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Marshall Lew
LeRoy Crandall and Associates, Los Angeles, California

Robert Chieruzzi
LeRoy Crandall and Associates, Los Angeles, California

Kenneth W. Campbell
TERA Corporation, Berkeley, California

C. Martin Duke
University of California, Los Angeles, California

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SYNOPSIS Correlations of seismic velocity have been made with depth for various geotechnical classifications of soil and rock described. The seismic velocities have been found to be dependent upon geologic age, gravel content, water table depth, dry density and depth of overburden.

INTRODUCTION

This paper presents correlations among seismic velocity, depth and geotechnical parameters. These correlations are based on a geotechnical classification system that defines ranges of seismic velocity according to soil or rock type, geologic age, gravel content, water table depth, dry density, and depth of overburden.

Such correlations may be useful in earthquake engineering and machine vibration problems. The knowledge of shear-wave and compressional-wave velocities and the associated shear and elastic moduli and Poisson's ratio is necessary for understanding and predicting ground motion response due to earthquake or induced machine vibration excitation. Knowledge of shear-wave velocity profile to depths where a shear-wave velocity of 2,500 feet per second or greater is encountered is required to evaluate the characteristic site period of a given site which, in turn, is needed to evaluate the soil-structure interaction coefficient, S, defined in the Uniform Building Code (1979).

SEISMIC VELOCITY DATA

Shear-wave and compressional-wave velocities measured at some 111 sites comprise the data base on which this study is based. Some 63 of these sites were investigated by the Earthquake Laboratory at UCLA (Duke, et al, 1971 and Eguchi, et al, 1976); these sites were all at or near accelerograph sites in the Los Angeles area that had recorded ground motions from the 1971 San Fernando earthquake. The compressional- and shear-wave velocities at these sites were determined by seismic refraction surveys to depths of 30 to 80 feet.

An additional 48 sites were investigated by LeRoy Crandall and Associates. Most of these sites were studied as part of comprehensive geotechnical investigations which required characteristic site period and/or site response studies (see Campbell, et al, 1979). Ten of the sites were investigated by the refraction technique, three sites by the crosshole technique, and the remaining 35 measurements by downhole surveys. The depths penetrated by the downhole surveys generally ranged from 50 to 135 feet, with most being about 75 feet deep; one site was investigated to a depth of 410 feet. Like the other sites, most of these 48 additional sites were in Southern California. Some 37 of these measurements were obtained at sites in the Los Angeles and Orange Counties area; the other nine measurements included one in nearby Ventura County, one in Kern County, four in San Diego County, and the remaining three were in the San Francisco Bay area.

The measured shear- and compressional-wave velocities represent the average velocities of layers with thicknesses of at least five feet.

GEOTECHNICAL CLASSIFICATION SYSTEM

The geotechnical classification outlined in Table I was developed to describe major and minor classifications of soil and rock types. It was determined that conventional classification systems, such as the Unified Soil Classification System, would either be inadequate or inappropriate.

The major classifications of this geotechnical classification system are Natural Soils, Fill Soils and Rock. The minor components of this system include the effects of water table, gravel content, dry density, rock hardness, rock type and geologic age. A complete description of the components of the classification system is given in Table I, Geotechnical Classification System.

SHEAR-WAVE VELOCITY CORRELATIONS

Statistical correlations for surface deposits and a few near surface deposits were performed on the shear wave velocities of the 111 sites, and the results are shown in Table II, Statistical Summary of Shear-Wave Velocities. The results are presented in terms of the sample size, velocity range, near velocity, standard deviation and the coefficient of variation. The coefficient of variation is the dimension-

TABLE I
GEOTECHNICAL CLASSIFICATION SYSTEM

Geotechnical Classification			Description	Dry Density (Lbs./Cu.Ft.)	Depth (Ft.)
Natural	<10% Gravel and Cobbles	Soft	Very recent Holocene floodplain, lake, swamp, estuarine, & delta deposits, & hydraulic fill soils; may contain organics.	<100	>0
			Saturated Holocene age soils.	90-110	>10-15
			Very low density Holocene soils; primarily fine-grained.	<90	≥0
			Soft to moderately soft Holocene and Pleistocene clays & clayey silts; generally dark grey to black.	<100 <80	0 ≥10
		Intermediate	Unsaturated Holocene age soils of moderate density; may contain moderate amounts of gravel at depths below 30 to 50 feet.	90-110	≥0
			Saturated, uncemented Pleistocene & Eocene age soils; may contain moderate amounts of gravel at depths below 10 to 20 feet.	95-115	>10-15
			Low density Pleistocene & Eocene age soils.	90-100	≥0
		Firm	High density Holocene age soils.	>110	≥0
			Unsaturated, uncemented Pleistocene & Eocene age soils of moderate density; may contain moderate amounts of gravel at depths below 10 to 20 feet.	100-115	≥0
		Very Firm	Pleistocene & Eocene age soils of high density.	>117	≥0
	>10% Gravel and cobbles	Surficial	Natural soils & engineered fill soils occurring at the surface containing gravel & cobbles or boulders; predominantly coarse grained; Holocene, Pleistocene & Eocene.		
			10-50% gravel; some cobbles & boulders.	115-130	0
			>50% gravel; some cobbles & boulders.	125-135	0
		Subsurficial	Natural soils occurring at depth containing 10-50% gravel, cobbles & boulders; predominantly coarse:		
			Holocene Pleistocene & Eocene	115-130 115-130	5-30 5-10
			Holocene Pleistocene & Eocene	125-135 125-135	5-20 5-20
Fill Soils	Non-Engineered	---	Loose or slightly compacted man-made fill soils (excluding hydraulic fill); containing <10% gravel & cobbles.	100-115	0
	Engineered	---	Mechanically compacted man-made fill & containing <10% gravel & cobbles.	110-125	0
Rock	Sedimentary	Soft	Highly weathered, low density Pliocene & Miocene siltstones & shales; usually light brown to light grey; Miocene shales are highly siliceous and diatomaceous.	65-90	15-50
		Intermediate	Moderately weathered, moderate density siltstones & shales; Pliocene siltstones & primarily massive & dark grey. Miocene shales are highly siliceous & diatomaceous.	90-105	≥0
		Hard	Moderately weathered, moderate to high density Miocene siltstones, shales, sandstones, & conglomerates.	>95	≥0
	Basement Complex	Highly Weathered	Igneous & Metamorphic rock; highly weathered.	---	≥0
		Moderately Weathered	Moderately weathered & fractured Igneous & Metamorphic rock.	---	≥0
		Slightly Weathered	Unweathered or slightly weathered & fractured Igneous & Metamorphic rock.	---	≥0

TABLE II. STATISTICAL SUMMARY OF SHEAR-WAVE VELOCITIES

Geotechnical Description	No. of Data	Shear-Wave Velocity (Ft/Sec) Range	Mean	Standard Deviation	Coefficient of Variation
Surficial Soil and Fill Deposits Containing Less Than 10% Gravel					
Soft Natural Soil	12	360 - 560	460	60	0.13
Soft Clay (>10 feet deep)	3	460 - 690	550	-	-
Intermediate Natural Soil	23	520 - 790	620	80	0.13
Firm Natural Soil	31	735 - 1180	940	100	0.11
Non-Engineered Fill	12	400 - 550	490	50	0.10
Engineered Fill	18	560 - 940	710	110	0.16
Near Surface Soils Containing More Than 10% Gravel (by Gravel Content)					
10 - 50% (Surficial)	7	805 - 1150	980	130	0.13
>50% (Surficial)	6	1220 - 1430	1320	80	0.06
10 - 50% (5 to 10-30 feet)	3	1180 - 1430	1430	-	-
10 - 50% with cobbles (5 to 20-50 feet)	8	1670 - 1980	1780	115	0.06
Near Surface Rock					
Soft and Intermediate Sedimentary Rock (Surficial)	5	1040 - 1260	1160	90	0.08
Hard Sedimentary Rock (Surficial)	6	1280 - 1480	1360	110	0.08
Soft Sedimentary Rock (15 - 50 feet)	8	1220 - 1500	1380	110	0.08
Moderately Weathered Basement Rock (0 - 100 feet)	6	3300 - 4610	4040	430	0.11

less ratio of the standard deviation to the mean and represents a convenient way to express statistical scatter. These coefficients are relatively small, in the range of 0.08 to 0.14, indicating relative consistency and small scatter of the shear-wave velocity data.

Similar statistical summaries have been performed for compressional-wave velocities and Poisson's ratios and may be found in a report by Campbell, et at (1979).

It has been found by Campbell and Duke (1976) that the correlation of shear-wave velocity with depth could be adequately given by the following expression:

$$V_s = Kd^n \tag{1}$$

where V_s is shear-wave velocity, d is depth, and n are constants dependent upon the geotechnical classification.

However, equation (1) may be slightly modified to account for the asymptotic behavior of shear-wave velocity at the ground surface. This new expression is given by:

$$V_s = K(d + c)^n \tag{2}$$

where the term c accounts for non-zero values of V_s at the ground surface. Thus, as d approaches zero, shear-wave velocity takes on the value $V_s = Kc^n$.

In order that a regression analysis could be used to estimate the constants K, d, and n for each of eight geotechnical classifications for which sufficient data were available, Equation (2) was linearized by taking the natural logarithm of both sides, giving

$$\text{Ln } V_s = \text{Ln } K + n \text{ Ln } (d + c) \tag{3}$$

A summary of the regression analysis is given in Table III, with shear-wave velocity in units of feet per second and depth in units of feet. For this purpose, the depth was taken as the vertical distance from the ground surface to the top of the layer, not to the midpoint of the layer as some investigators have used. For the surface layer, the depth was taken as one-third the thickness of the layer. From the statistical summary presented in Table III, the average correlation coefficient was found to be 0.94 and the average standard deviation to be 0.13. These values suggest that Equation (3) represents the data rather well. The value of 0.13 for the standard deviation of Ln V_s corresponds to a multiplicative factor in V_s of 1.14.

Plots of the data, the regression equations, and the one standard deviation limits for the eight geotechnical classifications are found in Figures 1 and 2. The squares represent data obtained at depth and plotted as the distance to the top of the respective layers. The circles represent surface shear-wave velocity data plotted at one-third the thickness of the layer. In Figure 1(b), Soft Natural Soils, the triangles represent downhole seismic velocity data from El Centro in Imperial Valley and from Cholame (near Parkfield) as obtained in a study prepared for the Nuclear Regulatory Commission

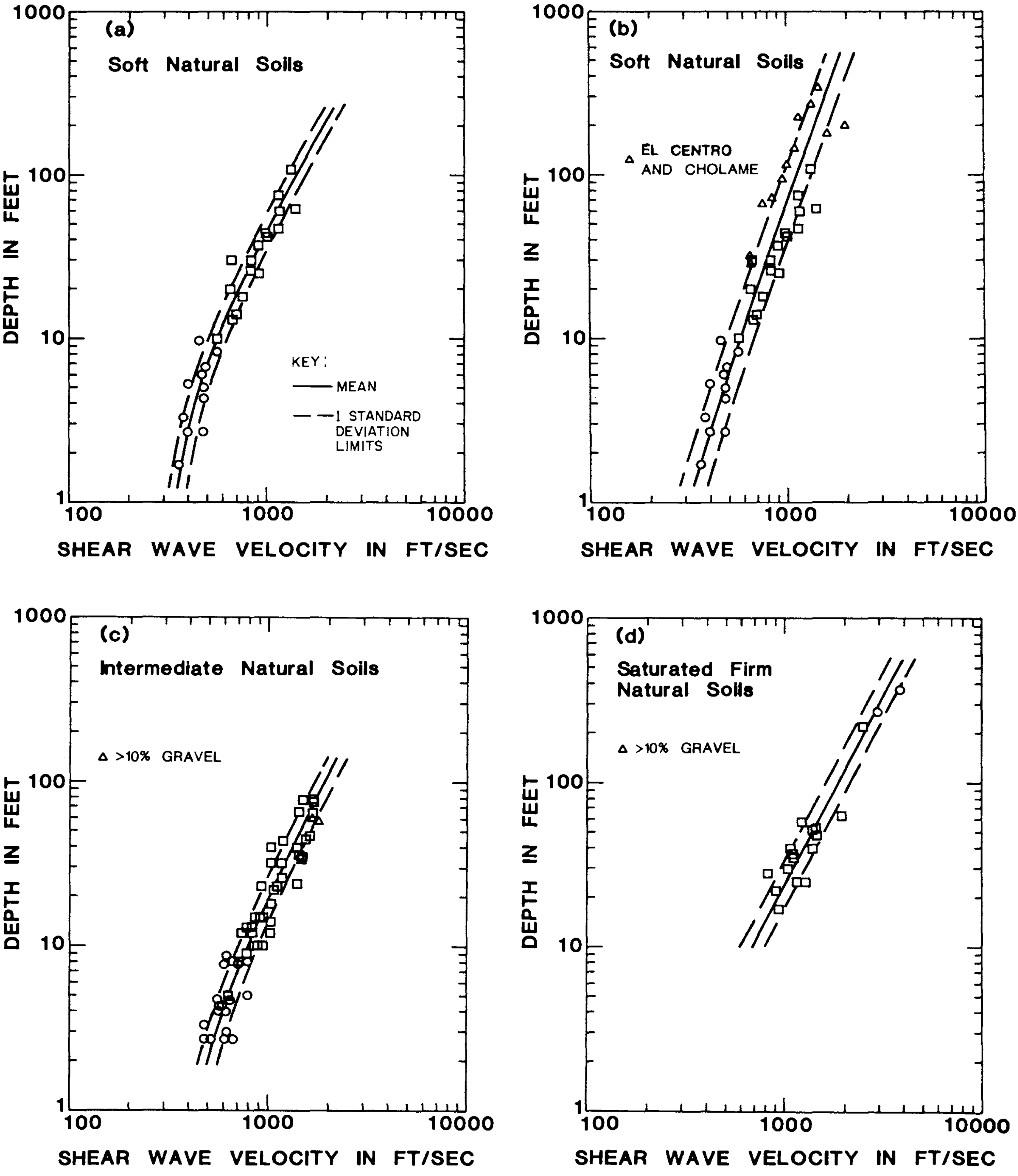

FIGURE 1. SHEAR WAVE VELOCITY VERSUS DEPTH

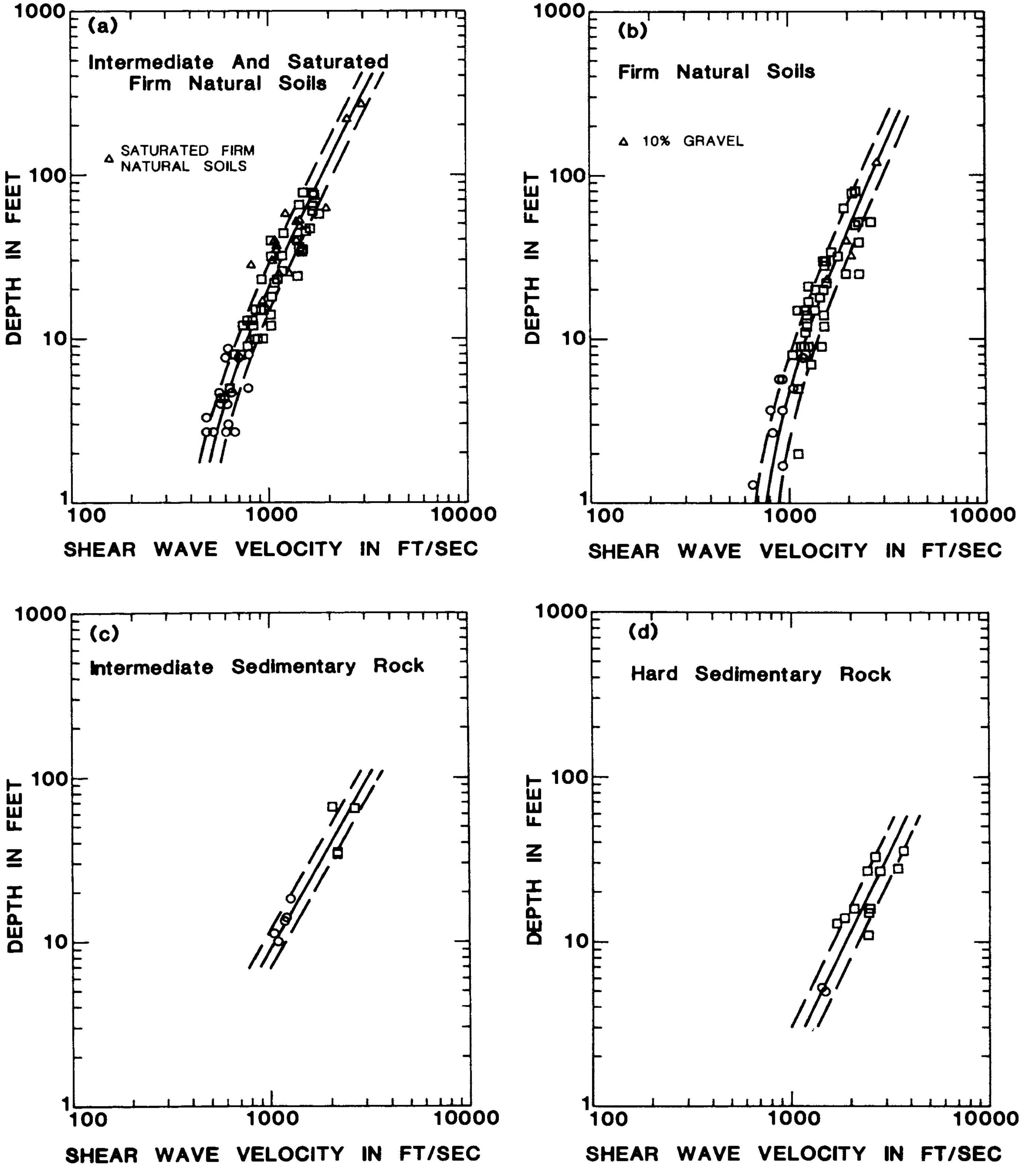

FIGURE 2. SHEAR WAVE VELOCITY VERSUS DEPTH

TABLE III. SUMMARY OF REGRESSION ANALYSIS FOR V_s

$Ln_s = Ln\ K + n\ Ln\ (d + c)$

Geotechnical Description	Regression Coefficients Ln K	n	c	Correlation Coefficient	Standard Deviation of Ln V_s	No. of Data
Soft Natural Soils	5.134	0.456	3.9	0.97	0.11	29
Soft Natural Soils including El Centro and Cholame	5.665	0.296	0.30	0.93	0.16	41
Intermediate Natural Soils	5.674	0.408	1.8	0.95	0.12	59
Saturated Firm Natural Soils	5.432	0.460	0.0	0.95	0.14	18
Intermediate and Saturated Firm Natural Soils	5.628	0.413	2.4	0.95	0.13	76
Firm Natural Soils (Unsaturated)	6.251	0.349	2.0	0.93	0.13	50
Intermediate Sedimentary Rock	5.862	0.472	0.0	0.95	0.13	9
Hard Sedimentary Rock	6.607	0.405	0.0	0.87	0.15	13

(Shannon & Wilson, Inc. and Agbabian Associates, 1975). These velocities are somewhat lower than those obtained in the greater Los Angeles area.

The data available was insufficient at this time to provide correlations for all of the components of the aforementioned geotechnical classification system.

CONCLUSIONS

Statistical correlations of shear-wave velocity and depth have been made for various geotechnical classifications of soil and rock. The elements of this classification system include geologic age, rock or soil type, water table depth, gravel content, dry density and depth of overburden. It should be noted that the velocity correlations were derived from data obtained at low strain levels ($<10^{-4}\%$) and that almost all of the data was obtained in Southern California. Further studies would be required to prove the applicability of these correlations to similar soils and rocks in other regions.

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