NEHRP Site Class and Liquefaction Susceptibility Mapping of the Charleston Quadrangle, South Carolina

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Investigations Undertaken

Charleston is one of the most seismically active regions in the eastern U.S. Of particular importance are the soft, thick soil deposits where amplifications of earthquake ground motion are possible. Because shear-wave velocity (V_S) is a key engineering property for predicting ground shaking, the goal of the first phase of this project is to develop a three-dimensional V_S model of sediments within the Charleston quadrangle. This summary report documents a database of 59 V_S profiles from the Charleston quadrangle and presents initial results.

Shown in Figure 1 are locations of the 59 V_S test sites plotted on the geologic map by Weems et al. [1]. Also shown are locations of an additional 125 non-V_S Cone Penetration Test (CPT) sites, and 45 auger hole sites investigated by Weems and Lemon [2]. Grouping the V_S test sites by surficial geology, 29 are in artificial fill deposits (af), 2 are in Holocene tidal-marsh deposits (Qht), 2 are in middle Holocene to late Pleistocene estuarine deposits (Qhec), 2 are in late Pleistocene beach to barrier-island deposits (Qhes), 1 is in Pleistocene clayey sand and clay facies of the Wando Formation (Qwc), and 16 are in Pleistocene barrier sand facies of the Wando Formation (Qws). A summary of the V_S profiles is given in Table 1.

As noted in Table 1, the V_S profiles are compiled from various project reports [3-10]. The organizations performing the tests are: ConeTec, Inc. (COT); Gregg In Situ, Inc. (GRG); Georgia Institute of Technology (GIT); U.S. Geological Survey (USG); RedPath Geophysics (RDP); S&ME, Inc. (SME); and Wright Padgett Christopher, Inc (WPC). Fifty-four of the V_S profiles were determined by the Seismic Cone Penetration Test (SCPT) or the Downhole (DH) test. The other 5 profiles were determined by the Spectral-Analysis-of-Surface-Waves (SASW) test, the Seismic Refraction/Reflection (SRR) test, or the Suspension Logger (SL) test. Values of V_S reported by the investigator(s) are entered directly into the database and assigned to the average depth of the measurement intervals.

Values of latitude and longitude for each V_S test site are given in Table 1. Some of these values are obtained directly from the project reports. For many of the sites, however, latitudes and longitudes are approximated based on project location descriptions and addresses. In addition, several sites have been re-visited to determine more accurate values using hand-held GPS units. The accuracy of the values is reflected in the significant digits shown in the table.

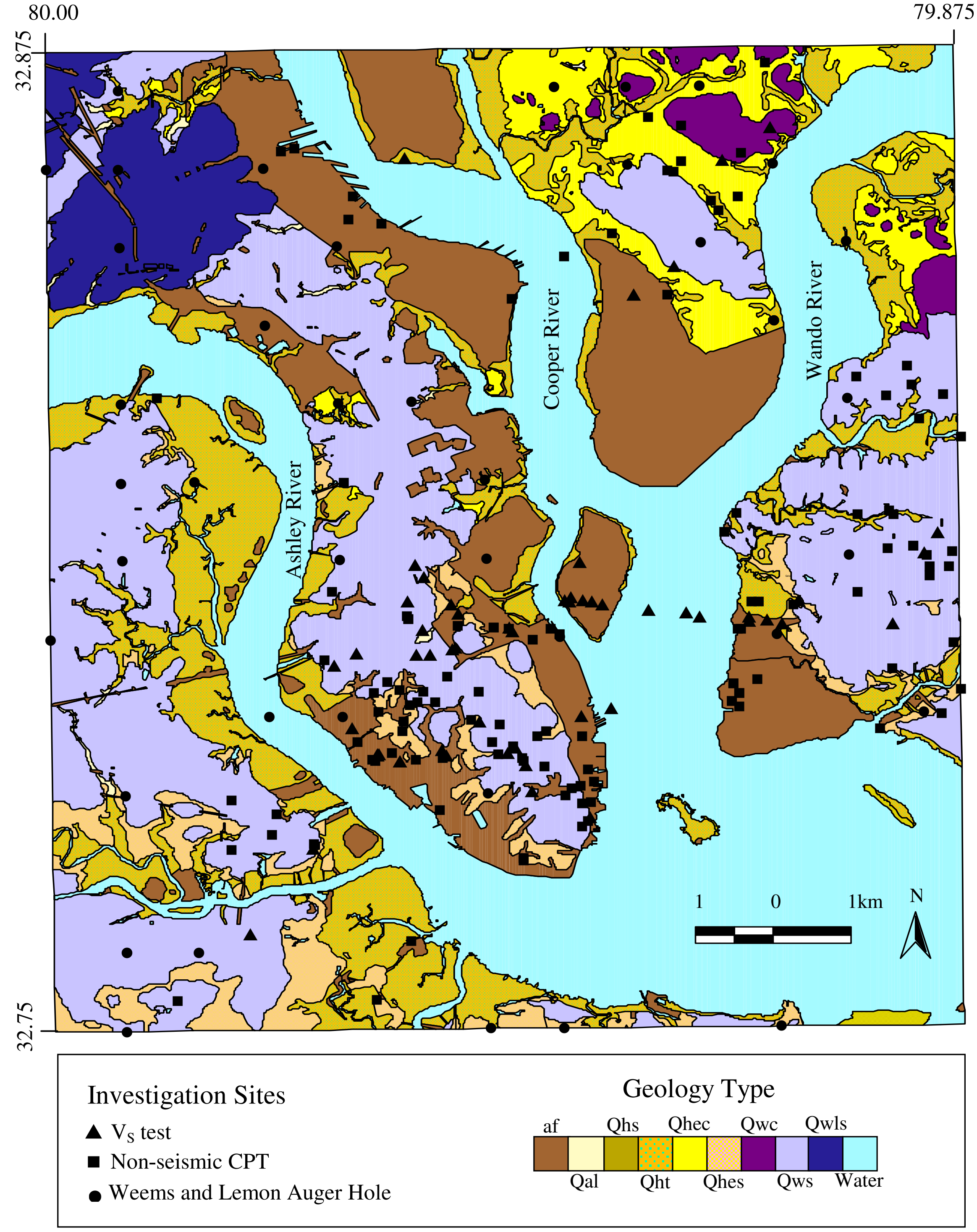


Figure 1: Geologic map of the Charleston Quadrangle by Weems et al. (1997) showing locations of V_s and non-V_s test sites.

TABLE I. SUMMARY OF V_S PROFILES FROM THE CHARLESTON QUADRANGLE.

Site Code	Latitude (degree)	Longitude (degree)	Surficial Geology	Elevation (m)	Maximum Depth (m)	V_{S30} [b] (m/s)	Test Type[c]	Source
C98706A	32.8611	-79.9506	Qht	3.72	42	235	SCPT	[3]
C98706B	32.8075	-79.9486	af	1.58	42	182	SCPT	[3]
C98706C	32.8008	-79.9488	Qws	3.29	42	257	SCPT	[3]
C98706D	32.7983	-79.9447	af	N/A[a]	43	239	SCPT	[3]
C98706E	32.8006	-79.9366	af	1.89	54	126	SCPT	[3]
C98706F	32.8042	-79.9286	af	8.75	42	145	SCPT	[3]
C98706G	32.8094	-79.9272	af	0.26	25	159	SCPT	[3]
C98706H	32.8022	-79.9108	water	N/A	43	N/A	SCPT	[3]
C98706I	32.8022	-79.9039	af	1.3	53	227	SCPT	[4]
C98706J	32.8011	-79.8842	Qws	3.35	53	233	SCPT	[4]
GRG 2	32.833	-79.927	af	N/A	9	N/A	SCPT	[5]
GIT 3	32.7524	-80.01335	-	0	25	236	SCPT	[6]
GIT 10	32.8127	-79.8778	Qws	5	15	N/A	SASW	[7]
USG 6	32.798	-79.958	Qws	N/A	80	248	SRR	[8]
USG 7	32.785	-79.955	af	N/A	30	182	SRR	[8]
RDP 1	32.752347	-80.013015	-	0	107	245	DH	[9]
RDP 2	32.801699	-79.901492	af	3	107	209	DH	[9]
S99634A	32.801699	-79.901492	af	3	34	223	SCPT	[9]
S99634B	32.801313	-79.899534	af	2	18	238	SCPT	[9]
S99634C	32.801603	-79.903918	af	4	27	222	SCPT	[9]
S99876A	32.809109	-79.949866	Qws	4	39	255	SCPT	[9]
S99876B	32.798518	-79.944342	af	4	40	235	SCPT	[9]
S99876C	32.804013	-79.944936	af	2	46	214	SCPT	[9]
S99876D	32.802878	-79.943953	af	1	37	108	SCPT	[9]
S99876E	32.8032	-79.9178	water	0	88	N/A	SL	[9]
S99876F	32.8028	-79.9126	water	0	89	N/A	SL	[9]
S99876G	32.804469	-79.929199	af	1	15	N/A	SCPT	[9]
S99876H	32.804822	-79.928455	af	8	22	140	SCPT	[9]
S99876I	32.804435	-79.92665	af	9	21	144	SCPT	[9]
S99876J	32.804169	-79.925511	af	1	21	122	SCPT	[9]
S99876K	32.803882	-79.924222	af	1	15	N/A	SCPT	[9]
S01018	32.8100	-79.8700	-	N/A	24	212	SCPT	[9]
S01039	32.7622	-79.9730	Qws	N/A	22	243	SCPT	[9]
S01049	32.8433	-79.9194	af	N/A	23	286	SCPT	[9]
S01317	32.7964	-79.9611	Qws	N/A	23	299	SCPT	[9]
S01369	32.7842	-79.9522	af	N/A	24	171	SCPT	[9]
S01420	32.7883	-79.9586	af	N/A	23	137	SCPT	[9]
S01772	32.8042	-79.8972	Qhes	N/A	25	303	SCPT	[9]
S02105	32.7907	-79.9231	water	N/A	19	141	SCPT	[9]
S02315	32.8469	-79.9136	Qhec	N/A	31	162	SCPT	[9]
S02354	32.7848	-79.9458	af	N/A	30	181	SCPT	[9]
S02457	32.7834	-79.9348	Qws	N/A	22	179	SCPT	[9]
S02578	32.7851	-79.9373	Qws	N/A	30	219	SCPT	[9]
S03462	32.7858	-79.9363	Qws	N/A	30	213	SCPT	[9]
W99175	32.7897	-79.9271	af	6	38	138	SCPT	[10]
W00363	32.7798	-79.9336	af	7	19	223	SCPT	[10]

TABLE I. (Continued)

Code	Latitude (degree)	Longitude (degree)	Surficial Geology	Elevation (m)	Maximum Depth (m)	V_{S30} [b] (m/s)	Test Type [c]	Source
W01165	32.7452	-79.9458	Qht	1	18	221	SCPT	[10]
W01343	32.7977	-79.9497	Qws	5	22	178	SCPT	[10]
W01352	32.7843	79.9558	af	0	20	205	SCPT	[10]
W02092	32.8011	-79.9369	af	N/A	18	129	SCPT	[10]
W02100	32.8045	-79.9509	Qws	N/A	18	219	SCPT	[10]
W02120	32.8605	-79.9069	Qhec	N/A	11	N/A	SCPT	[10]
W02219	32.8787	-79.9315	-	N/A	10	N/A	SCPT	[10]
W02233	32.8371	-79.9315	Qws	N/A	15	N/A	SCPT	[10]
W02288	32.7890	-79.9411	Qhes	N/A	17	N/A	SCPT	[10]
W03058	32.8646	-79.9002	Qwc	N/A	13	N/A	SCPT	[10]
W03088	32.7730	-79.9643	Qws	N/A	13	N/A	SCPT	[10]
W03106	32.7767	-79.9261	Qws	N/A	12	N/A	SCPT	[10]
W03114	32.7854	-79.9463	af	N/A	25	184	SCPT	[10]

[a] N/A = Not available.
[b] Only calculated for profiles extending below 18 m.
[c] SCPT = Seismic CPT, SASW = Spectral Analysis of Surface Wave, SRR = Seismic Refraction/Reflection, DH = Downhole, SL = Suspension Logger

The average V_S in the upper 30 m, V_{S30}, is computed using the following equation [11]:

$$V_{S30} = \sum_{i=1}^{n} d_i \Big/ \sum_{i=1}^{n} d_i / V_{si} \qquad (1)$$

where d_i = thickness of the *i*th layer between the depths of 0 m and 30 m, V_{Si} is the shear-wave velocity of that layer, and thicknesses of the n layers sum up to 30 m. To avoid inaccurate V_{S30} values, only profiles extending to depths $\geq$ 18 m are included in the V_{S30} calculations. For profiles not extending to 30 m, V_S between the maximum measured depth and 30 m is assumed to be equal to the average of the three deepest V_S measurements.

Results

The 59 V_S profiles are plotted in Figures 2a-2f. In Figure 2a, the 29 V_S profiles from af sites are plotted. The af sites are characterized by a lower V_S (generally < 250 m/s) zone at the top, a transition zone in the middle, and a higher V_S (generally > 300 m/s) zone at the bottom. Thicknesses of the top lower V_S layers range from less than 10 m to 25 m, with most around 20 m. The transition zone consists of measurements from Holocene, Pleistocene and Tertiary sediments. The bottom zone consists predominantly of measurements from the Cooper Group, locally called the Cooper Marl.

In Figures 2b, 2c and 2d, 6 V_S profiles from the Qht, Qhec and Qhes sites are plotted. Similar to the af profiles, these profiles generally consist of a lower V_S (generally < 300 m/s) zone at the top, a transition zone in the middle, and a higher V_S (generally >300 m/s) zone at the bottom. Thicknesses of the top lower V_S layers appear to be similar, about 10 m to 20 m, to the thicknesses of the top lower V_S layers at af sites.

In Figures 2e and 2f, 16 V_S profiles from the Qwc and Qws sites are plotted. The profiles from these sites consist of a lower V_S (generally < 300 m/s) zone at the top, a transition zone in the middle, and a higher V_S (>300 m/s) zone at the bottom. Thicknesses of layers comprising the top lower V_S zone range from about 10 m to 25 m.

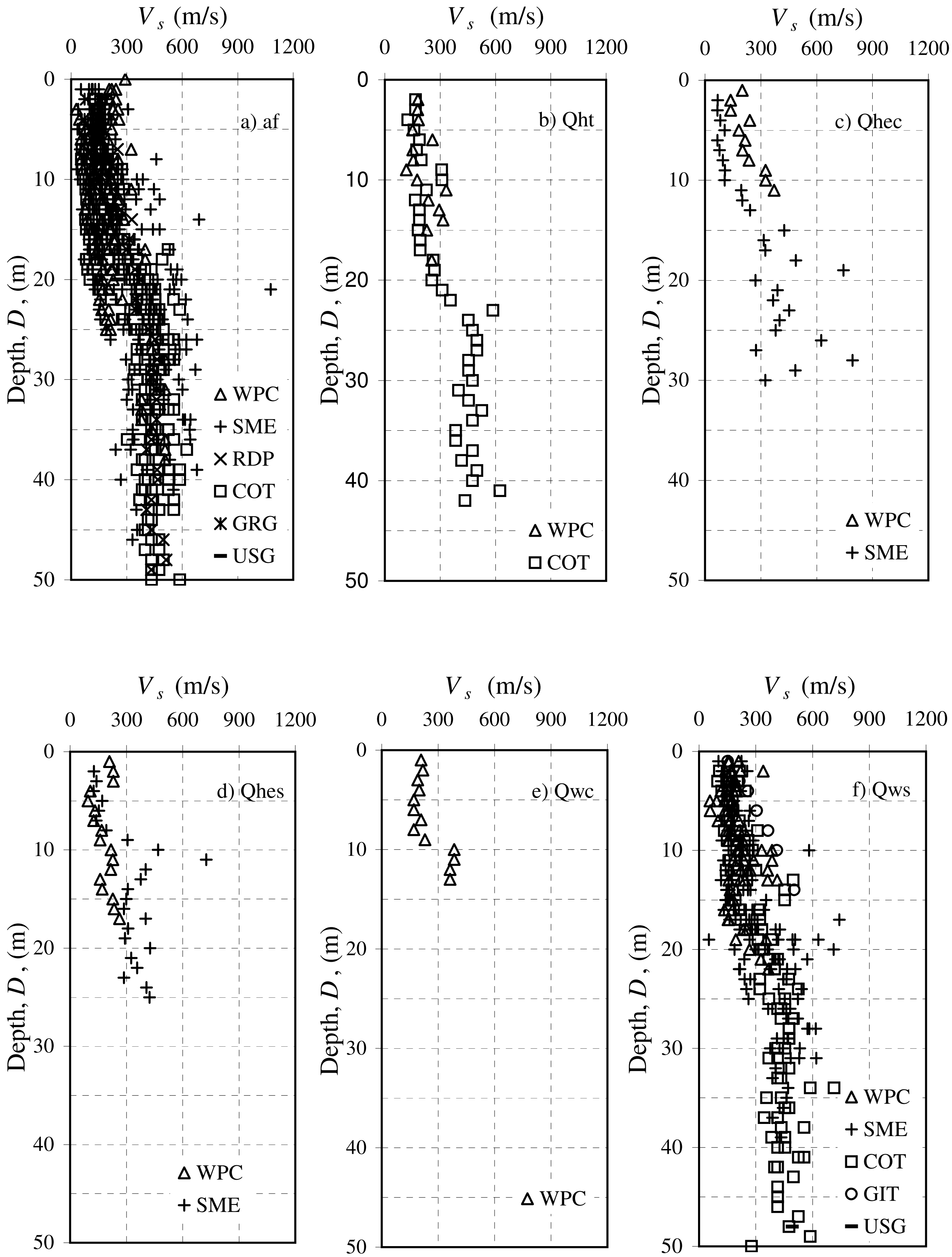


Figure 2: Compiled V_s profiles from the Charleston Quadrangle grouped by surficial geology.

To determine probability distributions of V_{S30} for the af and Qws groups, Rankit analysis [12] is used. As suggested by the name, the V_{S30} data are ranked from low to high first. Then, the same number of Rankit values are picked from the statistics table given in reference [13]. Next, the ranked V_{S30} values are plotted against the picked Rankit values. Such a plot is called a Rankit plot. Rankit analysis assuming a normal distribution is considered first. If the V_{S30} values are normally distributed, the Rankit plot should be a straight line. Otherwise, a different distribution is assumed and a Rankit plot is made based on the transformed data. For example, in this study, values of V_{S30} are transformed to Ln(V_{S30}) to see if they are log-normally distributed. Shown in Figure 3 are the Rankit plots of Ln(V_{S30}) for the af and Qws groups. Because the Ln(V_{S30}) values plot in straight lines, V_{S30} values for both groups are log-normally distributed.

Shown in Figure 4 are the probability density functions of V_{S30} for the af and Qws groups. A mean value of 184 m/s and a standard deviation range of 136-232 m/s characterize the probability density function of V_{S30}, for the af group. For the Qws group, a mean value of 231 m/s and a standard deviation range of 183-268 m/s characterize the probability density function of V_{S30}. Also shown in Figure 4 are the ranges of V_{S30} for NEHRP site classes E and D. Assuming no special NEHRP site class F conditions exist, about 52 % of the af profiles will classify as site class E (i.e., $V_{S30} < 180$ m/s). About 48 % of the af profiles will classify as site class D (i.e., $180 \leq V_{S30} \leq 360$ m/s). For the Qws profiles, about 39 % will classify as site class E and 61 % will classify as site class D.

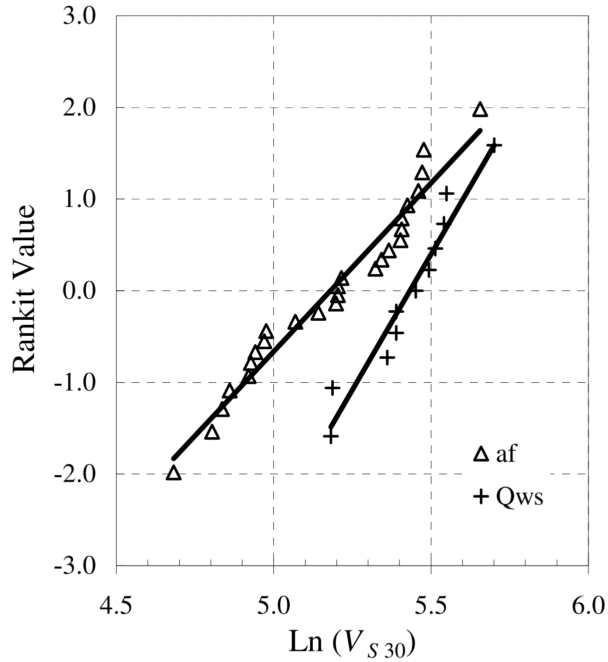
To characterize the variation of V_S with depth for the Cooper Group, measurements from this geologic unit are plotted in Figure 5. Also plotted is a tentative trend line for V_S. The trend line is derived from values of V_S averaged over a 3 m interval, denoted by open circles in the figure. The reason for basing the trend line on average values is because the large number of measurements above the depth of 50 m seems to dominate the regression. In some respects, the plotted V_S measurements suggest that a steeper trend line above a depth of 50 m and a less steep trend line below a depth of 50 m might be more appropriate. Other available test data, such as cone soundings, will be reviewed for evidence to support more complex trends of V_S within the Cooper Group. In addition, similar plots of V_S versus depth will be developed for other major geologic units.

Non-Technical Summary

Charleston is vulnerable to large earthquake shaking, particularly areas with soft, thick soil deposits. Shear-wave velocity (V_S) is a measure of soil softness, or stiffness. As a first step in developing seismic hazard maps for the Charleston quadrangle, V_S measurements are being compiled. The initial results indicate that soils in the upper 10 m to 20 m are generally soft and moderately to highly susceptible to ground motion amplifications. The degree to which they are susceptible depends on the V_S and thickness of the soft soil. The three-dimensional V_S model to be developed during the second year of this study will provide essential information for identifying those areas with the highest susceptibility to ground motion amplifications. The model will also provide essential information for seismic hazard zonation of Charleston.

Reports Published

Zhang, J., Andrus, R.D., Camp, W.M., Casey, T.J., and Cleary, T.J. "In situ V_S and NEHRP site classification in the greater Charleston area," *Proc., Joint Meeting of the 11th Int. Conf. on Soil Dynamics and Earthquake Engrg. and the 3rd Int. Conf. on Earthquake Geotechnical Engrg.*, to be held in Berkeley, CA, on January 7-9, 2004.



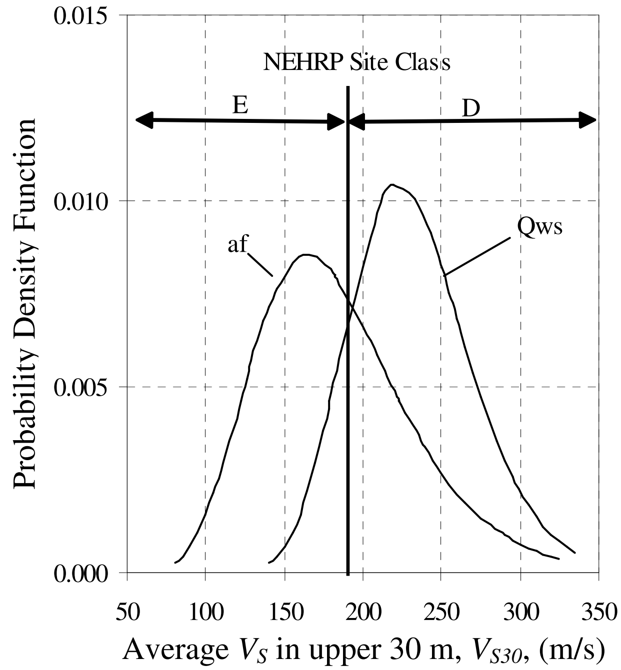


Figure 3: Rankit plot of Ln(V_{S30}) for two surficial geology groups assuming log-normal distributions.

Figure 4: Distributions of V_{S30} for two surficial geology groups with respect to NEHRP site classes.

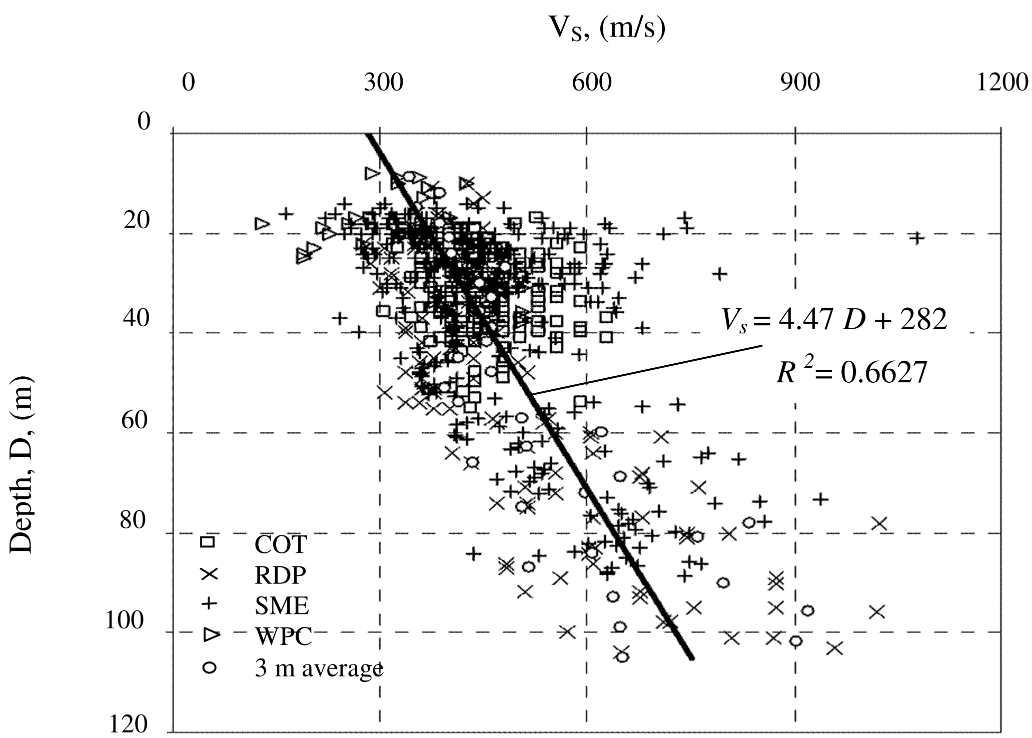


Figure 5: Compiled V_S profiles from the Charleston Quadrangle for the Cooper Group with tentative trend line.

Availability of Processed Data

The processed V_S profiles summarized in Table 1 are available in electronic format from the PI. Professor Andrus can be reached at the telephone number and e-mail address listed on the first page of this summary report.

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