Prepared for the
National Science Foundation
under Grant No. GI 44056

UCLA-ENG-7662
JUNE 1976

CORRELATIONS AMONG SEISMIC VELOCITY, DEPTH AND GEOLOGY IN THE LOS ANGELES AREA

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50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/RA-761671	2.	3. Recipient's Accession No. PB-253920

4. Title and Subtitle
Correlations Among Seismic Velocity, Depth and Geology in the Los Angeles Area

5. Report Date
June 1976

6.

7. Author(s)
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8. Performing Organization Rept. No.
UCLA-ENG-7662

9. Performing Organization Name and Address
University of California
School of Engineering and Applied Science
Earthquake Laboratory
Los Angeles, California 90024

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G) GI44056

12. Sponsoring Organization Name and Address
Applied Science and Research Applications (ASRA)
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Correlations among seismic velocity, Poisson's ratio, depth, and a geotechnical classification scheme was developed from 63 in-situ velocity measurements in the greater Los Angeles area. Average shear-wave velocities at the surface for 11 soil and geologic materials were found to vary from about 500 ft/sec for unconsolidated soils to about 3900 ft/sec for fractured basement complex. A preliminary estimate of Poisson's ratios for the near surface yielded values of approximately 1/4 for compacted fill, 1/4 for rock, 1/3 for soil above the water table, and 1/2 for soil below the water table. The functional relationship between shear-wave velocity and depth was found to be adequately given by $V_S = Kd^n$ between depths of 10 and 100 feet, approximately, where the constants K and n are dependent upon the geotechnical classification. The correlations were used to estimate low-strain shear and P-wave velocity profiles at two sites in the Los Angeles area for which velocity data were available but had not been used to establish the correlations. The good agreement between the estimated and measured velocities at the two sites suggests that the correlations may be used in establishing synthetic near-surface velocity profiles from shallow geotechnical data when actual velocity data are unavailable.

17. Document Analysis a. Descriptors

Poisson ratio
Earthquakes
Seismology
Dynamic structural analysis
Geology
Soils
Phase velocity

b. Identifiers/Open-Ended Terms
Los Angeles

c. COSATI Field/Group

18. Availability Statement
NTIS

19. Security Class (This Report)

20. Security Class (This Page)

22. Price
PC A03 / MF A01

(See ANSI-Z39.18) *See Instructions on Reverse*

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

CAPITAL SYSTEMS GROUP, INC.
6110 EXECUTIVE BOULEVARD
SUITE 2[illegible]
ROCKVILLE, MARYLAND 20852

UCLA-ENG-7662
JUNE 1976

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The research reported herein was supported by the National Science Foundation, under Grant GI 44056

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ACKNOWLEDGEMENTS

The authors wish to thank R. T. Eguchi and J. A. Johnson whose comments and suggestions are greatly appreciated.

Financial support by the National Science Foundation is gratefully acknowledged.

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ABSTRACT

Correlations among seismic velocity, Poisson's ratio, depth, and a geotechnical classification scheme was developed from 63 in-situ velocity measurements in the greater Los Angeles area. Average shear-wave velocities at the surface for 11 soil and geologic materials were found to vary from about 500 ft/sec for unconsolidated soils to about 3900 ft/sec for fractured basement complex. A preliminary estimate of Poisson's ratios for the near surface yielded values of approximately 1/4 for compacted fill, 1/4 for rock, 1/3 for soil above the water table, and 1/2 for soil below the water table. The functional relationship between shear-wave velocity and depth was found to be adequately given by $V_s = Kd^n$ between depths of 10 and 100 feet, approximately, where the constants K and n are dependent upon the geotechnical classification.

The correlations were used to estimate low-strain shear and P-wave velocity profiles at two sites in the Los Angeles area for which velocity data were available but had not been used to establish the correlations. The good agreement between the estimated and measured velocities at the two sites suggests that the correlations may be used in establishing synthetic near-surface velocity profiles from shallow geotechnical data when actual velocity data are unavailable.

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INTRODUCTION

Shortly after the San Fernando earthquake of February 9, 1971, a program of measuring in-situ shear and P-wave velocities in the greater Los Angeles area was undertaken by the Earthquake Laboratory of the University of California at Los Angeles. This program has yielded some 63 shallow velocity measurements, primarily by surface refraction techniques, over the past five years [Duke et al., 1971, 1973; Eguchi et al., 1976].

Although the program was primarily intended to determine near-surface velocities at accelerograph sites that recorded the San Fernando earthquake, some sites were chosen for their geological interest. A preliminary attempt to correlate surface shear-wave velocity (V_s) with the type of ground was very encouraging [Duke et al., 1973], based on 30 measurements.

With 63 velocity measurements subsequently available, the previous correlations between V_s and the type of ground have been strengthened and some new correlations were developed primarily among shear velocity, depth and the type of ground. A preliminary attempt was made to correlate P-wave velocity (V_p) and Poisson's ratio (ν) with the type of ground, which is based on only a limited amount of data.

Of special interest was the relationship found between V_s and depth (d) for several geotechnical groups. This relationship was found to be adequately described by the simple formula $V_s = Kd^n$, where the constants K and n are dependent upon the type of ground. The interest in such a relationship came from the increasing importance of velocity-depth data over the last decade as the technology of earthquake-resistant design has advanced.

Since it may be desirable to estimate velocities at a site when measurements are not available, a technique was developed by which a synthetic

velocity profile can be established from soil and geologic profiles, making use of the correlations among velocity, depth and type of ground developed herein. The technique was used to establish V_s and V_p profiles at two sites of varied soil and geologic conditions for which velocity data were available for comparison.

It should be emphasized that the shear and P-wave velocities treated herein are low-strain ($\sim 10^{-4}$%) values obtained through shallow seismic surveys. An adjustment is needed to modify these values for earthquake level strains. A simple technique to do this is discussed in Appendix A.

RESULTS

Near Surface Velocity

In the previous study (Reference 2) it was found that there existed definite velocity ranges for different types of near surface conditions encountered in the Los Angeles area. Based on these initial 30 shallow seismic surveys, average shear-wave and P-wave velocities, velocity ranges and V_s/V_p ratios were developed for nine geotechnical groups, representing various degrees of firmness from unconsolidated soils to fractured basement complex.

With the availability of 33 new seismic surveys [Eguchi et al., 1976]. the previous velocity-geotechnical correlations could be strengthened. However, since only shear-wave velocities were measured in this latter study, no new information on P-wave velocity or V_s/V_p ratios was obtained. The additional data called for a slight modification of some of the geotechnical groups used previously.

The revised geotechnical classification system, Figure 1, is described as follows:

I. Soil

- Unconsolidated Soils — loose or soft natural or artificially placed soils; low gravel content.
- Recent Alluvium — Holocene[1] age alluvial deposits- slightly older and more consolidated than Unconsolidated Soils; includes weathered in-place soils.
- Old Alluvium — Pleistocene age alluvial and terrace deposits; partially consolidated.
- Sand and Gravel — soils containing moderate to large amounts of gravel.

[1] See Appendix B for a description of the geologic time scale used.

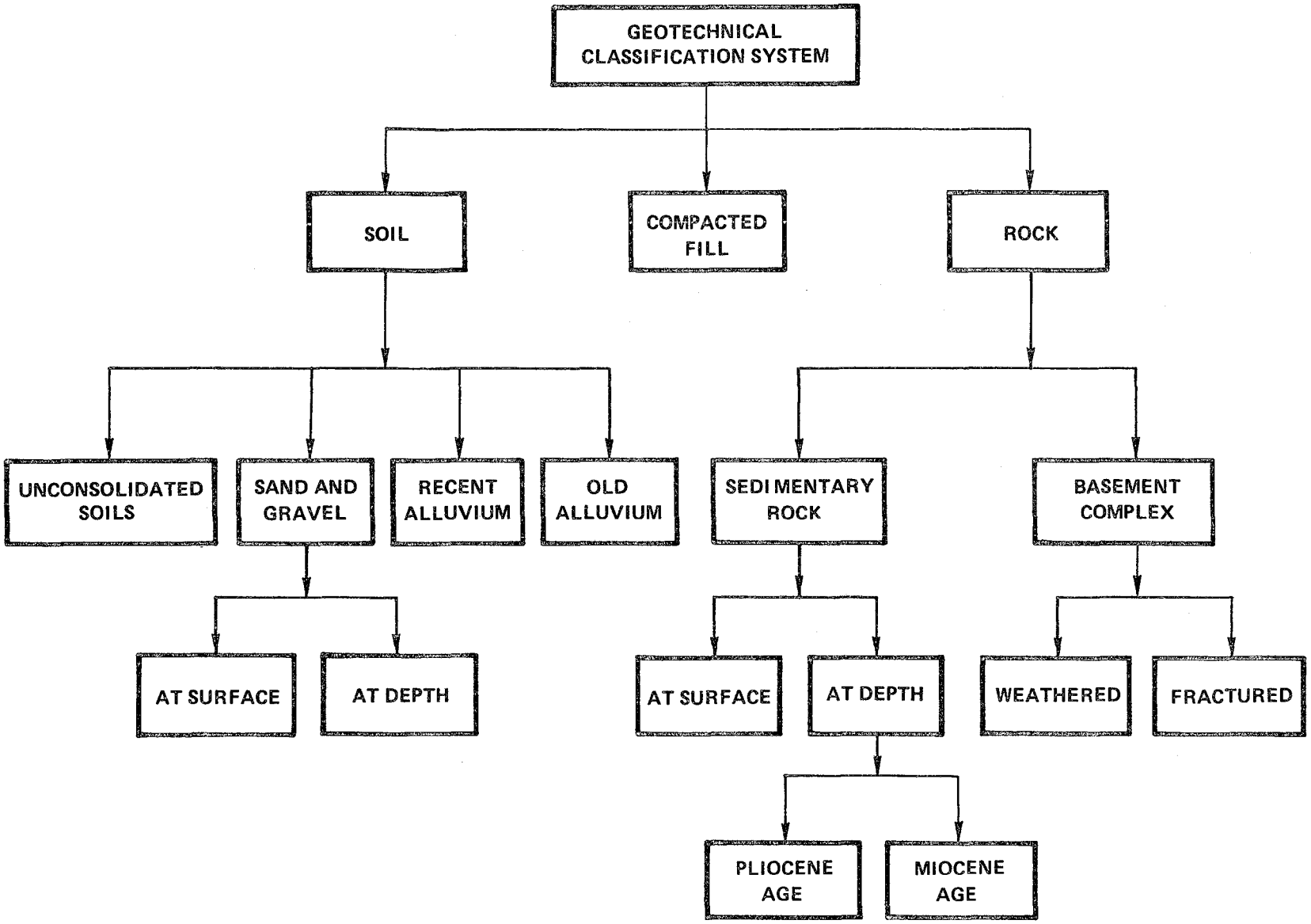

Figure 1. Diagram Showing the Relationship Among the Elements of the Geotechnical Classification System.

At Surface — gravelly Recent Alluvium occurring at the surface.

At Depth — gravelly Recent and Old Alluvium occurring at depths of about 15 to 25 feet.

II. Compacted Fill — mechanically compacted natural or artificially placed soils.

III. Rock

- Sedimentary — Siltstone, Sandstone, Shale and Conglomerate of Pliocene and Miocene age.

  At Surface — sedimentary rock of the Fernando, Pico, Repetto, Modelo, Puente and Monterey formations occurring at the surface; weathered.

  At Depth — sedimentary rock occurring at depths of about 15 to 25 feet.

  Pliocene — Fernando, Pico and Repetto formations of Pliocene age.

  Miocene — Modelo, Puente, and Monterey formations of Miocene age.

- Basement Complex — Igneous and metamorphic rock

  Weathered — highly weathered; decomposed.

  Fractured — weathered and fractured.

From the 63 velocity measurements and geotechnical descriptions of the sites, means, standard deviations and ranges were computed for shear-wave velocity and to a limited extent P-wave velocity for each geotechnical group, Tables 1 and 2. It is seen that the shear and P-wave velocities for each geotechnical group tend to fall within relatively well defined intervals,

TABLE 1

Average Shear Wave Velocities in Near Surface Materials

Geotechnical Description	Geologic Age*	No.	Shear Wave Velocity (ft/sec) Mean	Standard Deviation	Range
Unconsolidated Soils	Holocene	11	500	50	410 - 590
Recent Alluvium	Holocene	15	620	60	560 - 790
Compacted Fill	Holocene	7	690	60	590 - 760
Sand and Gravel	Holocene	3	910	-	810 - 1050
Old Alluvium	Pleistocene	25	920	90	740 - 1110
Sedimentary Rock	Pliocene and Upper Miocene	8	1270	130	1040 - 1470
Pliocene Sedimentary Rock (at 15'-20')	Pliocene	2	1390	-	1370 - 1420
Sand and Gravel (at 15'-35')	Holocene and Pleistocene	6	1720	190	1460 - 1980
Weathered Basement Complex		3	2190	-	1510 - 2670
Miocene Sedimentary Rock (at 15'-35')	Upper Miocene	5	2290	490	1690 - 2790
Fractured Basement Complex		5	3920	360	3300 -4210

*See Appendix B for a description of the geologic time scale.

Table 2

Preliminary Average P-Wave Velocities in Near Surface Materials

Geotechnical Description	Geologic Age	P-Wave Velocity (Ft/Sec)		
		No.	Mean	Range
Unconsolidated Soils	Holocene	3	930	820 - 990
Recent Alluvium	Holocene	3	1300	1240 - 1360
Compacted Fill	Holocene	4	1270	1170 - 1320
Sedimentary Rock	Pilocene and Upper Miocene	4	2350	1770 - 3330
Fractured Basement Complex		3	7200	5400 - 10,000
Soils (Below Water Table)	Holocene and Pleistocene	3	5600	5280 - 6280

with the average values generally increasing with increasing degree of firmness, geologic age and depth of burial. Average shear-wave velocities are found to range from about 500 ft/sec for Unconsolidated Soils to about 3900 ft/sec for Fractured Basement Complex, whereas average P-wave velocities for the same geotechnical groups are found to range from about 900 to 7000 ft/sec.

It is interesting to note the effect gravel content has on the average shear-wave velocity. For instance, the velocity of the Holocene age Sand and Gravel at the surface is roughly 1 1/2 times larger than that of Recent Alluvium of the same age, which presumably contains either no gravel or only a small amount. The Sand and Gravel encountered at depths of about 15 to 35 feet shows an average shear-wave velocity somewhat higher than the Pliocene-age Sedimentary Rock encountered at about the same depths. This suggests that the presence of gravelly layers within the geotechnical profile can significantly increase the velocities measured at a site.

The standard deviations for shear-wave velocity, Table 1, were computed only for those geotechnical groups for which five or more observations were obtained. The standard deviations of velocity for each group are seen to increase with increasing mean velocity. It is convenient to express this deviation as a dimensionless coefficient of variation, defined as the ratio in percent of the standard deviation to the mean. This measure can be used to indicate the relative consistency among the various groups. The coefficient of variation is relatively constant for all groups, being about 10%, which does indicate consistency in the actual variation of velocities within groups and in the errors involved in measuring and analyzing the data.

There were insufficient P-wave velocity data, Table 2, to establish mean values for many of the geotechnical groups. Since at most only four measurements were available for any one group, standard deviations were not computed, and the results presented in Table 2 should be considered only preliminary. Three measurements of P-wave velocity below the water table were available from the previous study. The average value of about 5600 ft/sec encountered at depths of about 5 to 25 feet is significantly higher than the velocity measured just above the water table. This confirms that P-wave seismic refraction surveys may be used to locate the water table at shallow depths.

Poisson's Ratio

Because of the difficulty in measuring and interpreting shear-wave velocities at some sites, Poisson's ratios are valuable in estimating shear-wave velocities from the sometimes more easily measured and available P-wave velocities. Poisson's ratio (ν) is computed from the ratio of P-wave velocity to shear-wave velocity [Richart et. al., 1970],

$$\nu = \frac{1}{2} \frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{\left(\frac{V_p}{V_s}\right)^2 - 1} \tag{1}$$

which assumes that the near surface soils can be treated as elastic media for the low dynamic strains induced during shallow seismic surveys.

By manipulating Equation (1), an expression for V_p/V_s in terms of Poisson's ratio is obtained as follows:

$$\frac{V_p}{V_s} = \sqrt{\frac{2(\nu-1)}{2\nu-1}} \, . \tag{2}$$

Thus, from a knowledge of Poisson's ratio and either shear-wave or P-wave velocity, an estimate of the other velocity is easily obtained.

Using the velocity and geotechnical data in Reference 2, Poisson's ratios were computed from Equation (1) for every layer for which both a shear and P-wave velocity was available. In general, this represented depths not exceeding about 100 feet. Although there was a large scatter in the data, the computed Poisson's ratios appeared to fall within four distinct geotechnical groups: Rock, Compacted Fill, Soil (above the water table) and Soil (below the water table). Means, standard deviations, and ranges of Poisson's ratio for the four groups are presented in Table 3. As before, standard deviations were not computed where the number of observations was less than five.

Due to the limited amount of data and its large scatter these computed values must be considered preliminary. Table 3 would indicate, however, that for unsaturated materials the following three rounded values of Poisson's ratio and corresponding value of V_p/V_s may be used in estimating velocities:

Geotechnical Description	Poisson's Ratio	V_p/V_s
Rock	1/4	1.7
Compacted Fill	1/4	1.7
Soil (above water table)	1/3	2.0

Based on four simultaneous measurements of shear and P-wave velocities in Compacted Fill, the average Poisson's ratio was found to be 0.22, comparable with that for Rock. This suggests that the compaction of artificially placed fill soils significantly affects the ratio of propagation velocities, decreasing V_p/V_s by about 15%. Although based on a limited amount of data, this result suggests that the velocity ratio could possibly be used in compaction control.

Table 3

Preliminary Average Poisson Ratios in Near Surface Materials

Geotechnical Description	Geologic Age	Poisson's Ratio			
		No.	Mean	Standard Deviation	Range
Compacted Fill	Holocene	4	0.22	-	0.20 - 0.25
Rock	Pliocene and older	9	0.24	0.05	0.18 - 0.32
Soil (Above Water Table)	Quaternary	14	0.32	0.07	0.20 - 0.43
Soil (Below Water TAble)	Quaternary	3	0.48	-	0.47 - 0.49

Velocity and Depth

Many empirical relations of propagation velocity and depth have appeared in the literature. Faust (1953) proposed a relation for the P-wave velocity of sedimentary rock for depths below about 1000 feet,

$$V_p = c(Td)^{1/6} \tag{3}$$

where T is the geologic age of the sediments in years, d is depth in feet, c is a constant dependent upon the geographic region, and V_p is velocity in ft/sec.

Hardin and Richart (1963) found that the shear-wave velocity in sands could be represented by two equations dependent only upon void ratio (e) and mean confining pressure ($\bar{\sigma}_o$). For round-grained sands they proposed,

$$V_s = [170 - (78.2)e]\ \bar{\sigma}_o^{1/4} \tag{4}$$

and for angular-grained materials,

$$V_s = [159 - (53.5)e]\ \bar{\sigma}_o^{1/4} \tag{5}$$

where V_s is in ft/sec and $\bar{\sigma}_o$ is in lb/sq. in. These equations are generally valid for $0.35 < e < 1.3$ and $\bar{\sigma}_o < 6000$ lb/sq. ft., consistent with depths less than about 80 feet. It is interesting to note that Hardin and Richart found that the relative density of the material has a negligible influence on the shear-wave velocity.

Hardin and Black (1968, 1969) found that Equation (5) could also be used to estimate the shear-wave velocity in undisturbed cohesive soils (clays) with the inclusion of an additional term, OCR,

$$V_s = [159 - (53.5)e]\ (OCR)^{C_o}\ \bar{\sigma}_o^{1/4} \tag{6}$$

where OCR is the overconsolidation ratio and C_o is a factor dependent upon the plasticity index (PI) of the soil. Equation (6) is valid for $e < 2$ and shear-strain amplitudes less than about 10^{-4}. Hardin and Drnevich (1972) in a later study confirmed the results of Hardin and Black. The constant C_o in Equation (6) can be obtained from the following table:

PI	C_o
0	0
20	0.18
40	0.30
60	0.41
80	0.48
≥ 100	0.50

Seed and Idriss (1970a), relying heavily upon previous work, suggested that the shear modulus is proportional to the square root of the mean principal effective stress for sands and proportional to the undrained shear strength for saturated clays. The functional form of these equations in terms of shear-wave velocity are as follows [Schnabel et. al., 1972]:

For sands,

$$V_s = \left[\frac{32.2\ K_s}{\gamma_T}\right]^{\frac{1}{2}} \left(\bar{\sigma}_o\right)^{\frac{1}{4}} \tag{7}$$

and for saturated clays,

$$V_s = \left[\frac{32.2\ K_c}{\gamma_T}\right]^{\frac{1}{2}} S_u^{\frac{1}{2}} \tag{8}$$

where K_s and K_c are empirical strain-dependent factors, γ_T is total unit weight, and S_u is undrained shear strength.

Seed and Idriss found K_s and K_c to be relatively constant for shear strains less than about 10^{-3}%, suggesting values of K_s = 61 for dense sand (D_r = 75%, e = 0.5) and K_c = 2300 for saturated clays. These values are consistent with units of ft/sec for velocity, kips/sq. ft. for unit weight and shear strength, and lb/sq. ft. for mean effective stress.

Some authors have attempted to correlate shear-wave velocity with the standard penetration blow count, N. Newmark and Rosenblueth (1971) present such a relationship,

$$V_s = aN^b \tag{9}$$

where the empirical constants were found to vary as follows a = 39, b = 0.66 for sands; a = 164, b = 0.66 for clays; and a = 63, b = 0.61 for transitional soils.

The mean effective confining pressure occurring in many of the equations previously discussed can be computed from the following equation [Richart et al., 1970],

$$(\bar{\sigma}_o)_A = \frac{1 + 2K_o}{3} \sum (h_1\gamma_T + h_2\gamma') \tag{10}$$

in which

K_o = coefficient of horizontal earth pressure at rest at point A,

h_1 = height of the column of unsaturated soil above point A,

h_2 = height of the column of saturated soil above point A,

γ_T = unit weight above the water table,

γ' = buoyant unit weight below the water table.

As a first order approximation, the mean effective confining pressure at point A can be considered proportional to the depth of point A. Since it is known that both undrained shear strength and N-value are in general also

proportional to depth, it may be desirable to generalize Equations (3) through (9) to the simpler form,

$$V_s = Kd^n \tag{11}$$

where K and n would in general be functions of void ratio, confining pressure, degree of saturation, grain characteristics, strain amplitude, frequency of vibration, soil structure, and temperature [Hardin and Black, 1968].

For a region in which the geologic and soil conditions are relatively uniform and well known, the constants K and n in Equation (11) may be expected to correlate with the type of ground. In this way one might eliminate the need, in some cases, for expensive field and laboratory data in estimating the velocity-depth profile at a site. However, such data are important in determining any special soil conditions that may exist beneath the site that can have a significant effect on the velocity profile beneath the site.

The velocity, depth and geotechnical data presented in References 2 and 4, were used to establish a correlation between V_s and the type of ground. Adequate data were available only for shear waves and four geotechnical groups (see Figure 1):

- Unconsolidated Soils
- Recent Alluvium
- Old Alluvium
- Sedimentary Rock

In order to perform a regression analysis, Equation (11) was linearized by taking the natural logarithm of both sides giving,

$$\text{Ln } V_s = \text{Ln } K + n \text{ Ln } d \tag{12}$$

To verify the form of Equations (11) and (12), a log-log plot of shear-wave velocity versus depth was made for each geotechnical group, Figures 2

through 5. Depth was taken to the top of the layer, to be consistent with the refraction survey results. The linear trend in the log-log plots suggests that the simple power law expression for velocity given by Equation (11) is adequate in modeling the observed increase of velocity with depth below about 10 feet. The constants in Equation (12) were then determined for each group by the method of least squares, omitting data above about 10 feet. A statistical summary of the analysis is presented in Table 4 and the regression equations together with their one standard deviation limits are plotted on Figures 2 through 5. The average shear-wave velocity determined for the top layer, Table 1, is also plotted as a vertical line on the figures. The relatively high correlations and low standard deviations confirm the use of the power law to model the increase of shear-wave velocity with depth.

The plot of V_s versus depth for Old Alluvium, Figure 4, contains some shallow data from depths of about 7 to 14 feet that apparently deviate from the trends observed for the deeper data. This "bending" of the data suggests that above a certain depth, the velocity-depth trend begins to curve and may asymptotically approach the surface layer velocity. Enough data were not available to observe this trend in the other geotechnical groups. This "bending" may occur at depths less than about 10 feet for Recent Alluvium, Unconsolidated Soils, and Miocene Sedimentary Rock. These shallow curved portions are added to the figures for reference. They are drawn so as to approach asymptotically the mean velocity determined for the top layer.

The regression for shear velocity versus depth for Unconsolidated Soil is based on only five points. For this reason, it may be subject to large error. Therefore, the mean value curve, Figure 2, should be used with this limitation in mind.

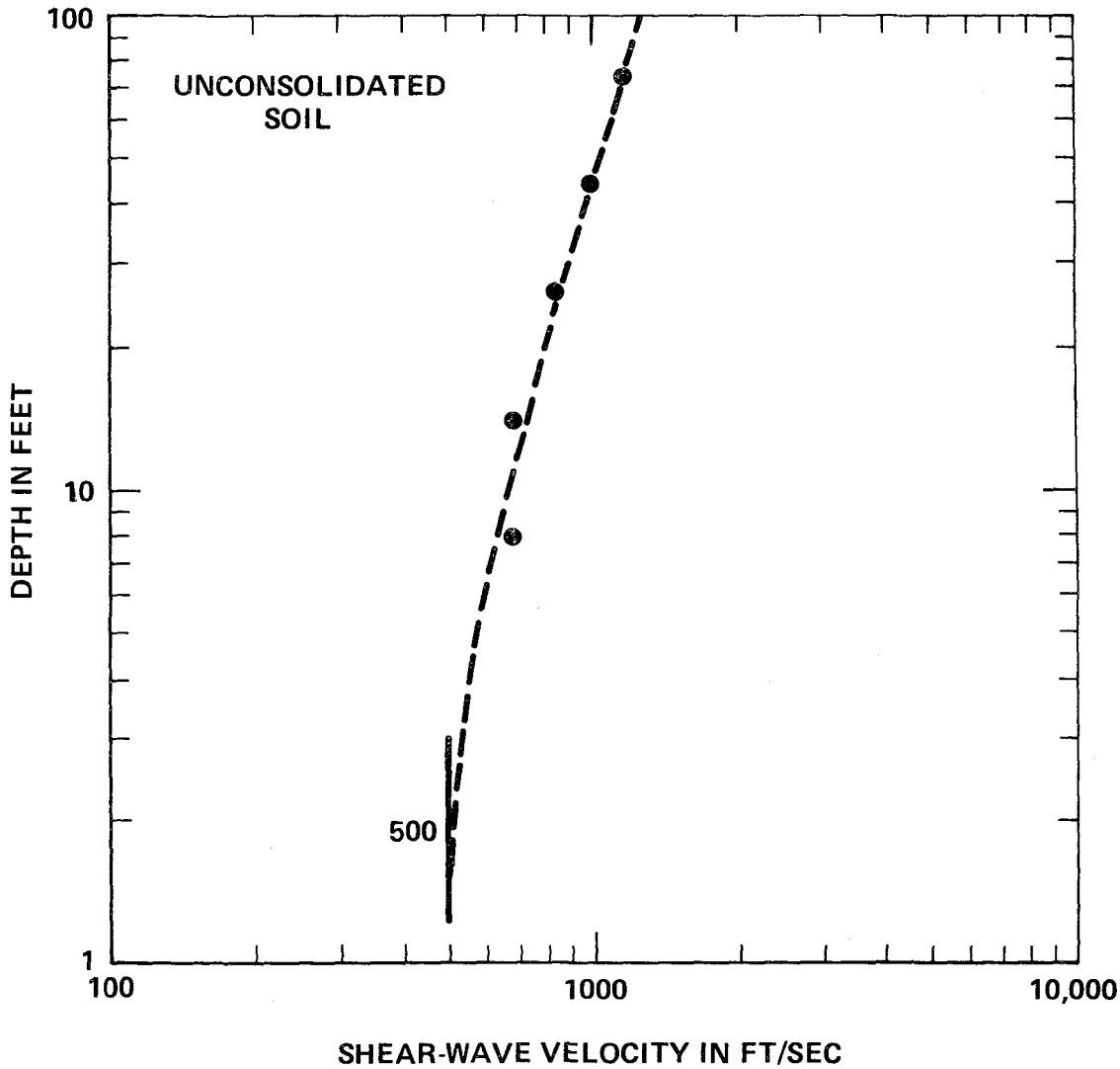

Figure 2. Plot of Shear-Wave Velocity Versus Depth for Unconsolidated Soils.

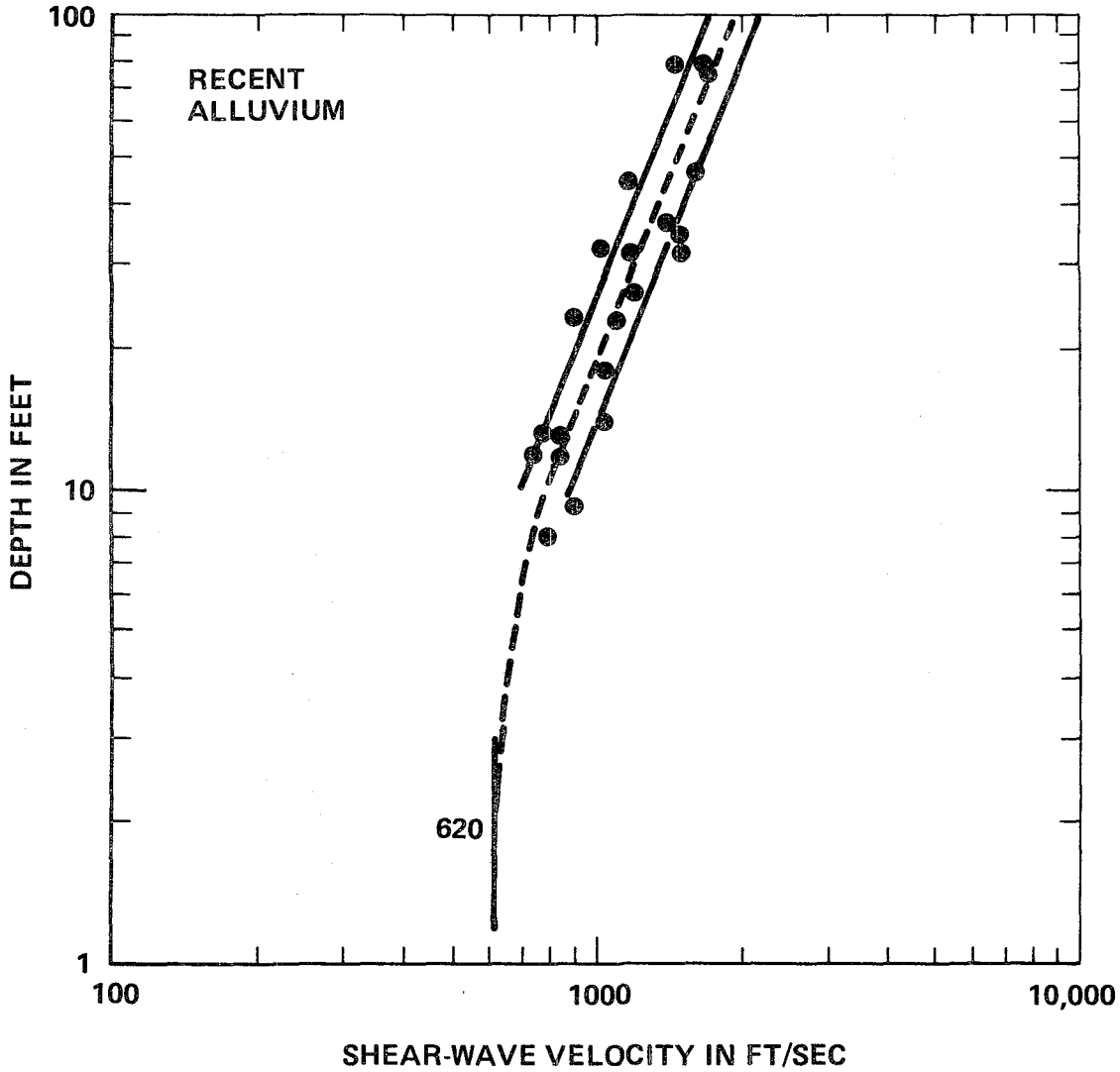

Figure 3. Plot of Shear-Wave Velocity Versus Depth for Recent Alluvium.

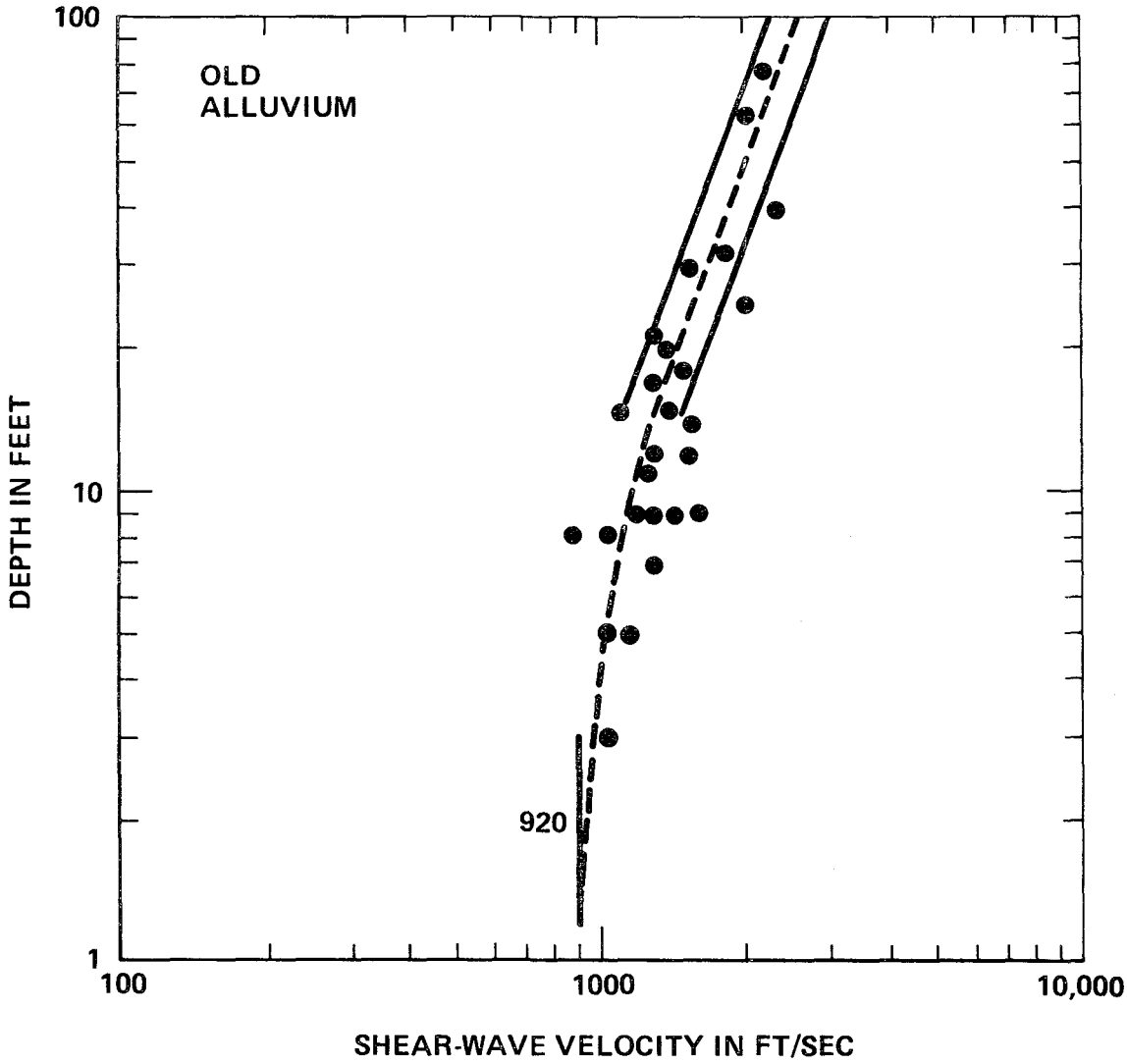

Figure 4. Plot of Shear-Wave Velocity Versus Depth for Old Alluvium.

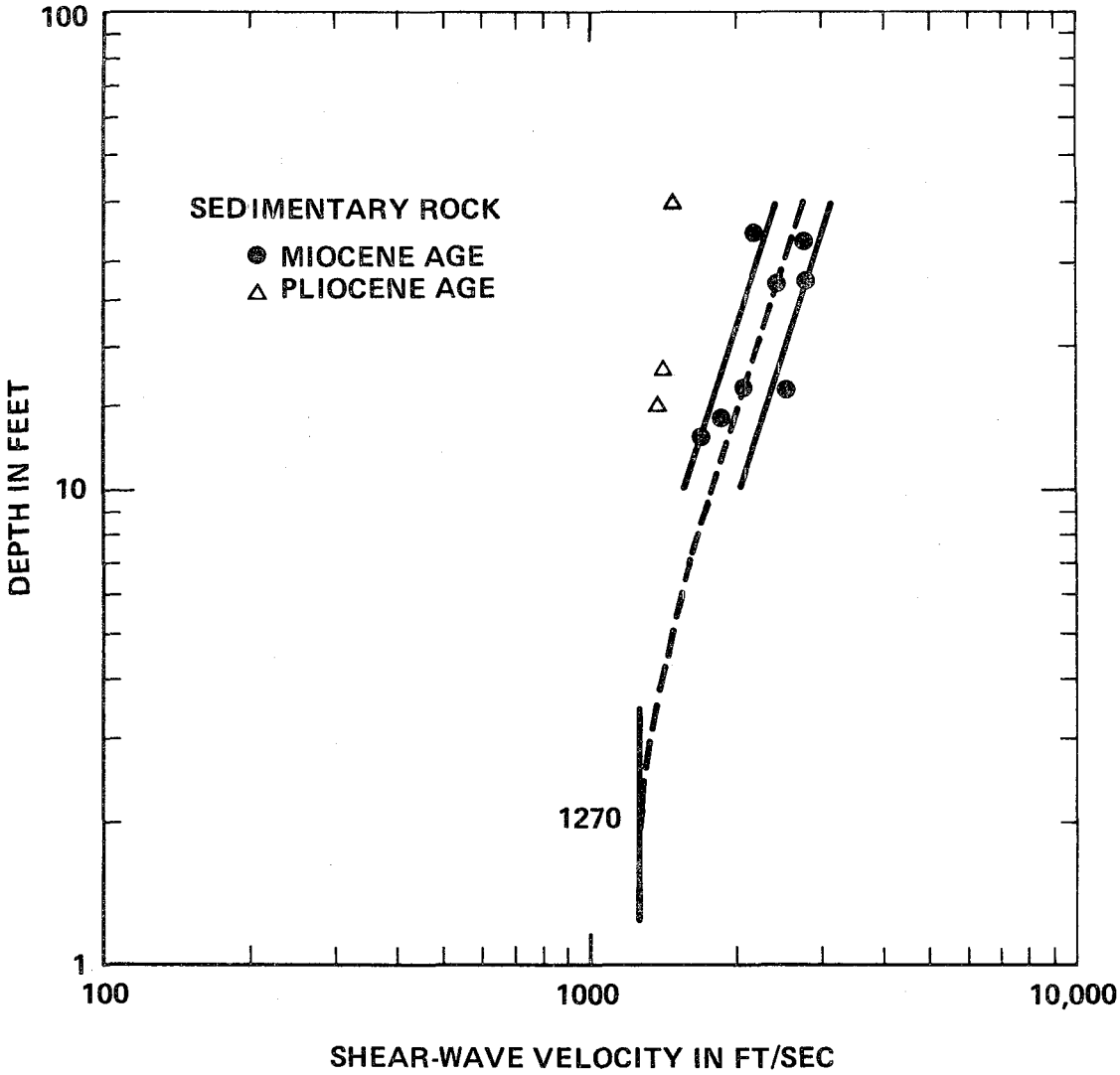

Figure 5. Plot of Shear-Wave Velocity Versus Depth for Sedimentary Rock.

Table 4

Statistical Summary of Regression Analysis

$$\text{Ln } V_s = \text{Ln } K + n \text{ Ln } d$$

Geotechnical Description	Regression Coefficients		Correlation Coefficient	Standard Deviation of Ln V_s	No. of Data
	Ln K	n			
Unconsolidated Soil	5.891	0.266	0.98	-	5
Recent Alluvium	5.766	0.386	0.90	0.12	19
Old Alluvium	6.196	0.358	0.82	0.14	12
Miocene Sedimentary Rock	6.762	0.312	0.70	0.14	8

The three points for Pliocene Sedimentary Rock do not permit a statistical analysis. However, it does appear that at any given depth the shear-wave velocity is less than that of the Miocene Rock. Furthermore, the velocity may increase at a slower rate with depth.

SIMULATED VELOCITY PROFILES

The correlations among velocity, Poisson's ratio, depth and the type of ground developed in the previous sections can be used to estimate the low-strain shear and P-wave velocity profiles at a site of interest in the Los Angeles area from only a modest amount of soil and geological data. Such estimates are useful when in-situ velocity data are not available and would be uneconomical to measure. A technique for estimating such velocity profiles from geotechnical data is demonstrated for two sites for which velocity measurements are available for comparison.

The two sites, one located in the city of Los Angeles, and the other in Long Beach, represent contrasting geotechnical characteristics; the former consisting of shallow alluvium over rock, and the latter consisting of deep hydraulic fill. Brief descriptions of the soil and geologic characteristics together with the measured velocity data for the two sites can be found in Table 5. The data were kindly provided by LeRoy Crandall and Associates, consulting geotechnical engineers in Los Angeles, California, and had not previously been used in developing the correlations.

The velocity boundaries determined from the seismic surveys, Table 5, represent clearly identifiable physical changes in the geotechnical profiles of the two sites. A possible exception is the increase in shear-wave velocity at 10 feet in the Long Beach profile. No obvious indication for such a change could be observed in the boring logs or dry densities of the fill. However, since the fill below 10 feet is below the water table, there is a notable increase in total unit weight below this depth. The Japanese have found from in-situ measurements that moist loose sand will have a higher shear-wave velocity than dry sand of the same dry density [Okamoto, 1973]. This could

Table 5

Geotechnical Profiles for Two Sites in the Greater Los Angeles Area

Los Angeles Site

Depth (ft)	S-Wave Velocity (ft/sec)	P-Wave Velocity (ft/sec)	Soil Type	Geology
0-13	630	1070	Silty Sand	Compacted Fill
13-25	1770	3170	Gravelly Sand	Recent Alluvium
25-35	1770	5000	Gravelly Sand	Recent Alluvium (Below Water Table)
35-80	2180	3600	Siltstone	Fernando Formation (Pliocene)

Long Beach Site

Depth (ft)	S-Wave Velocity (ft/sec)	P-Wave Velocity (ft/sec)	Soil Type	Geology
0-10	380	780	Sand	Hydraulic Fill ($D_r \approx 50\%$)
10-60	550	5000	Sand	Hydraulic Fill (Below Water Table)
60^+	1160	5000	Sand	Recent Alluvium - Estuarine Deposits (Loose)

possibly be due to an increase in the shear strength of moist sand. For the purposes of developing the velocity profiles, the layer boundaries are taken to coincide with the velocity boundaries presented in Table 5.

The shear and P-wave velocities for the layers can be estimated from the correlations presented in the previous sections. A generalized procedure used to estimate the velocities for the two Los Angeles area sites is summarized as follows:

- Surface layer shear and P-wave velocities are taken from Tables 1 and 2 directly or from Poisson's ratio by use of Table 3 and Equation (2).
- Deeper layer shear-wave velocities are taken from Table 1 or Figures 2 through 5. P-wave velocities are taken from Table 2 or estimated from shear-wave velocity and Poisson's ratio using Table 3 and Equation (2).
- The P-wave velocity for soils occurring below the water table is taken from Table 2.
- Standard deviations (σ) for the velocities are taken from Tables 1, 2 and 4. When standard deviations are not available, they are assumed to be about 10% of the mean velocity for values taken from the tables and equal to the average standard deviations from Table 4 for velocities taken from Figures 2 through 5.

The estimated and measured shear and P-wave velocity profiles determined by the above procedure are presented in Table 6 and in Figures 6 and 7. It is seen that the measured velocities generally fall within two standard deviations of the estimated velocities. More specifically, the mean estimated

Table 6

Estimated Velocity Profiles for Two Sites in the Greater Los Angeles Area

Los Angeles Site

Depth (ft)	Geotechnical Classification	S-Wave Velocity (ft/sec) V_s	σ	P-Wave Velocity (ft/sec) V_p	σ
0-13	Compacted Fill	690	60	1270	130
13-25	Sand & Gravel	1720	190	3440	340
25-35	Sand & Gravel (Below Water Table)	1720	190	5600	560
35-80	Pliocene Sedimentary Rock (Corrected for Overconsolidation)	1500 (1900)	210 (250)	2550 (3200)	360 (450)

Long Beach Site

Depth (ft)	Geotechnical Classification	S-Wave Velocity (ft/sec) V_s	σ	P-Wave Velocity (ft/sec) V_p	σ
0-10	Unconsolidated Soils	500	50	930	90
10-60	Unconsolidated Soils (Below Water Table)	650	90	5600	560
60^+	Unconsolidated Soils (Below Water Table)	1050	150	5600	560

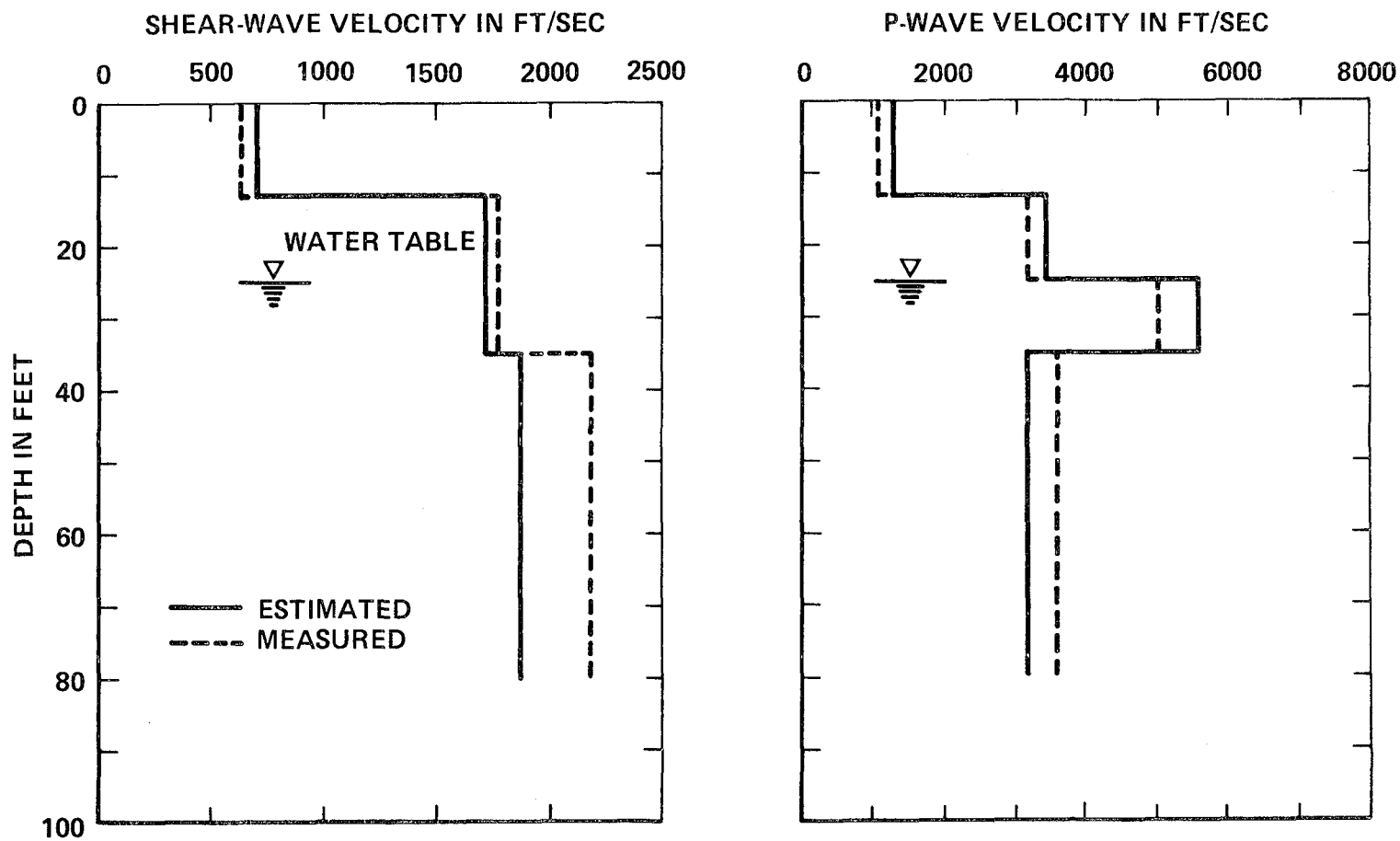

Figure 6. Comparison of Estimated and Measured Shear-Wave and P-Wave Velocity Profiles for the Los Angeles City Site.

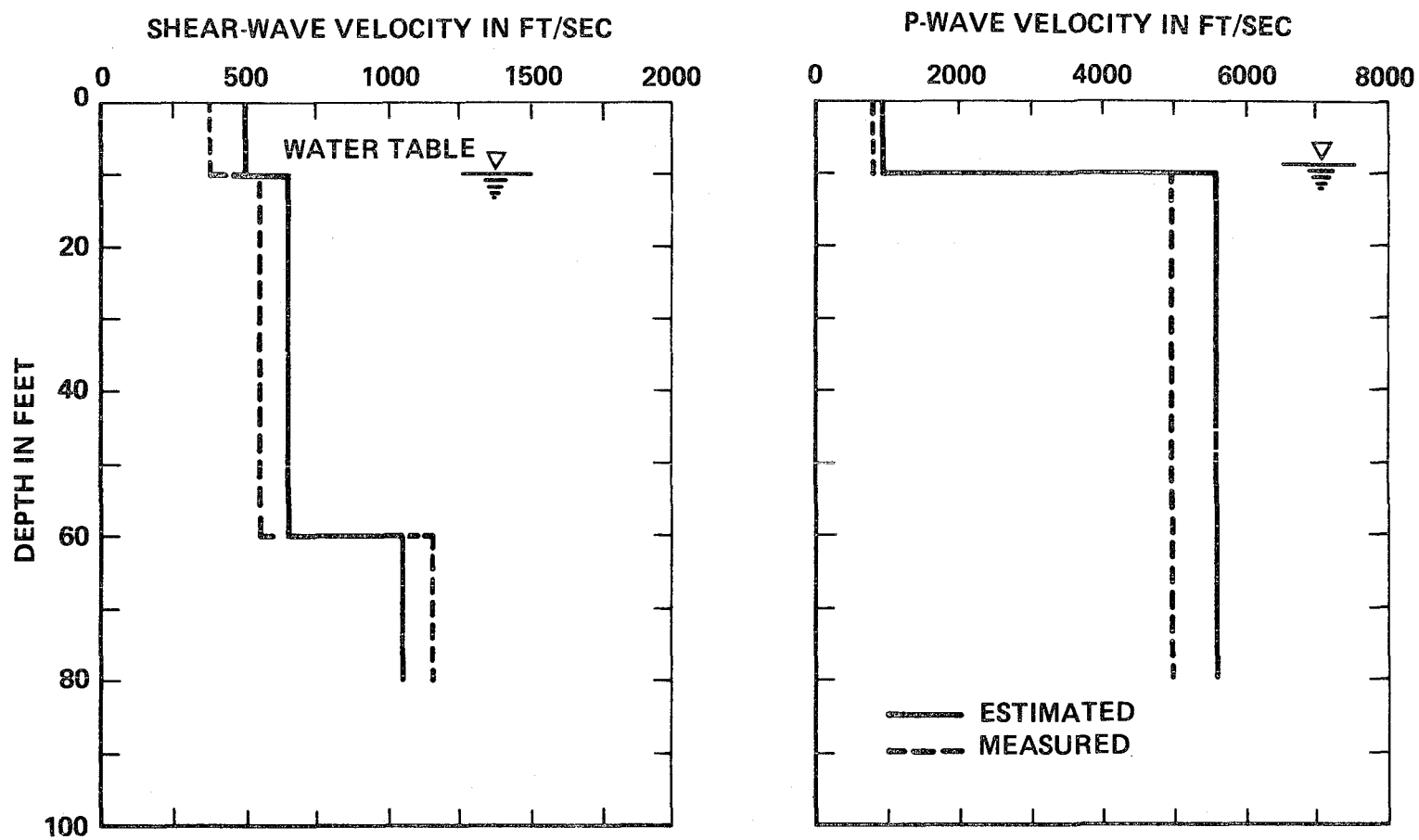

Figure 7. Comparison of Estimated and Measured Shear-Wave and P-Wave Velocity Profiles for the Long Beach Site.

velocities deviate from the measured velocities by less than about 20%. This agreement is considered quite good.

A notable exception to these observations involves the Pliocene Siltstone in the Los Angeles profile. The measured shear and P-wave velocities are much higher than the two standard deviation upper bound for the estimated values. This could be a result of using only three samples to determine the estimate, but the special geological conditions at the site may be significant. Since the siltstone occurring at a depth of about 35 feet represents a former river-cut terrace of the Los Angeles River, the upper more weathered zones of the siltstone have been eroded away by the river, leaving a more competent rock. Therefore, the measured velocity may be more indicative of Pliocene siltstone occurring at a much larger depth. This points out the importance of considering the possible overconsolidation of cohesive soils and soft rock in the estimation of the velocity.

The overconsolidation correction factor suggested by Hardin and Black (1968, 1969), which was incorporated in Equation (6), can be applied to the siltstone of the Los Angeles profile to increase the estimated velocity. The overconsolidation ratio of the siltstone was roughly estimated to be between 3-5 by estimating the thickness of overburden rock removed by erosion of the Los Angeles River. The plasticity index was estimated from laboratory data to be in the range 15-25. These data, used with the factor suggested by Hardin and Black, accounts for an increase of about 25% in velocity, making the new values about 1900 and 3200 ft/sec for shear-wave and P-wave velocity, respectively. The standard deviations are estimated to be 250 and 450 ft/sec, respectively. A comparison of the revised velocities with the values determined by the seismic survey, Table 5, shows that the estimated values are now

within 12% of the measured values. This correction has been incorporated in the plots of the velocity profiles, Figure 5, and in Table 6 where they appear in parentheses.

The selection of potential velocity boundaries may, in general, be more difficult for profiles other than the two presented here. When obvious changes in geology or soil conditions are absent in the field data, other changes may have to be identified. For instance, abrupt changes in dry densities, blow counts, gravel content, soil type, or relative firmness may indicate changes in velocity. When more detailed data such as water content, void ratios, shear strengths, and consolidation data are available, they may also be used to identify velocity boundaries.

Once the velocity boundaries have been identified for a specific site, the procedures used to develop the above two profiles can then be used to estimate shear and P-wave velocities for the site.

DISCUSSION

Correlations among velocity, Poisson's ratio, depth, and the type of ground have been developed in the previous sections, using in-situ velocity and geotechnical data in the greater Los Angeles area. These correlations are considered good enough to justify their use in estimating shear-wave or P-wave velocities to depths of about 100 feet, at a site where a generalized geotechnical classification can be assigned under one or more of the groups shown in Figure 1.

A procedure for constructing synthetic velocity profiles for low-strain, elastic conditions was outlined and demonstrated for two sites in the greater Los Angeles area for which in-situ velocity data were available. The good agreement between the estimated and measured velocities was encouraging and demonstrated to some extent the validity of the procedure. The importance of considering the effects of overconsolidation in estimating velocity was demonstrated in developing the synthetic profile for the City of Los Angeles site. This condition should be identified whenever possible so that these effects can be taken into account when developing a velocity profile.

The laboratory data of Hardin and Drnevich (1972) and Seed and Idriss (1970a) demonstrate the significant effect shear-strain amplitude has on the dynamic shear modulus and shear-wave velocity. The shear-strain amplitudes expected to occur in soil deposits during strong earthquake shaking may extend into the nonlinear range of dynamic stress-strain curves determined in the laboratory. Low-strain velocity profiles determined by the procedures described in the previous sections would have to be modified for the effects of shear-strain amplitude in order to represent earthquake conditions. One method for doing this is simply to reduce the shear-wave velocities by a

constant factor dependent upon the expected intensity of seismic shaking. Such a procedure has been adopted in the building codes for determining characteristic site periods from low-strain seismic survey data [ICBO, 1976; SEAOC, 1974]. A more sophisticated technique which incorporates the effects of depth of burial and ground acceleration is described in Appendix A.

The procedure described for constructing synthetic velocity profiles requires only a moderate amount of geotechnical data. The data required consists of a description of the geology, soil types and depths of the material below the site, in order that the layers can be identified and classified with respect to the various geotechnical groups, Figure 1. However, any additional laboratory or field data, such as moisture content, density, shear strength, blow counts, etc., will help considerably in identifying velocity boundaries or in comparing estimated velocities with those computed by other methods, and should be used when available.

It should be emphasized that the statistical correlations developed herein are based on a limited amount of data to depths of about 100 feet, thus, careful judgment should be exercised in the application of the results. It is hoped that the correlations can be strengthened in the future with the accumulation of more data.

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NOTATION

a_{max}	maximum ground acceleration
d	depth below ground surface
D_r	relative density
e	void ratio
g	acceleration of gravity
G	shear modulus at specified strain level
G_{max}	maximum shear modulus at low strain
h_1	height of column of unsaturated soil
h_2	height of column of saturated soil
K_c, K_s	empirical strain-dependent factors
K_o	coefficient of earth pressure at rest
N	standard penetration blow count
N_c	number of cycles of vibration
OCR	overconsolidation ratio
PI	plasticity index
r_d	stress-depth reduction factor
S_u	undrained shear strength
T	geologic age of sediments
V_p	P-wave velocity at low strain
V_s	shear-wave velocity at low strain
V_s^{γ}	shear-wave velocity at specified strain level
γ	shear strain amplitude
γ_h	hyperbolic shear strain
γ_r	reference shear strain

γ'	buoyant unit weight
γ_T	total unit weight
ν	Poisson's ratio
ρ	mass density
σ	standard deviation
$\bar{\sigma}_o$	mean effective confining pressure
σ'_v	vertical effective stress
τ	average uniform shear stress during seismic vibration

APPENDIX A

THE EFFECT OF SHEAR-STRAIN AMPLITUDE ON SHEAR MODULUS

During earthquake shaking, the shear strains developed in the soil deposit may be several orders of magnitude larger than the strains developed during in-situ seismic surveying. Since this difference in shear strains can significantly affect the shear-wave velocity of the medium, the estimated low strain velocities at a site should be adjusted for shear-strain amplitude effects. Simplified procedures for incorporating these effects have been developed by Hardin and Drnevich (1972) and Seed and Idriss (1970a).

Using laboratory test data results, Hardin and Drnevich found that the shear modulus, G, at any shear strain amplitude, γ, was related to the shear modulus at low strain, G_{max}, by the simple hyperbolic relation,

$$\frac{G}{G_{max}} = \frac{1}{1 + \gamma_h} \tag{A1}$$

where hyperbolic strain, γ_h, is computed in terms of a reference strain γ_r and soil constants a and b,

$$\gamma_h = \frac{\gamma}{\gamma_r}\left[1 + a\, e^{-b\left(\frac{\gamma}{\gamma_r}\right)}\right] \tag{A2}$$

where

$$\gamma_r = \frac{\tau_{max}}{G_{max}} \tag{A3}$$

$$\tau_{max} = \left\{\left(\frac{1 + K_o}{2}\ \sigma'_v\ \sin\phi' + c'\cos\phi'\right)^2 - \left(\frac{1 - K_o}{2}\ \sigma'_v\right)^2\right\}^{\frac{1}{2}} \tag{A4}$$

K_o = coefficient of lateral stress at rest

σ'_v = vertical effective stress, and

c', ϕ' = static strength soil parameters in terms of effective stress.

The a and b values in Equation (A2) can be determined for any soil, through laboratory tests, but average values presented by Hardin and Drnevich can be computed as follows:

- Clean Dry Sands $a = -0.5$ $b = 0.16$
- Clean Saturated Sands $a = -0.2 \log_{10} N_c$ $b = 0.16$
- Saturated Cohesive Soils $a = 1 + 0.25 \log_{10} N_c$ $b = 1.3$

where N_c is the number of cycles of vibration.

Seed and Idriss (1970a) present average curves for modifying shear moduli for the effects of shear strain. Their curves can be used in lieu of Equation (A1). These curves incorporate implicitly the effects of the previously discussed parameters, thus no specific data other than a knowledge of soil type, maximum shear modulus at low strain, and shear strain amplitude are required. The curves plotting $\frac{G}{G_{max}}$ versus shear strain for Sands and Saturated Clays are presented in Figure A1.

Once the reduction factor $\frac{G}{G_{max}}$ has been determined for a given shear strain, the ratio of velocities $\frac{V_s^{\gamma}}{V_{s_{max}}}$ can be computed from the simple relation between shear modulus and shear velocity,

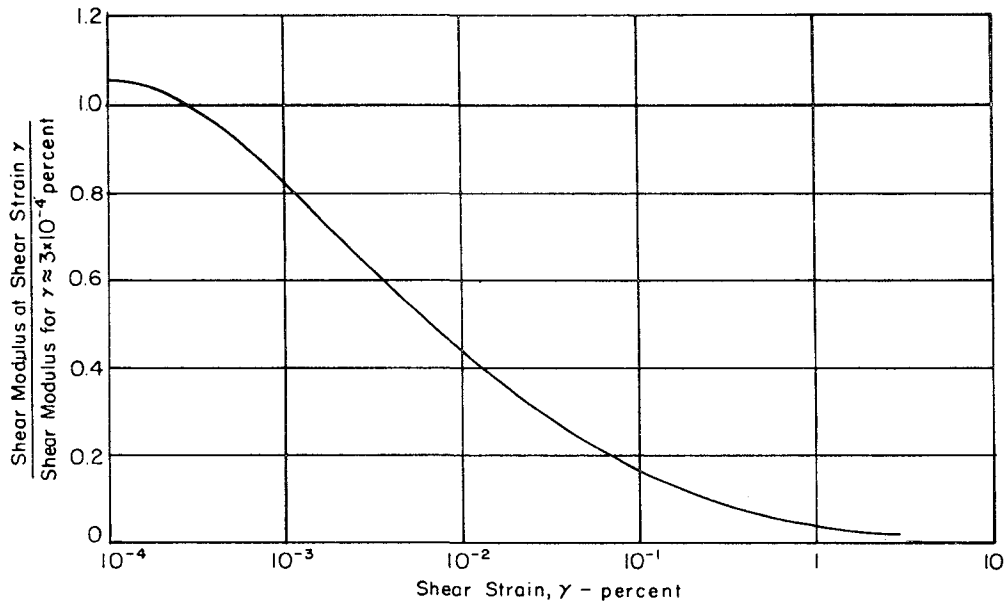
$$G = \rho V_s^2 \tag{A5}$$

where ρ is mass density, giving

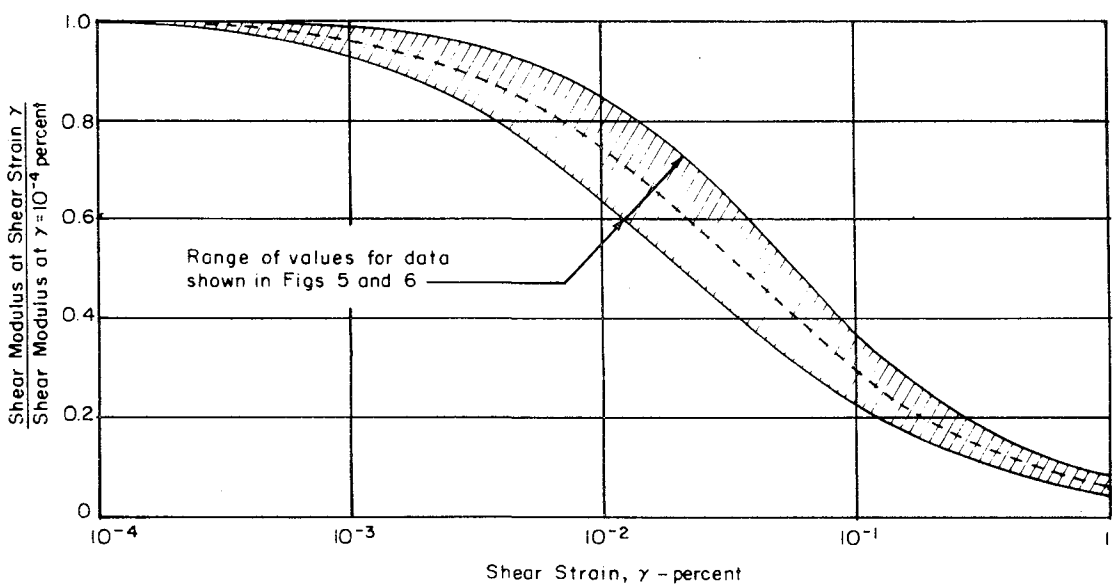
$$\frac{V_s^{\gamma}}{V_s} = \sqrt{\frac{G}{G_{max}}} \tag{A6}$$

which can be used to modify the estimated low-strain shear-wave velocity for the effects of shear strain amplitude.

The estimation of the shear strain amplitude during seismic shaking is in general a difficult task. Seed and Idriss (1970b) have developed a



TYPICAL REDUCTION OF SHEAR MODULUS WITH SHEAR STRAIN FOR SATURATED CLAYS.



VARIATION OF SHEAR MODULUS WITH SHEAR STRAIN FOR SANDS.

Figure A1. Variation of Shear Modulus With Shear Strain for Soils (After Seed and Idriss, 1970a).

simplified procedure for evaluating shear stresses induced by an earthquake to be used in liquefaction analyses. Their equation for the average uniform shear stress of strong shaking at any depth d in the soil profile is given by,

$$\tau = 0.65 \frac{\gamma_T d}{g} a_{max} r_d \tag{A7}$$

where γ_T is the total unit weight at depth d, g is the acceleration of gravity, a_{max} is the maximum surface acceleration, and r_d is a stress-depth reduction coefficient used to modify the stress for the flexibility of the soil column. Average values of r_d for a wide variety of earthquake motions and soil conditions shows that r_d falls within the range of values shown in Figure A2 [Seed and Idriss, 1970b].

Shear strain can then be computed from the relation,

$$\gamma = \frac{\tau}{G} \tag{A8}$$

However, since, shear modulus is also a function of shear strain, an iterative procedure must be used to compute both γ and G. An initial estimate of G will yield a value of γ from Equation (A8). This value of shear strain can then be used to compute G by Equation (A1) or Figure A1. The computed value is then compared to the initial estimate, the estimate is adjusted as required, and the procedure is repeated until the two values converge.

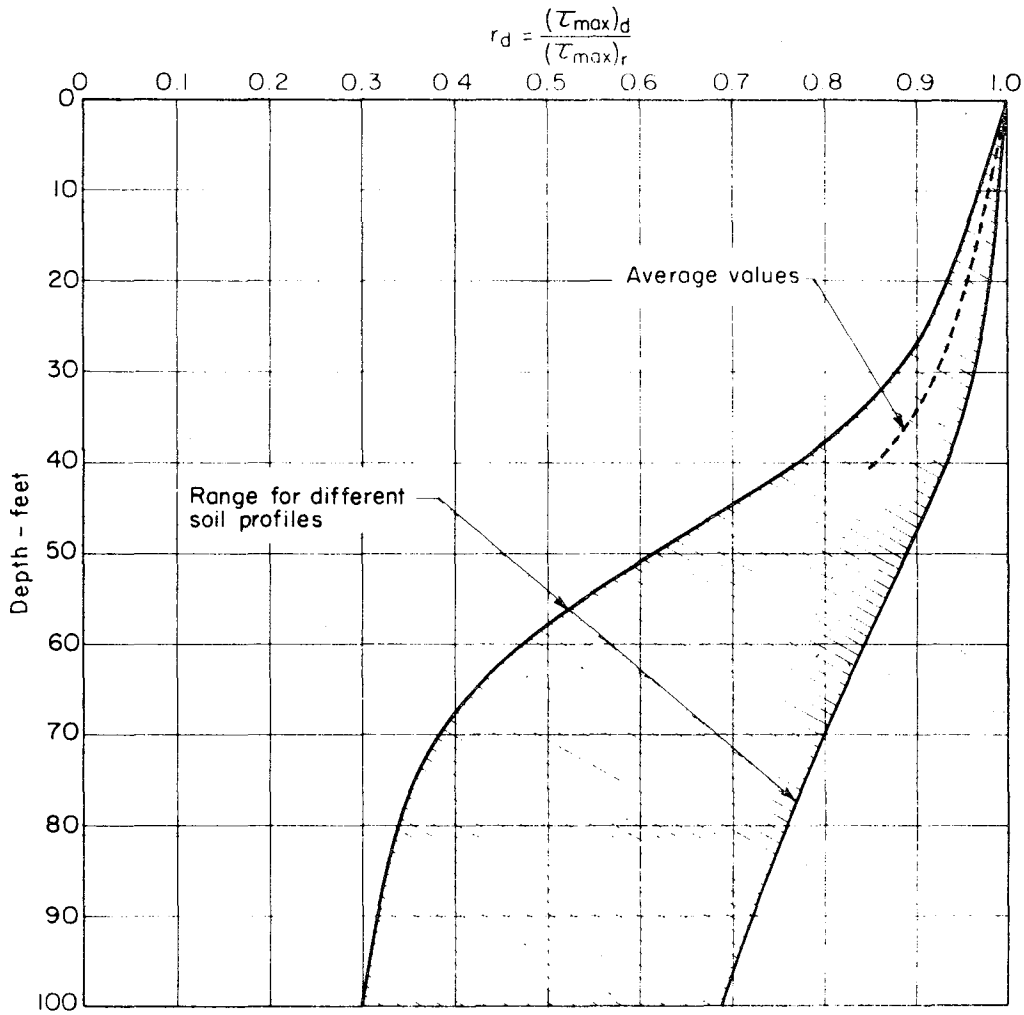


Figure A2. Range of Values of Stress Reduction Factor, r_d, for Different Soil Profiles (After Seed and Idriss, 1970b).

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APPENDIX B

ABRIDGED GEOLOGIC TIME SCALE

Era	Period	Epoch	Approximate Duration* in Millions of Years	Millions of* Years Ago
Cenozoic	Quaternary	Holocene	0.01	0
		Pleistocene	2.5	2.5
	Tertiary	Pliocene	4.5	7
		Miocene	19.0	26
		Oligocene	12.0	38
		Eocene	16.0	54
		Paleocene	11.0	65

*After Bolt et al. (1975)

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