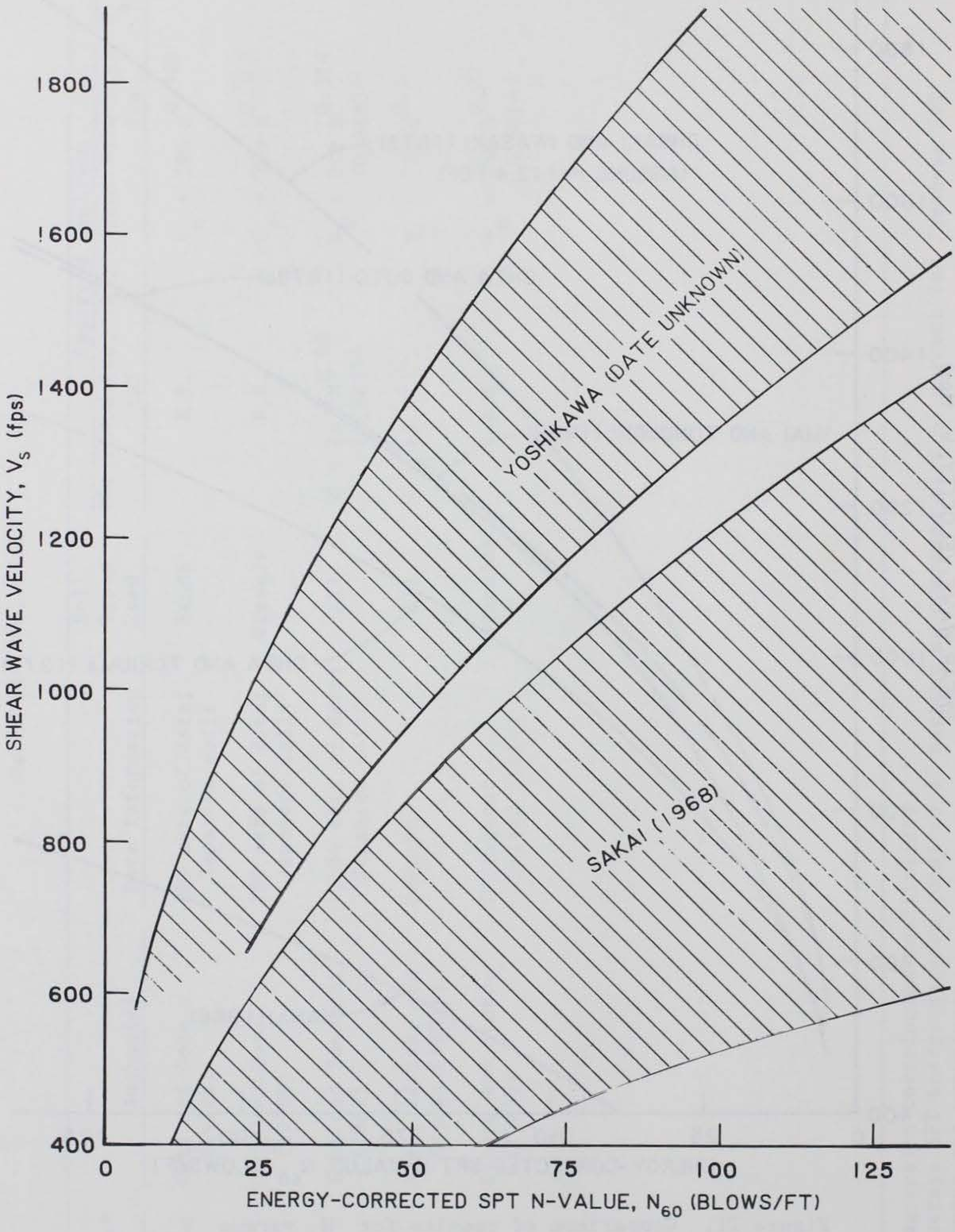

Figure 22. Comparison of ranges in data for N versus V_s correlations (proposed by various studies)

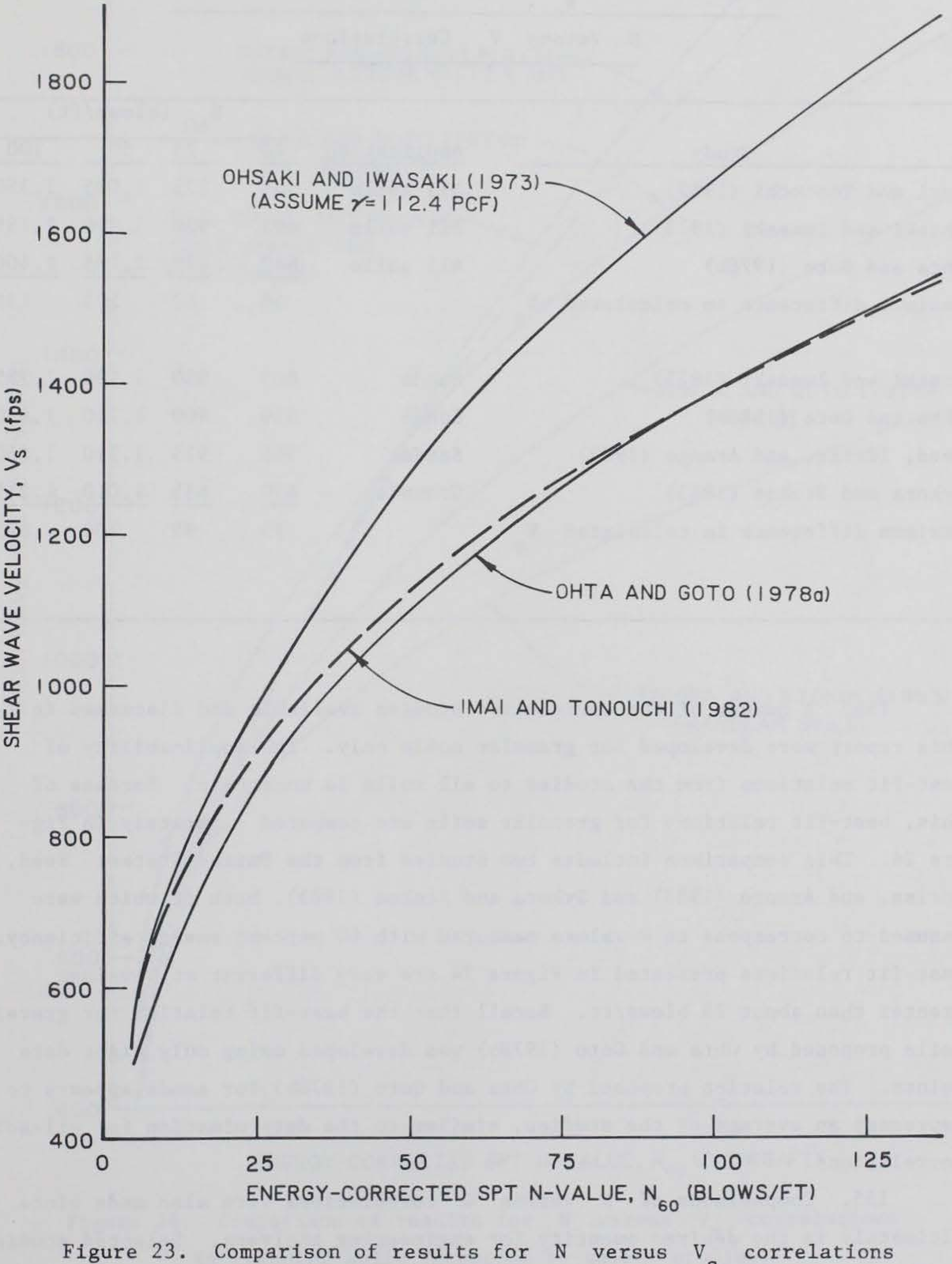

Figure 23. Comparison of results for N versus V_s correlations (proposed by select studies)

Table 17

Comparison of V_s Values Estimated Using Select N Versus V_s Correlations

		N_{60} (blows/ft)			
Study	Application	10	25	50	100
Imai and Tonouchi (1982)	All soils	655	875	1,085	1,350
Ohsaki and Iwasaki (1973)	All soils	605	930	1,290	1,785
Ohta and Goto (1978b)	All soils	640	870	1,105	1,400
Maximum difference in calculated V_s		50	60	205	435
Ohsaki and Iwasaki (1973)	Sands	605	930	1,290	1,785
Ohta and Goto (1978b)	Sands	650	900	1,140	1,440
Seed, Idriss, and Arango (1983)	Sands	585	925	1,310	1,850
Sykora and Stokoe (1983)	Granular	650	835	1,010	1,215
Maximum difference in calculated V_s		75	95	300	635

154. A number of the correlative studies available and discussed in this report were developed for granular soils only. The applicability of best-fit relations from the studies to all soils is uncertain. Because of this, best-fit relations for granular soils are compared separately in Figure 24. This comparison includes two studies from the United States: Seed, Idriss, and Arango (1983) and Sykora and Stokoe (1983), both of which were assumed to correspond to N-values measured with 60 percent energy efficiency. Best-fit relations presented in Figure 24 are very different at N-values greater than about 25 blows/ft. Recall that the best-fit relation for gravel soils proposed by Ohta and Goto (1978b) was developed using only eight data points. The relation proposed by Ohta and Goto (1978b) for sands appears to represent an average of the studies, similar to the determination for all-soil correlations.

155. Comparisons of N versus G correlations were also made since G ultimately is the desired quantity for engineering analyses. Selected studies which presented equations to estimate G were by Seed, Idriss, and Arango

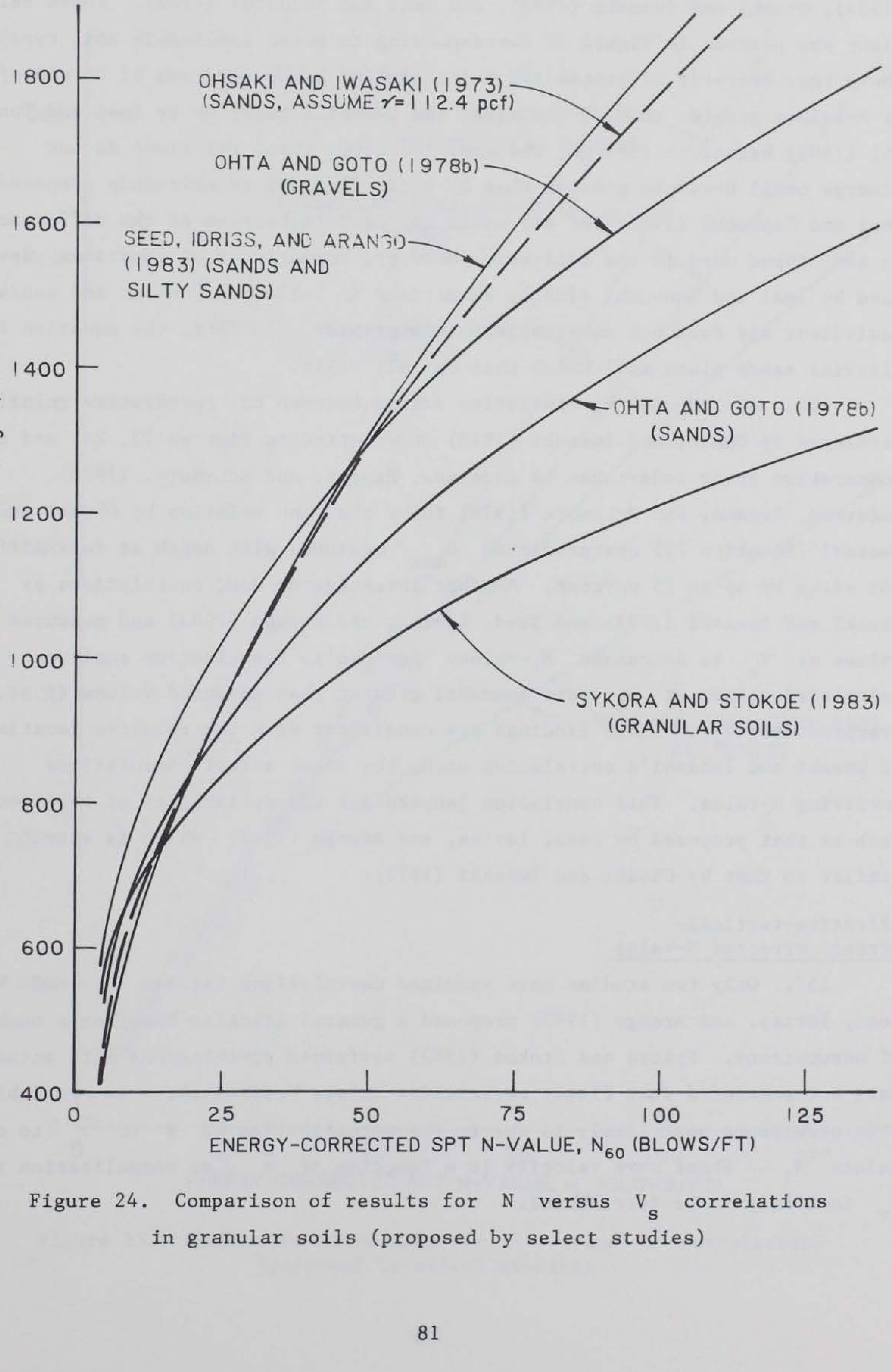

Figure 24. Comparison of results for N versus V_s correlations in granular soils (proposed by select studies)

(1983), Ohsaki and Iwasaki (1973), and Imai and Tonouchi (1982). These relations are plotted in Figure 25 corresponding to noted applicable soil types. These four best-fit relations are quite similar below N-values of 25 blows/ft. At N-values greater than 25 blows/ft, the best-fit relation by Imai and Tonouchi (1982) begins to diverge; whereas, the other three relations do not diverge until N-values greater than 50 blows/ft. The relationship proposed by Imai and Tonouchi (1982) for all soils may deviate because of the difference in soil types used in the analyses. However, comparisons of equations, developed by Imai and Tonouchi (1982), summarized in Table 6 for clays and sands of equivalent age does not substantiate this premise. In fact, the equation for alluvial sands plots well below that for all soils.

156. An interesting similarity exists between the correlative relation developed by Ohsaki and Iwasaki (1973) and plotted in Figures 23, 24, and a comparative study undertaken by Anderson, Espana, and McLamore, (1978). Anderson, Espana, and McLamore (1978) found that the relation by Ohsaki and Iwasaki (Equation 22) overpredicted G_{max} measured with depth at four different sites by up to 25 percent. Another investigator used correlations by Ohsaki and Iwasaki (1973) and Seed, Idriss, and Arango (1983) and measured values of V_s to calculate N_1-values for use in liquefaction analyses. Calculated values of N_1 were somewhat greater than measured values (i.e., overpredicts V_s). These findings are consistent with the relative location of Ohsaki and Iwasaki's correlation among the other select correlations involving N-value. This conclusion jeopardizes the reliability of relations, such as that proposed by Seed, Idriss, and Arango (1983), which is very similar to that by Ohsaki and Iwasaki (1973).

Effective-vertical-stress-corrected N-value

157. Only two studies have examined correlations between N_1 and V_s. Seed, Idriss, and Arango (1983) proposed a general equation based on a number of assumptions. Sykora and Stokoe (1983) performed correlations with actual data but concluded that little correlation exists between these two variables. This occurrence most likely is due to the normalization of N to $\bar{\sigma}_v$ to calculate N_1. Shear wave velocity is a function of $\bar{\sigma}_v$, so normalization to $\bar{\sigma}_v$ is likely to be detrimental.

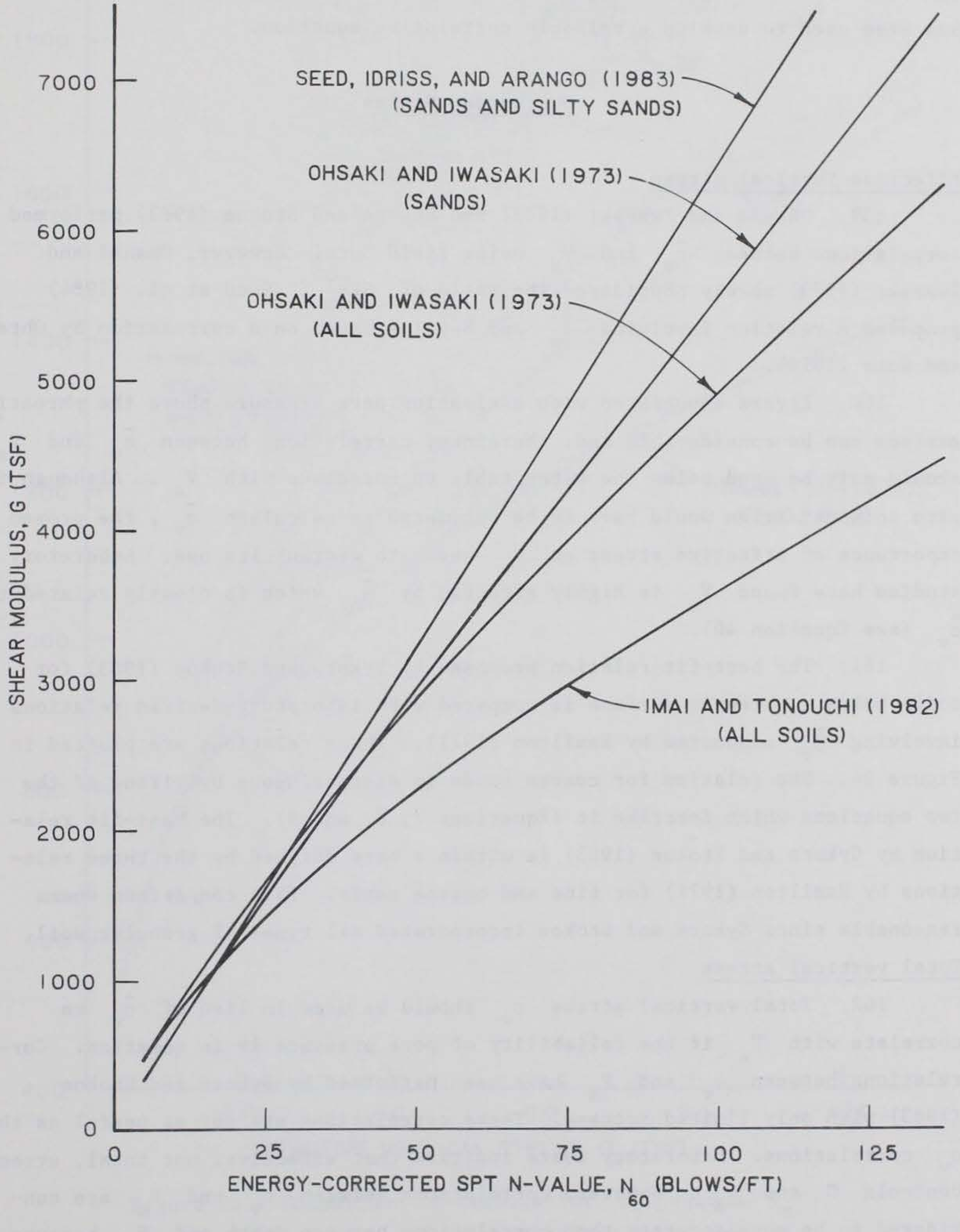

Figure 25. Comparison of results for N versus G correlations (proposed by select studies)

158. Conversely, a correlation between N_1 and V_s or G that also includes $\bar{\sigma}_m$ holds promise (Seed et al. 1984). However, little field data has been used to develop a reliable correlative equation.

Overburden Stress

Effective Vertical stress

159. Ohsaki and Iwasaki (1973) and Sykora and Stokoe (1983) performed correlations between $\bar{\sigma}_v$ and V_s using field data. However, Ohsaki and Iwasaki (1973) merely considered the ratio of $G\sqrt{\sigma_m^{\prime}}$. Seed et al. (1984) proposed a relation involving $\bar{\sigma}_m$ and N-value based on a correlation by Ohta and Goto (1976).

160. Errors associated with estimating pore pressure above the phreatic surface can be considerable and, therefore, correlations between $\bar{\sigma}_v$ and V_s should only be used below the water table to correlate with V_s. Although in situ soil densities would have to be estimated to calculate $\bar{\sigma}_v$, the proven importance of effective stress on V_s seems to warrant its use. Laboratory studies have found V_s is highly affected by $\bar{\sigma}_A$ which is clearly related to $\bar{\sigma}_v$ (see Equation 40).

161. The best-fit relation proposed by Sykora and Stokoe (1983) for soils below a phreatic surface is compared with laboratory-derived relations involving $\bar{\sigma}_v$ conducted by Hamilton (1971). These relations are plotted in Figure 26. The relation for coarse sands is discontinuous by virtue of the two equations which describe it (Equations 7, 8, and 9). The best-fit relation by Sykora and Stokoe (1983) is within a band defined by the three relations by Hamilton (1971) for fine and coarse sands. This comparison seems reasonable since Sykora and Stokoe incorporated all types of granular soil.

Total vertical stress

162. Total vertical stress σ_v should be used in lieu of $\bar{\sigma}_v$ to correlate with V_s if the reliability of pore pressure is in question. Correlations between σ_v and V_s have been performed by Sykora and Stokoe (1983) with only limited success. These correlations are not as useful as the $\bar{\sigma}_v$ correlations. Laboratory tests indicate that effective, not total, stress controls G and V_s. However, correlations between σ_v and V_s are considered to be more accurate than correlations between depth and V_s because σ_v is more closely related to $\bar{\sigma}_A$ than depth.

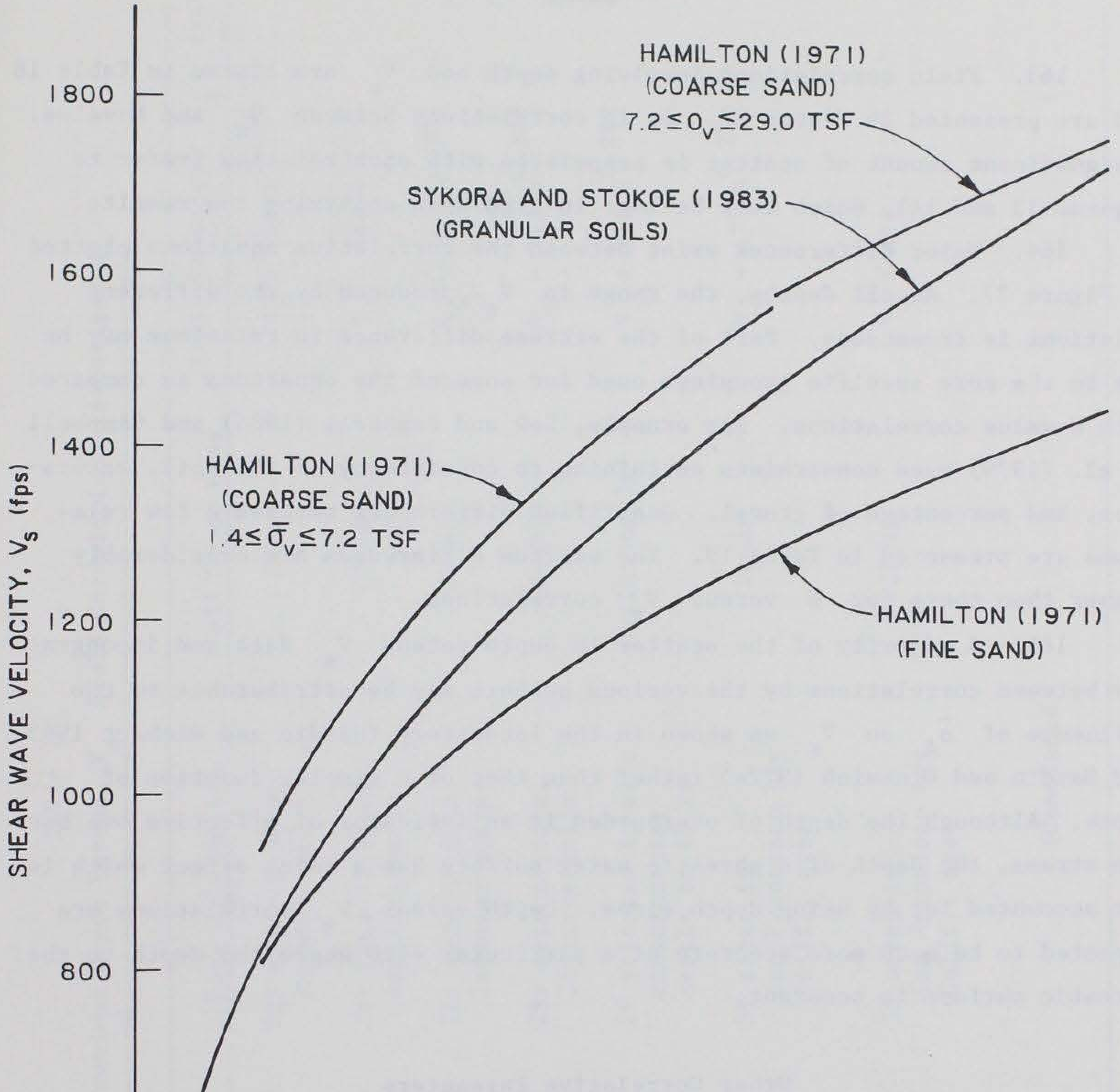

Figure 26. Comparison of results for $\bar{\sigma}_v$ versus V_s correlations (performed using field and laboratory measurements in granular soils)

Depth

163. Field correlations involving depth and V_s are listed in Table 18 and are presented in Figure 27. As in correlations between V_s and N-value, a significant amount of scatter is associated with each relation (refer to Figures 13 and 14), which must be kept in mind when analyzing the results.

164. Major differences exist between the correlative equations plotted in Figure 27. At all depths, the range in V_s produced by the different relations is tremendous. Part of the extreme difference in relations may be due to the more specific groupings used for some of the equations as compared with N-value correlations. For example, Lew and Campbell (1985) and Campbell et al. (1979) used constraints pertaining to consistency of the soil, saturation, and percentage of gravel. Quantified differences between a few relations are presented in Table 19. The maximum differences are considerably higher than those for N versus V_s correlations.

165. A majority of the scatter in depth versus V_s data and incongruity between correlations by the various authors may be attributable to the influence of $\bar{\sigma}_A$ on V_s as shown in the laboratory (Hardin and Richart 1963 and Hardin and Drnevich 1972a) rather than that of a simpler function of depth. Although the depth of overburden is an indicator of effective overburden stress, the depth of a phreatic water surface has a major effect which is not accounted for by using depth alone. Depth versus V_s correlations are expected to be much more accurate at a particular site where the depth to the phreatic surface is constant.

Other Correlative Parameters

166. Various other parameters obtainable as the result of field investigations have been proposed to correlate with V_s. These include the parameters e and D_r on which V_s is known to be highly dependent. However, these parameters are not easy to obtain and consequently such data are scarce. The use of these correlative variables is to be preferred when the data are available. Other parameters such as q_c show promise but have not yet been examined extensively. Parameters such as unconfined compressive strength offer a means to confirm estimated values but do not seem to offer a plausible new approach.

Table 18

Comparison of Previous Depth Versus V_s Field Correlations Investigated

Equation No.	Authors(s)	Data Information	Soil Types Used	Shear Velocity, V_s, fps
1	Ohta and Goto (1978b)	289 sets of data; Japanese soils	All	$V_s = 202\ D^{0.339}$
2	Ohta and Goto (1978b)	289 sets of data; Japanese soils	Clays	$V_s = 181\ D^{0.308}$
3	Ohta and Goto (1978b)	289 sets of data; Japanese soils	Sands	$V_s = 232\ D^{0.308}$
4	Ohta and Goto (1978b)	289 sets of data; Japanese soils	Gravels	$V_s = 313\ D^{0.308}$
5	Hamilton (1976)	29 selected in situ measurements; depths to 40 ft	Marine sands	$V_s = 301\ D^{0.280}$
6	Fumal (1978)	59 sites in San Francisco Bay Calif., area	Sands	$V_s = 471\ D^{0.20}$
7	Fumal (1978)	59 sites in San Francisco Bay Calif., area	Clays	$V_s = 462 + 15.4 \cdot D$

(Continued)

Note: D = Depth, ft

Table 18 (Concluded)

Equation No.	Authors(s)	Data Information	Soil Types Used	Shear Velocity, V_s, fps
8	Lew and Campbell (1985)	270 sites in southern California	Soft, natural soils	$V_s = 220\ (D + 5.33)^{0.385}$
9	Lew and Campbell (1985)	270 sites in southern California	Intermediate and saturated firm natural soils	$V_s = 262\ (D + 5.24)^{0.402}$
10	Lew and Campbell (1985)	270 sites in southern California	Firm soils	$V_s = 523\ (D + 0.54)^{0.280}$

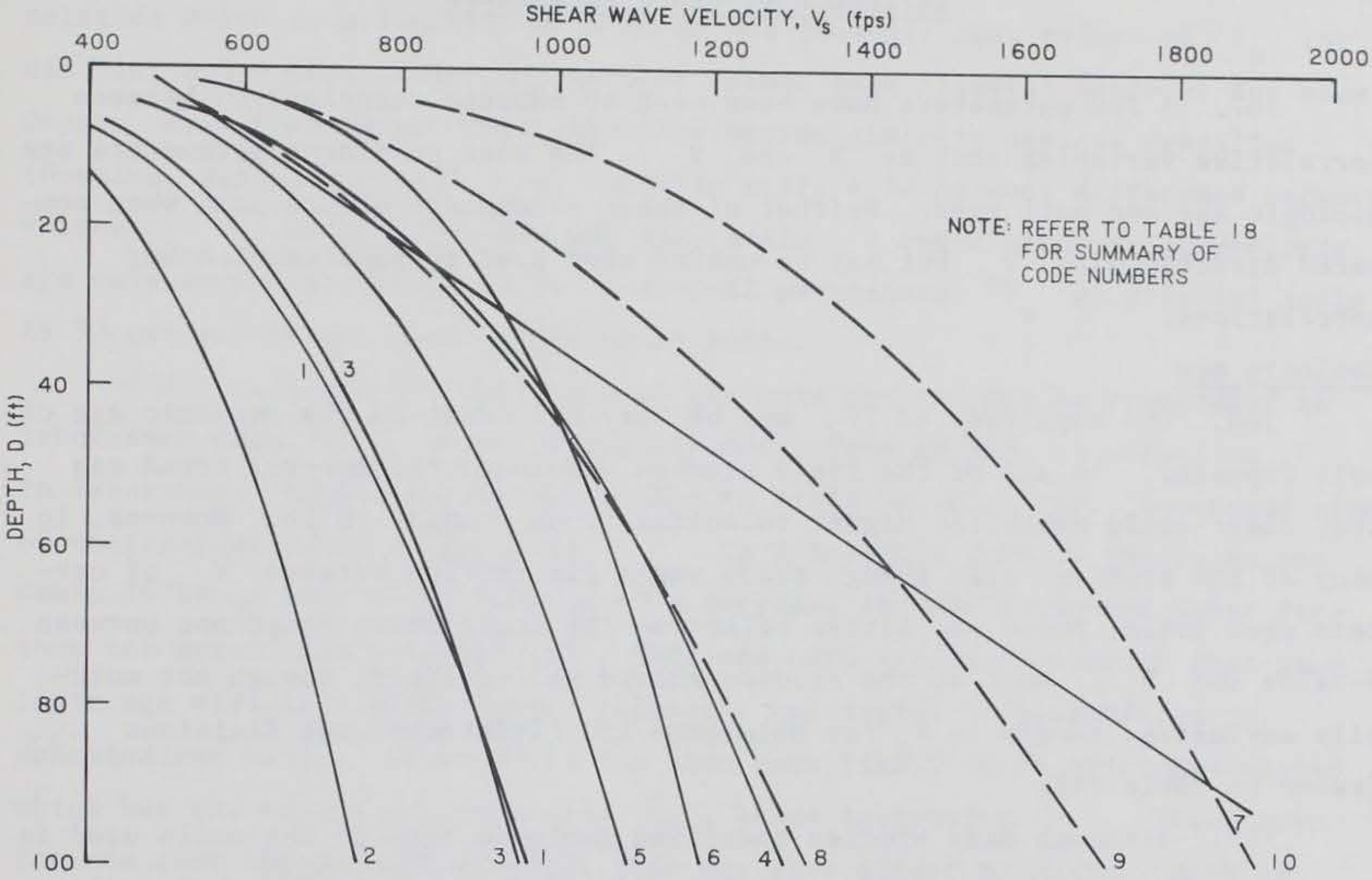

Figure 27. Comparison of best-fit relations (from depth versus V_s correlation studies)

Table 19

Comparison of V_s Values Estimated Using

Select Depth Versus V_s Correlations

Study	Application	Depth, ft 10	30	50	100
Ohta and Goto (1978b)	Clays	365	515	605	750
Ohta and Goto (1978b)	Sands	470	660	775	960
Hamilton (1976)	Marine sands	575	780	900	1,095
Fumal (1978)	Sands	745	930	1,030	1,185
Lew and Campbell (1985)	Soft, natural soils	630	870	1,030	1,320
Lew and Campbell (1985)	Firm soils	1,011	1,360	1,570	1,900
Maximum difference in calculated V_s		646	845	965	1,150

Influence of Other Parameters

167. A few parameters have been used to enhance correlations between correlative variables such as N and V_s. The most prominent parameters are geologic age and soil type. Neither of these parameters offers much when compared directly with V_s but may be useful when used to supplement other correlations.

Geologic age

168. The magnitude of V_s may be very dependent on the geologic age of soil deposits. In all of the field studies examined, the general trend was that older soils exhibited higher velocities than younger soils. However, in many of the studies, even though there was a distinction between V_s of certain aged soils, there was little effect on the correlative equations between N-value and V_s. Most of the studies showed well-defined, though not mutually exclusive, ranges in V_s for Holocene- and Pleistocene-age divisions (refer to Table 14).

169. Although many studies specified geologic ages of the soils used in the analyses, only three studies specifically used such data for their relations. Ohsaki and Iwasaki (1973) derived equations for three geologic age groups: Tertiary, Pleistocene (diluvial), and Holocene (alluvial) (refer to Table 3). Ohsaki and Iwasaki found that the best correlative equation did include data from all geologic ages, and that Tertiary soils exhibited slightly smaller values of V_s than did diluvial soils at N-values less than 80 blows/ft even though Tertiary soils are older. Ohta and Goto (1978b) derived equations which included geologic age as a quantified variable in addition to equations based strictly on N-value or on depth.

170. Contrary to three previous correlative studies, Imai and Tonouchi (1982) presented the results of N versus V_s correlations using geologic age (and soil type) divisions. Correlative equations developed for the three age divisions (Holocene, Pleistocene, and Tertiary) differ, although not significantly. In general, the value of the exponent decreased and the linear coefficient increased with age. The same occurrence generally held true for N versus G correlations except for sands where the equation for diluvial sands had a higher exponent.

171. The effect of geologic age on the magnitude of V_s may be best expressed from the results of Ohta and Goto (1978b) given in Table 4. For the

relation which is a function of N-value and geologic age, values of V_s for diluvial soils show 54 percent greater values than alluvial soils at the same depth. Even when three other variables beside geologic age are specified (N-value, depth, and soil type) there is still a 30 percent difference between values of V_s in alluvial and diluvial soils. A correlation using geologic age only suggests that given no other soil parameters, V_s of diluvial soils is 92 percent larger than for alluvial soils.

172. Although the influence of geologic age can not be reproduced in laboratory samples, a number of factors determined to have an effect on V_s in laboratory samples may be applicable to field correlations. Increased time of confinement tends to increase G_{max} in laboratory samples (Marcuson and Wahls 1972 and Tono 1971) because of a decrease in void ratio and other factors not specifically identified. Ohta and Goto (1978a,b) suggest that geologic age divisions sufficiently represent the degree of cementation in cohesionless soils. Older soils are also more likely to be overconsolidated which has the effect of increasing $\bar{\sigma}_A$, hence increasing V_s. These same factors that change with geologic time may also affect parameters such as N-value which are used in correlations. Divisions between the V_s in soils from different geologic epochs should also take into consideration the relative depths of the soil deposits. Older soils are more likely to be at greater depths than do younger soils. Therefore, older soils are more likely to exist at a higher state of stress, thereby increasing V_s.

Soil type

173. Similarly, but to a lesser extent, soil type influences the magnitude of V_s. Soils with wide ranges of grain sizes tend to have smaller average void ratios, and, therefore, exhibit larger values of V_s. Hardin and Drnevich (1972a) who found that G is highly dependent on void ratio and hardly affected by grain characteristics, size, shape, gradation, and mineralogy. Ohta and Goto (1978b) suggested that the use of soil type in correlations involving V_s improves the accuracy because a certain range in void ratio is represented. Their equations give a systematic change of V_s for soil types where: $\left(V_s\right)_{gravel} \geq \left(V_s\right)_{sand} \geq \left(V_s\right)_{clay}$, mostly due to $e_{gravel} \leq e_{sand} \leq e_{clay}$. The use of soil type as a means to group data, then, reflects the average void ratio of the soils. However, since wide ranges in void ratio are associated with specifying soil type, the influence

of soil type is diminished. Of the four variables used in their analyses, soil type had the least influence. However, as indicated in the discussion of their study, soil type plays a more important role in equations that do not include N-value. For instance, the correlative equation which is a function of depth and soil type suggests that V_s of a gravel is 73 percent larger than V_s of a clay at the same depth.

174. Imai and Tonouchi (1982) divided data among five soil groups--peat, clay, loam, sand, and gravel--to examine N versus V_s and N versus G correlations. The different soil types produced very different best-fit relations. However, the accuracy of some of the correlations was poor, especially for clay and loam soils.

175. One question which remains unresolved is whether clays or sands exhibit higher values of V_s at equal values of N. Ohsaki and Iwasaki (1973) utilized data from Kanai (1966) to propose that the V_s of clays is larger than that of sands at equal N-values. The results of Ohsaki and Iwasaki's statistical analyses on data they accumulated (Table 3) also substantiated this claim (at N-values less than 20 blows/ft). Contrary to this conclusion, Ohta and Goto (1978a) found that clays exhibited lower values of V_s than did sands at equal N-values. Data from Imai and Tonouchi (1982) are inconclusive.

176. Most authors used data from all soils (types) measured to develop a relation for correlative studies involving N-value and V_s. Even though different soils exhibited different ranges in V_s, there was little effect of soil type on best-fit relations. On the other hand, studies based on depth and V_s were more dependent on soil type. This agrees with the statistical results of Ohta and Goto (1978b).

PART V: SUMMARY

177. Previous correlations between shear wave velocity or shear modulus and field parameters have not been refined to a level such that they can be confidently used to accurately estimate V_s . A majority of previous correlations examined have investigated relationships between V_s and N-value or depth, or both, with some authors making further distinctions with regard to geologic age, soil type, effective stress, relative firmness, and degree of saturation. When analyzed individually, previous correlations involving only V_s and N-value are more accurate than are previous correlations involving only V_s and depth. However, results of some statistical analyses suggest using as many variables as are known to improve the accuracy of V_s correlations.

178. The results of laboratory tests corroborated by both direct and indirect field measurements and indicate that void ratio and effective stress states are the most important functional variables of V_s and G , especially for granular soils. In addition, it can be concluded that "other" factors related to the geologic age of a soil deposit affect V_s and G to a greater extent than effects from changes in void ratio and $\bar{\sigma}_A$. These factors most likely include cementation and soil fabric. Laboratory tests indicate that time of confinement for samples not only decreases void ratio, but alters the soil fabric. Both these changes increase V_s and G . Field studies indicate that changes (decreases) in void ratio over geologic time are significant and independent of effective stress. The rate of decrease is considerably larger for clays as compared to sands.

179. Given parameters that are known to affect V_s or G from laboratory studies, field correlations may be substantiated in terms of these parameters. SPT N-value is known to be influenced by several in situ conditions, especially void ratio and effective stress states (same as V_s). Therefore, N-value offers a readily-available parameter to use to estimate V_s . Other correlations rely on effective stress to correlate with V_s and use of factors such as geologic age and soil type to define potential ranges in void ratio. Correlations which use depth without a parameter such as N are not very reliable, or even justified, except on site-specific bases. Use of geologic age and soil type improves their usefulness.

180. Variables found to be most influential on previous correlations

involving V_s and N are geologic age and depth. Division of data among different geologic age groups significantly improved the accuracy of the correlations. In general, V_s increases with increasing N-value, depth, and geologic age. Soil type was found to have varied effects on the different correlations and its influence is unknown.

181. Previous correlations involving V_s and depth were greatly influenced by the inclusion of SPT N-value, geologic age, and soil type. Correlative equations were quite different with much improved accuracy when geologic age and soil-type differentiations were made. In general, V_s increases with increasing depth, geologic age, and relative grain size.

182. Ranges in V_s offer the practitioner with a reference to substantiate or compare measured values. The nature by which the lower-bound V_s, upper-bound V_s and range in V_s of these ranges increases with increased geologic age and relative grain size has been noted in previous studies but not so definitely. Even differences in soil type or geologic age are not considered important to development or use of a best-fit relation, yet these parameters are important in defining ranges in V_s.

183. Many inconsistencies exist between studies reviewed in this report, especially field studies. The nature of correlations and characteristics of data from previous studies could and should have significant effects on the results of correlations, especially in the absence of a large data base. These differences are difficult to quantify. However, some discussion has been provided in this report to assist the practitioner in using available correlations in an appropriate manner.

PART VI: RECOMMENDATIONS

184. This report was compiled to familiarize practitioners with the evolution and juxtaposition of various shear wave velocity and shear modulus correlations so that the applicability of correlations to geotechnical engineering practice can be ascertained for each individual project. General recommendations are provided to assist in solving the question of applicability and are based primarily on results of comparisons made in this report heretofore. These recommendations are:

- a. Existing V_s correlations should be incorporated into engineering studies to capitalize on the abundant data available and experience of others. Ideally, V_s correlations would be used in all phases of an overall engineering study, including:
  - (1) Optimizing surface and subsurface (especially seismic geophysical) exploration.
  - (2) Delineating zones with poor soil conditions for more detailed subsurface investigation.
  - (3) Assigning values of shear modulus to various soil units.
  - (4) Design analyses, especially sensitivity analyses.
- b. Correlations should not replace in situ measurements but rather complement an overall exploration program.
- c. The use of Japanese relationships should be contingent on adjusting N-values for differences in equipment and techniques, in particular, for differences in energy efficiency.
- d. Practitioners should be cognizant of the methodologies used to conduct the correlative studies which will be used. In particular, the type of geophysical measurements, the method of data reduction, distribution of correlative variables, and representativeness of the data should be considered.
- e. Correlative equations proposed by Kanai (1966) differ substantially from nearly all other relationships, producing very low values of V_s or G. Therefore, these equations should not be used.
- f. Practitioners should exercise caution when using relationships between SPT N-value and V_s proposed by Ohsaki and Iwasaki (1973) and Seed, Idriss, and Arango, (1983). The equations may produce high values of V_s at larger values of N (>25).
- g. Practitioners should expect a substantial range of error associated with each "best-fit" relation. For SPT N-value versus V_s correlations, this error may range from +50 percent to -40 percent of the calculated value.

h. Correlations solely between effective-overburden-stress-corrected N-value N and V_s should not be used except in an experimental mode. There appears to be little correlative behavior between N_1 and V_s.

i. For liquefaction analysis or development of a worst-case scenario, relations between N, $\bar{\sigma}_v$, and q_c with minimum values of V_s proposed by Sykora and Stokoe (1983) should be used in conjunction with measured values in situ.

j. The relationship proposed by Hardin and Drnevich (and other laboratory relationships) appears to underestimate dynamic soil stiffness, especially for older soils.

k. Further research studies in the United States are recommended to develop a larger and more viable data base. These studies should be compared with Japanese studies to examine the compatibility of their relationships to US soils. The characteristics of correlations for soil embankment materials are very important for dynamic stability of these structures.

l. Site-specific correlations are expected to produce much better results than correlations using data from various sites. Site specificity eliminates or minimizes the effects of a number of important variables including geology, phreatic surface conditions, and consistency in measured values (i.e., SPT techniques).

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APPENDIX A: AUTHOR INDEX

APPENDIX B: DEVELOPMENT OF MINIMUM SHEAR WAVE VELOCITY RELATIONSHIPS

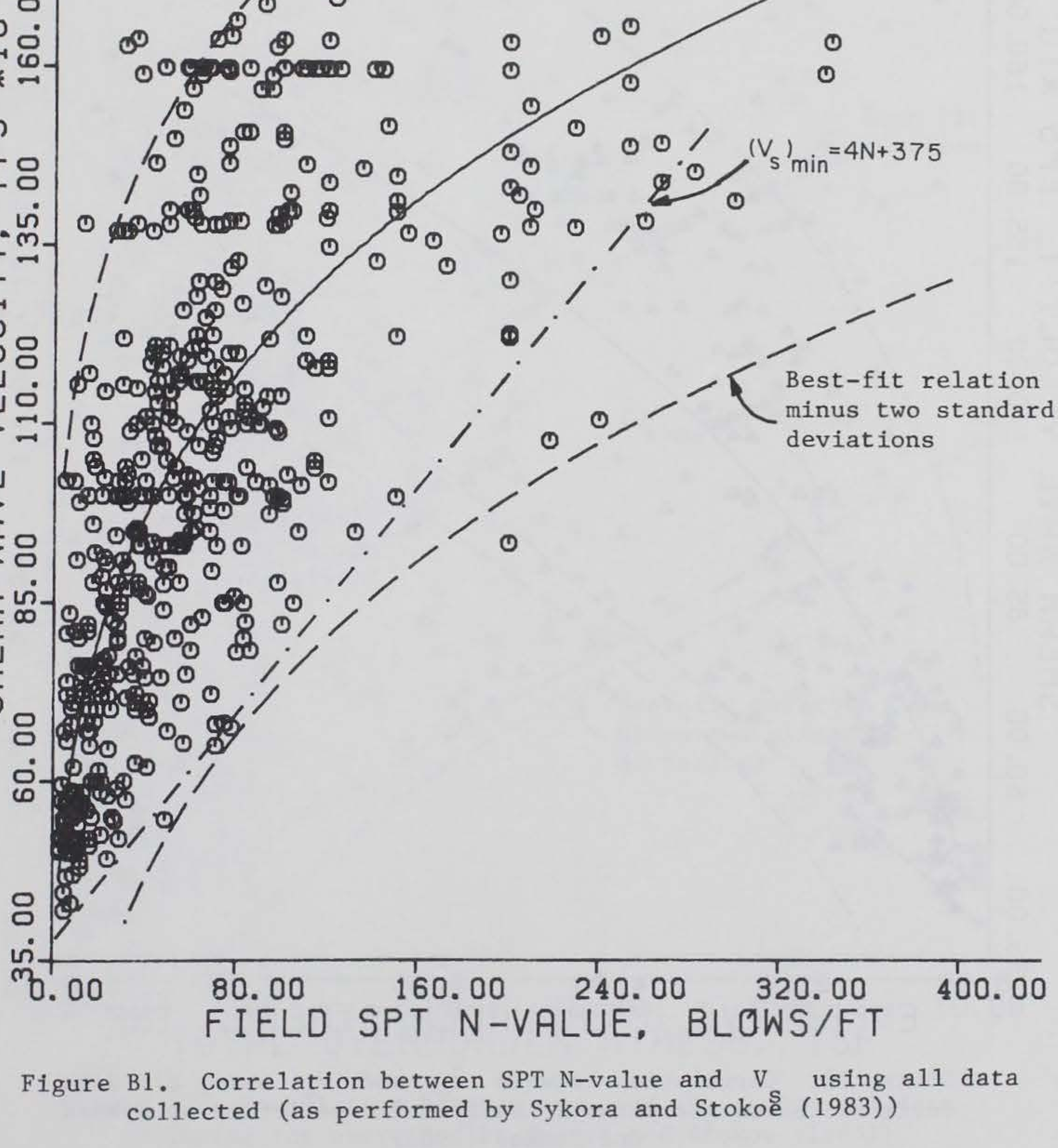

Figure B1. Correlation between SPT N-value and V_s using all data collected (as performed by Sykora and Stokoe (1983))

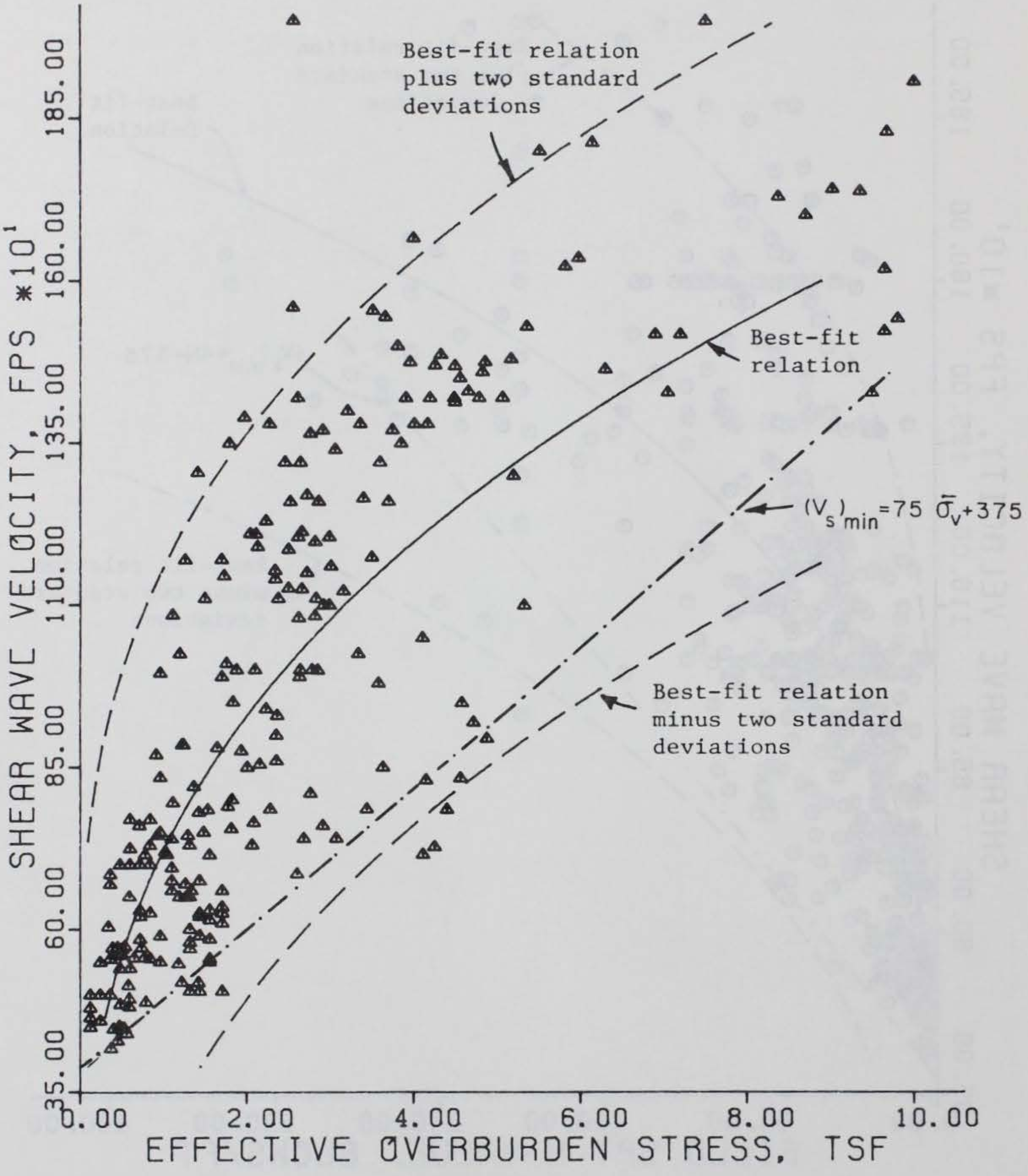

Figure B2. Correlation between $\bar{\sigma}_v$ and V_s using all data collected below the phreatic surface (as performed by Sykora and Stokoe (1983))

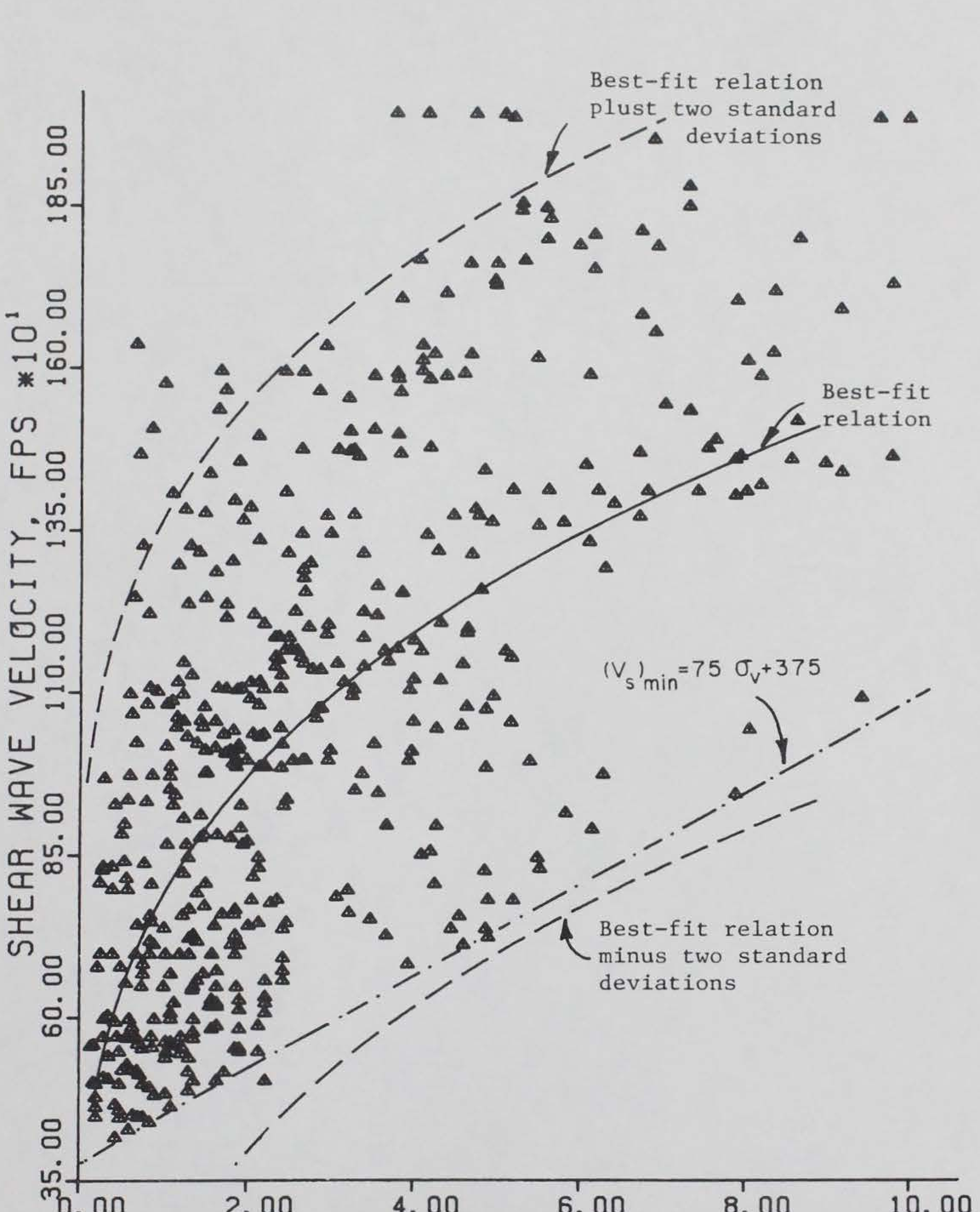

Figure B3. Correlation between σ_v and V_s using all data collected (as performed by Sykora and Stokoe (1983))