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SHEAR-WAVE VELOCITY AND SEISMIC RESPONSE OF NEAR-SURFACE SEDIMENTS IN THE CHARLESTON QUADRANGLE, SOUTH CAROLINA

Final Report to the
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ABSTRACT

Six major geologic units in the Charleston quadrangle are characterized in terms of shear-wave velocity (V_S) in this report. The characterization is based on in situ V_S measurements at 91 sites. The six geologic units are: man-made fills, Holocene and late Pleistocene deposits, the Wando Formation, the Ten Mile Hill beds, the Penholoway Formation and Daniel Island beds, and Tertiary sediments. Calculated mean V_S values for these units in the top 25 m are 141 m/s, 108 m/s, 190 m/s, 178 m/s, 309 m/s and 393 m/s, respectively, assuming data are log-normally distributed. For Tertiary sediments in the depth intervals of 25-55 m, 55-75 m and 75-100 m, calculated mean V_S values are 433 m/s, 553 m/s, and 670 m/s, respectively. To predict the approximate range of fundamental site periods for the area, a seismic response parametric study is conducted assuming several soil/rock models and two input ground motions with durations typical of magnitude 7.3 earthquakes. The two input ground motions have peak acceleration values of 0.3 g and 0.08 g. It is found that Quaternary sections with V_S of 190 m/s (e.g., the Wando Formation overlying Tertiary sediment) and thicknesses of about 7 m to 15 m exhibit fundamental site periods of about 0.26 s to 0.41 s. These site periods match fundamental periods of many existing buildings in the old city district of Charleston. Thus, greater intensity shaking is predicted for buildings located on the Wando Formation than on the younger soil deposits.

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INTRODUCTION

Charleston, South Carolina, is the second most seismically active regions in the eastern U.S., after the New Madrid seismic zone. The 1886 Charleston earthquake (moment magnitude, $M_w \approx 7.3$) resulted in about 60 deaths and an estimated \$23 million (1886 dollars) in damage. Based on paleoliquefaction studies conducted during the past 20 years (*e.g.,* Obermeier et al. 1985; Talwani and Cox 1985; Amick and Gelinas 1991), Talwani and Schaeffer (2001) estimate a recurrence rate between 500 and 600 years for magnitude 7+ earthquakes near Charleston and about 2000 years for magnitude 6.0 events near Georgetown and Bluffton, South Carolina. This evidence has lead the U.S. Geological Survey in 1996 and 2002 to map significantly higher expected ground shaking levels for Charleston than indicated on previous national maps, with the 2002 levels even higher than the 1996 levels (http://geohazards.cr.usgs.gov/eq/). A repeat of the 1886 earthquake or even a smaller moderate-sized event could be devastating to Charleston and the surrounding areas (FEMA 2000; Silva et al. 2003).

Numerous studies have identified small-strain shear-wave velocity (V_S) as a primary controlling factor for earthquake ground motion (e.g., Seed et al. 1976; Idriss 1990; Borcherdt 1994; Boore et al. 1994; Joyner et al. 1994; and Midroikawa et al. 1994). Seed et al. (1976) and Idriss (1990) observed distinct differences in average response spectral shapes of sites with different subsurface conditions. The differences in spectral shapes result from vertical variations in soil material properties and strongly depend on V_S of the near-surface materials. The determinant effect of V_S on ground motion has lead to new site coefficients and classification system used in recent building seismic code provisions (Dobry et al. 2000).

Because V_S is a key engineering property for earthquake ground shaking prediction, several efforts to compile V_S measurements and other geotechnical information from sites in the greater Charleston area have been initiated in recent years (e.g., Silva et al. 2003; Chapman et al. 2003; Andrus et al. 2003; Zhang et al. 2004; Fairbanks et al. 2004). The conference paper by Zhang et al. (2004) presents composite plots of V_S profiles and characterizes average V_S in the top 30 m for four major surficial geology groups. The data report by Fairbanks et al. (2004) provides electronic files of V_S and Cone Penetration Test (CPT) measurements from the

Charleston quadrangle. Electronic copies of the paper by Zhang et al. (2004) and the data report by Fairbanks et al. (2004) are included on the compact disk provided in the Appendix.

In this report, characteristic V_S properties of major near-surface geologic units within the Charleston quadrangle are developed using the data compiled by Zhang et al. (2004) and Fairbanks et al. (2004). The characteristics V_S properties are defined in terms of mean and standard deviation values. They are used to illustrate the effects of V_S and thickness of Quaternary sediments on seismic ground response. Based on the results of a seismic ground response parametric study, the values of V_S and thicknesses of the Quaternary section providing fundamental site periods that match the typical range of fundamental building periods in the old city district of Charleston are identified.

DATA

Zhang et al. (2004) and Fairbanks et al. (2004) compiled V_S data from 104 test sites in the greater Charleston area. Shown in Figure 1 are the locations of 60 V_S test sites in the Charleston quadrangle plotted on the geologic map by Weems et al. (1997). The locations of the other 44 test sites lie outside the quadrangle, and are plotted on a map of the greater Charleston area published in Zhang et al. (2004). Summary information for the V_S measurements made at the locations shown in Figure are given in the data report by Fairbanks et al. (2004).

The V_S measurements were conducted by various investigators (i.e., Applied Research Associates, Inc.; ConeTec, Inc.; Georgia Institute of Technology; Gregg In Situ, Inc.; RedPath Geophysics; S&ME, Inc.; Wright Padgett Christopher, Inc.; and U.S. Geological Survey) between 1998 and 2004, as cited in Zhang et al. (2004) and Fairbanks et al. (2004). Most tests were made by the Seismic Cone Penetration Test (SCPT) using the downhole method with typically 1-m-depth measurement intervals. A few were made by the seismic downhole method in boreholes, the Spectral-Analysis-of-Surface-Waves (SASW) method at the ground surface, and the seismic refraction/reflection (SRR) method at the ground surface. Values of V_S reported by the investigator(s) were entered directly into a database, and assigned to the depths corresponding to the center of the reported measurement intervals. Maximum measurement depths ranged from less than 10 m to 107 m.

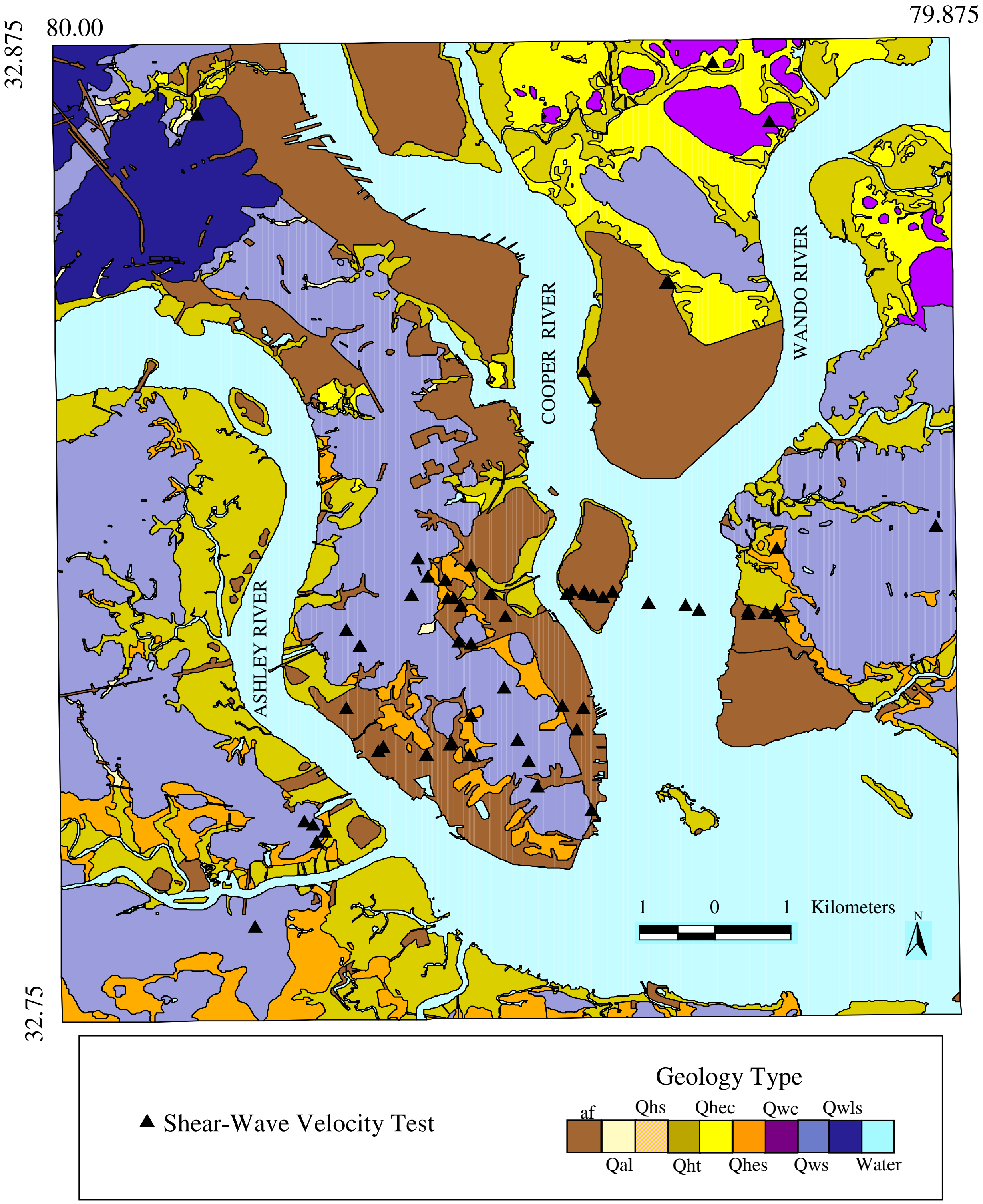

Figure 1. Geologic map of the Charleston quadrangle by Weems et al. (1997) showing locations of V_S investigation sites.

Ground surface elevations at the V_S test sites ranged from 0 m to 12 m above the mean sea level. About two-thirds of the test sites have ground surface elevations less than 5 m above the mean sea level. Only three V_S test sites have ground surface elevation greater than 10 m.

Sufficient subsurface information is available to infer major geologic units beneath 91 of the 104 test sites. Key information considered in the identification of subsurface geology includes: several 1:24,000 geologic maps and auger hole logs available for the greater Charleston area (e.g., Weems and Lemon 1985, 1993); the 1:250,000 geologic map by McCartan et al. (1984); CPT tip, sleeve and pore pressure measurements; and geologic interpretations provided in project reports. The V_S data grouped by subsurface geology are discussed next.

V_S AND GEOLOGY

Presented in Figures 2(a)-2(f) are V_S data from the top 25 m grouped into six major geologic units and plotted versus depth. To avoid incorrect V_S assignments, measurements made on the boundaries separating units are not included. Only V_S data measured completely within a unit are plotted. For the downhole measurements, at least two data points within a geologic unit at a test site are required for the data to be included in the grouping. For the few SASW and SRR measurements, average V_S values are assigned to the layer center. The six major geologic units are: (1) man-made fills; (2) Holocene and late Pleistocene deposits; (3) the Wando Formation; (4) the Ten Mile Hill beds; (5) the Penholoway Formation and the Daniel Island beds; and (6) Tertiary sediments. A brief description of each unit is given below

Man-made fills in Charleston include artificial fill and phosphate spoil (Weems and Lemon 1993). Artificial fill (af) is less than about 300 years old and includes sands or clayey sands of diverse origin, ranging from road fill to building construction fill to non-engineered fill. Phosphate spoil (ps) is less than about 130 years in age, and is material removed and backfilled during phosphate mining primarily in northwest Charleston. As shown in Figure 2(a), compiled values of V_S from artificial fill and phosphate spoil range between 35 m/s to 325 m/s.

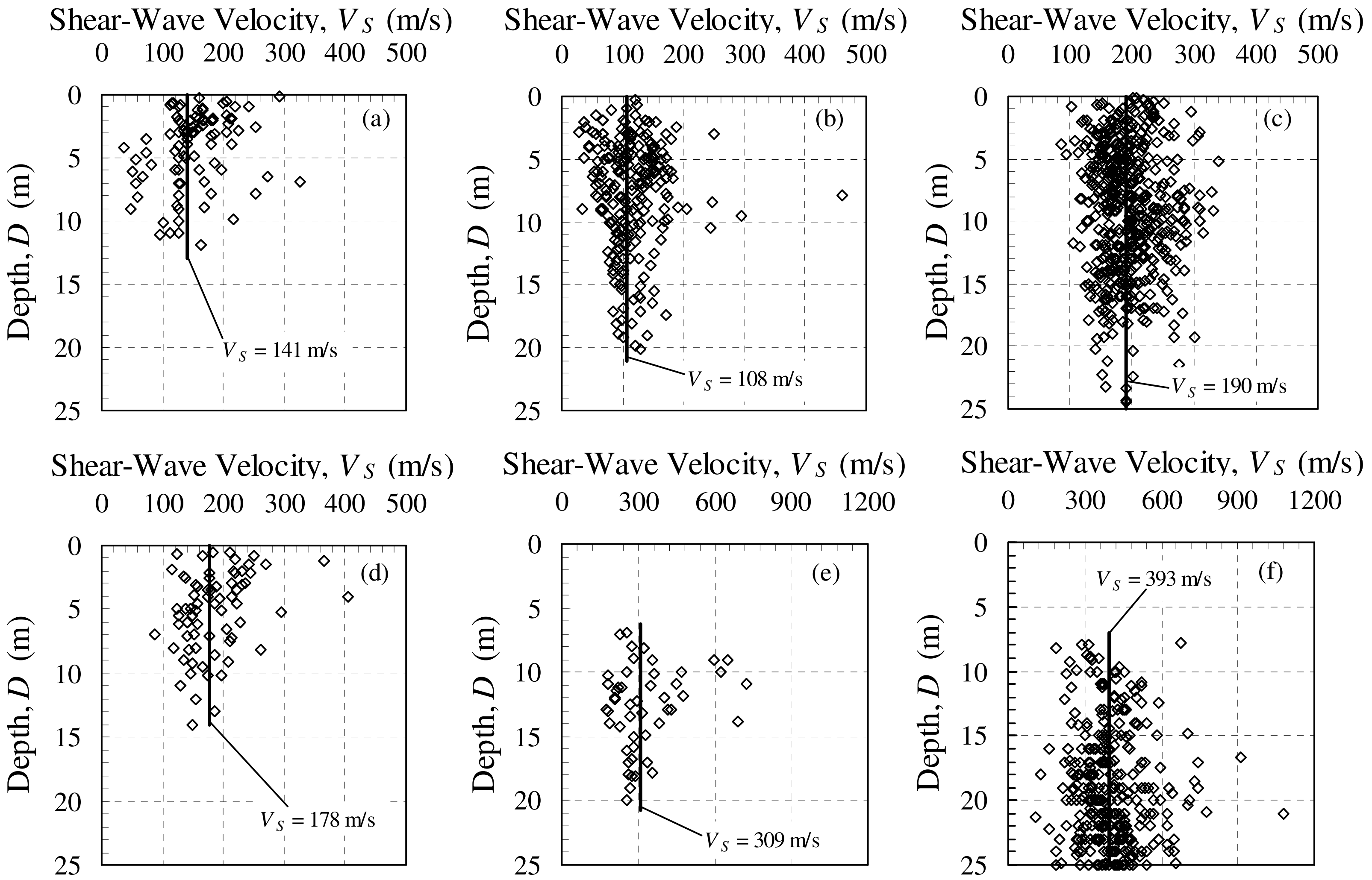

Figure 2. Variation of V_S data from top 25 m separated by geology--(a) man-made fills, (b) Holocene and late Pleistocene sediments, c) Wando Formation, (d) Ten Mile Hill beds, (e) Penholoway Formation and Daniel Island beds, and (f) Tertiary sediments. Mean V_S values shown are determined assuming data are log-normally distributed. (After Zhang 2004.)

Several different types of Holocene and late Pleistocene deposits are present in the Charleston area. From the geological map by Weems and Lemon (1993), Holocene (<10,000 years or <10 ka) deposits include beach to barrier-island sands (Qhs), and tidal-marsh clayey sands and clays (Qht). Early Holocene to late Pleistocene (6 ka to 85 ka) deposits include estuarine silty to sandy clays and quartz sands (Qhec). Late Pleistocene (33 ka to 85 ka) deposits include beach to barrier-island sands (Qhes). No attempt is made to differentiate these deposits in this study. As shown in Figure 2(b), compiled values of V_S from the Holocene and late Pleistocene deposits range from as low as 30 m/s to nearly 240 m/s, with maximum measurement depth of about 20 m.

The Wando Formation is about 70 ka to 130 ka in age. Weems and Lemon (1993) identified six facies in the Wando Formation: two fluvial to estuarine facies comprised of clayey sands and clays (Qwc, Qwlc), two barrier sand facies (Qws, Qwls), and two fossiliferous shelf sand facies (Qwf, Qwlf). No attempt is made to differentiate between V_S measurement in these six facies in this study. Based on comparisons between geologic profiles determined from borings (Weems and Lemon 1985, 1993) and CPT results, one characteristic that can sometimes be used to infer younger clayey deposits from older clayey deposits below the ground water table is the trend of cone tip resistance measurements. Holocene clays tend to have cone tip resistance profiles that project to near a value of 0.0 MPa at the ground surface. Whereas, cone tip resistances in the older clays of the Wando Formation project to values greater than 0.0 MPa at the ground surface. Compiled values of V_S from various facies of the Wando Formation are plotted in Figure 2(c). They range from 85 m/s to over 300 m/s.

The Ten Mile Hill beds are approximately 200 ka to 240 ka in age. Weems and Lemon (1993) identified three facies in the Ten Mile Hill beds: fluvial and estuarine facies comprised of clays and clayey sands (Qtc), beach to barrier-island facies comprised primarily of well-sorted quartz sands (Qts), and shallow marine shelf facies comprised of fine-grained, fossiliferous and bioturbated sands (Qtf). No attempt is made to differentiate between the three facies. CPT profiles in the Ten Mile Hill beds are similar to profiles in the Wando Formation. Fortunately, the Ten Mile Hill beds do not lay beneath the Wando Formation at the majority of the V_S test locations. Plotted in Figure 2(d) are compiled values of V_S from the Ten Mile Hill beds. These V_S values range from around 100 m/s to over 300 m/s.

According to Weems and Lemon (1993), the Penholoway Formation (Qpf) is a fossiliferous sand facies with age between 730 ka and 970 ka; and the Daniel Island beds (Qdc) are clayey sands to clays with similar age, ranging from 730 ka to 1600 ka. No attempt is made to differentiate between these two deposits. Sands in these deposits are often identified in CPT profiles by very high cone tip resistance measurements compared to cone tip resistances measured in overlying and underlying units. As shown in Figure 2(e), compiled values of V_S from the Penholoway Formation and the Daniel Island beds range from about 180 m/s to over 600 m/s.

Tertiary sediment layers mapped by Weems and Lemon (1993) are marine deposits, ranging in age from about 2 Ma to 38 Ma. They include, from youngest to oldest: the Goose Creek Limestone (Tgc), the Marks Head Formation (Tmh), the Edisto Formation (Te), the Chandler Bridge Formation (Tcb), the Ashley Formation (Ta), and the Parkers Ferry Formation (Tpf). The Ashley and Parkers Ferry Formations, along with the older Harleyville Formation (not mapped in the Charleston quadrangle by Weems and Lemon 1993) are three stiff, impermeable limestone members that form the Cooper Group (locally known as the "Cooper Marl"). The Cooper Marl exists throughout the subsurface in the Charleston area and can be up to 100 m thick. In CPT profiles, the Cooper Marl is characterized by: (1) fairly uniform cone tip resistances that do not project to 0.0 MPa at the ground surface, with occasional high values; (2) fairly uniform cone friction ratios; and (3) very high cone pore water pressures, compared to pore pressures measured in the Holocene and Pleistocene clays. No attempt is made in this study to differentiate between Tertiary deposits. However, the majority of the compiled V_S measurements from Tertiary sediments in the upper 25 m are believed to be from the Ashley Formation. Compiled values of V_S from Tertiary sediments in the top 25 m of are plotted in Figure 2(f). These V_S values range from less than 180 m/s to over 700 m/s.

Presented in Figure 3 are all compiled V_S values from Tertiary sediments, both above and below the depth of 25 m. Measurements from depths greater than 50 m are based on two seismic downhole tests and two suspension logging tests conducted in four deep boreholes. One borehole was part of the Maybank Highway Bridge replacement project, which connects the Charleston peninsula to Johns Island across the Stono River. The other three deep boreholes were for the new Cooper River Bridge project along U. S. Highway 17. The plotted V_S measurements generally increase with depth, and can be divided into five depth ranges.

Based on geologic cross-sections by Weems and Lemon (1993), values of V_S plotting in the top 25 m are primarily from the Ashley Formation, and possibly other younger Tertiary-age deposits. Between 25 m and 55 m, plotted V_S values are likely from the Ashley and Parkers Ferry Formations. Below 55 m, plotted V_S values are likely from the Parkers Ferry and Harleyville Formations.

While individual V_S profiles often exhibit an increasing trend with depth within a geologic unit, the data plotted in Figures 2(a)-2(f) exhibit little depth dependency as a whole. Therefore, the V_S data are considered directly, without any correction for depth or overburden pressure, in the statistical analysis. The V_S data in each interval of the Tertiary sediments plotted in Figure 3 are also considered directly in the statistical analysis.

STATISTICAL ANALYSIS

Histograms of the V_S data grouped by geology are presented in Figures 4(a)-4(f) and 5(a)-5(c). The histograms suggest that either normal or log-normal distributions can be used to represent the data. To determine the type of distribution most suitable, the chi-square test (Ang and Tang 1975) is applied to the six data sets. In the chi-square test, the similarity between the considered data and the assumed distribution is evaluated by the total chi-square value (χ^2), which is defined as:

$$\chi^2 = \sum_{i=1}^{k} \frac{(n_i - e_i)^2}{e_i} \tag{1}$$

where k is the number of data intervals, n_i is the observed outcomes for the *ith* bin, and e_i is the theoretically expected outcomes for the *ith* bin based on the assumed distribution. Generally, it is necessary to have $k \geq 5$ and $e_i \geq 5$. Smaller χ^2 values indicate the appropriateness of the selected distribution. Higher χ^2 values imply a significant difference between the data and the assumed distribution. Thus, the distribution with the smallest χ^2 value is the most suitable distribution to represent the data.

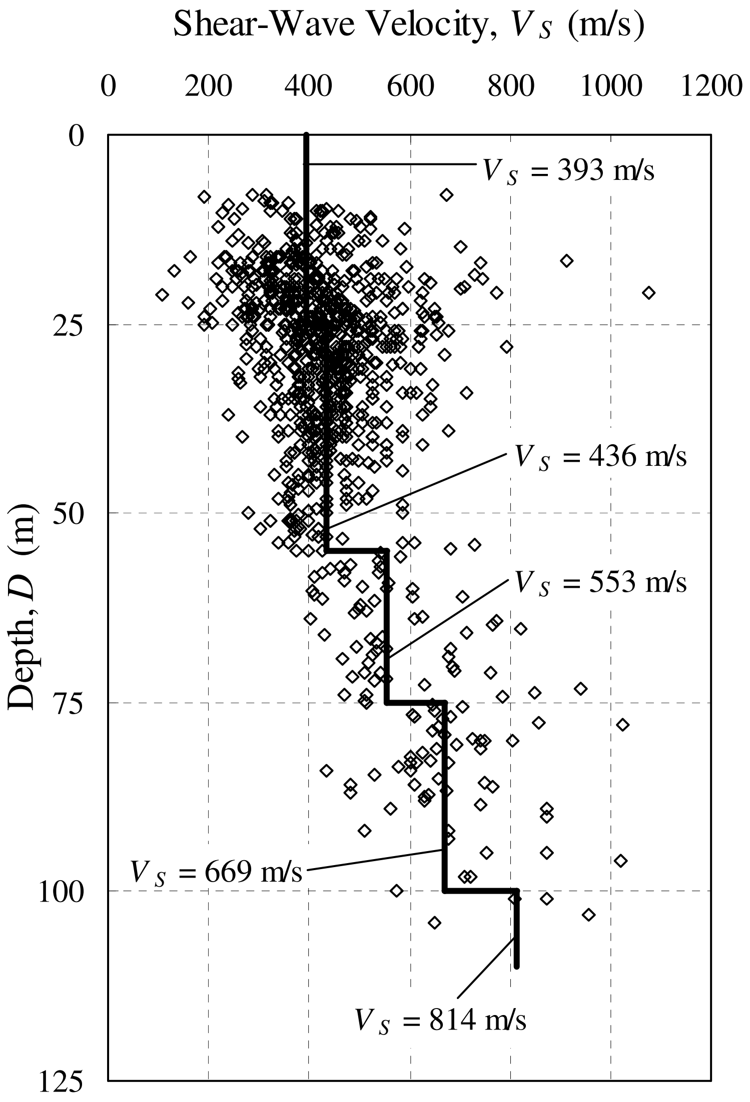

Figure 3. Compiled V_S data from Tertiary sediments.

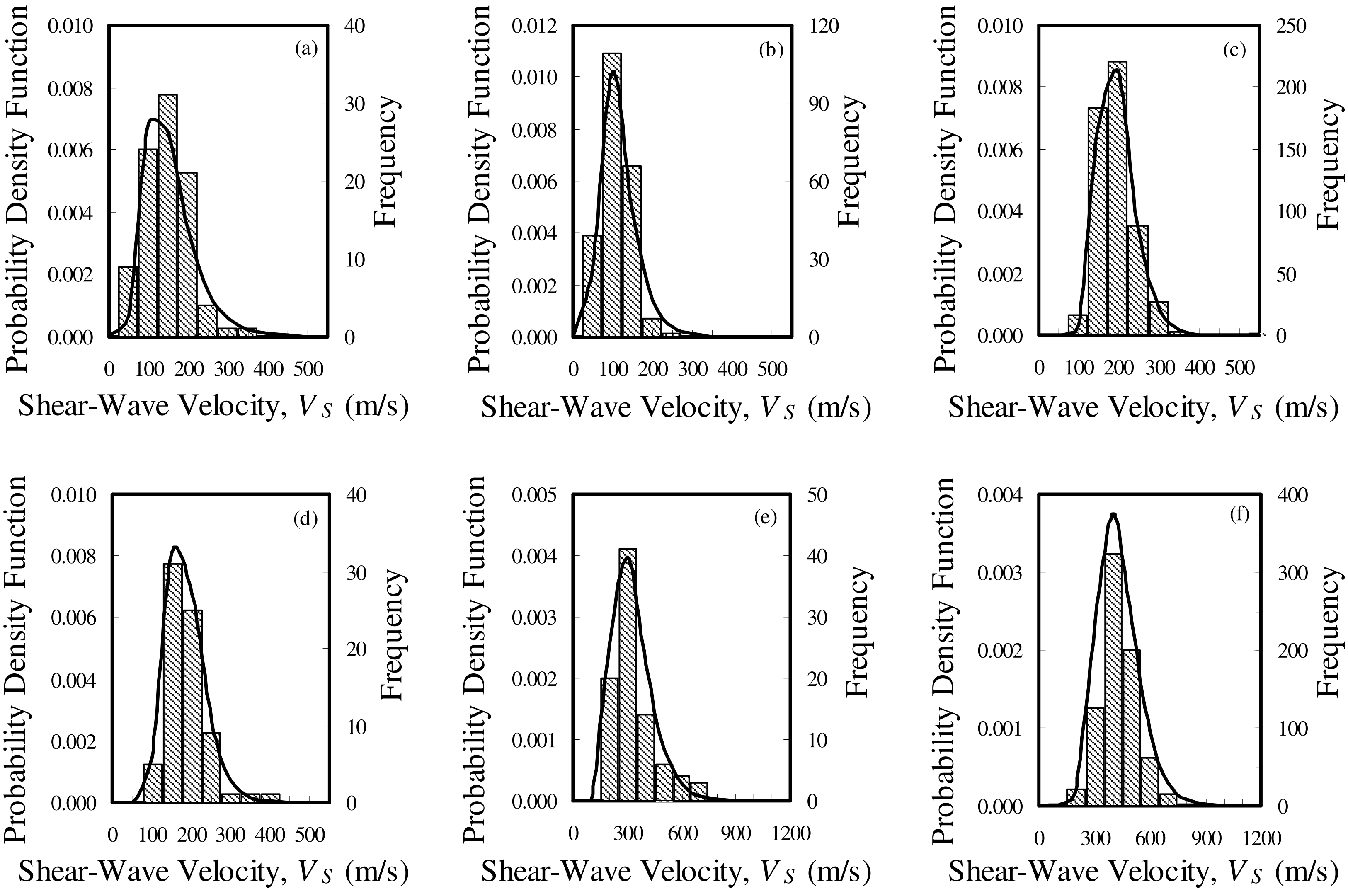

Figure 4. Statictical distribution of V_S data from top 25 m separated by geology - (a) man-made fills, (b) Holocene and late Pleistocene sediments, (c) Wando Formation, (d) Ten Mile Hill beds, (e) Penholoway Formation and Daniel Island beds, and (f) Tertiary sediments. (After Zhang 2004.)

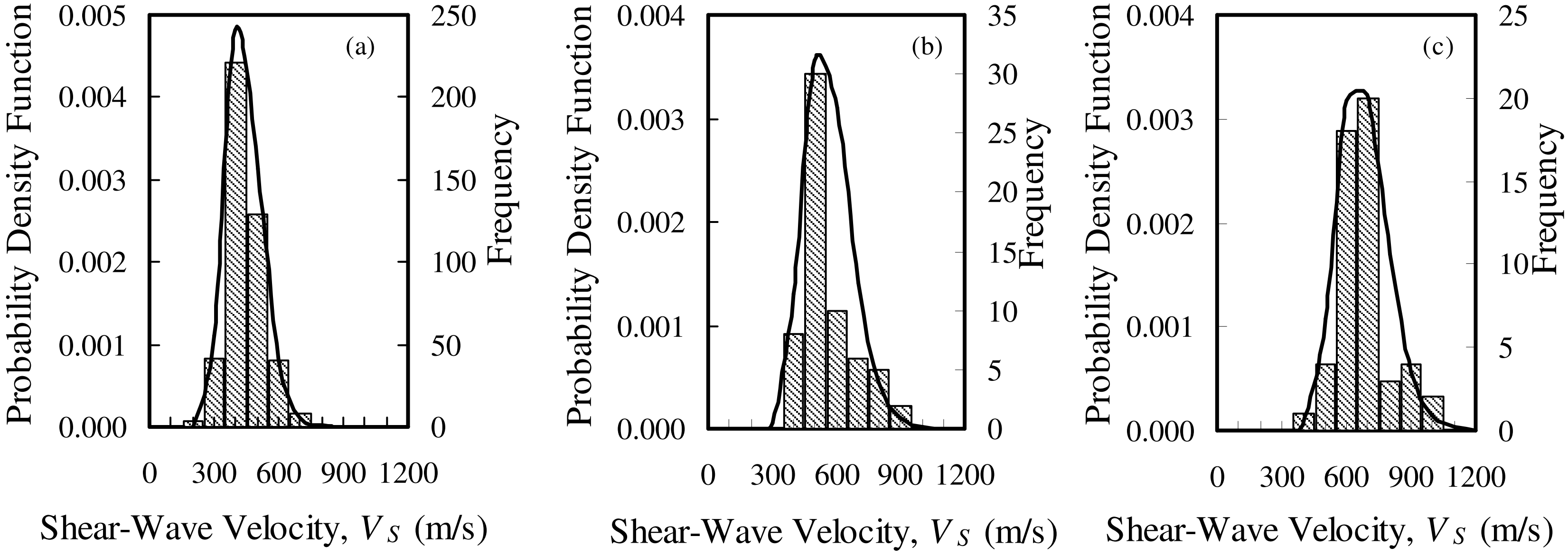

Figure 5. Statictical distribution of V_S data from depths of (a) 25 - 55 m, (b) 55 - 75 m, and (c) 75 - 100 m.

Calculated values of χ^2 for the six geologic units assuming both normal and log-normal distributions are presented in Table 1. Also presented in Table 1 are the mean values and one standard deviation ranges assuming both normal and log-normal distributions. Mean values and standard deviations for the log-normal distribution are calculated based on $Ln(V_S)$. By taking the natural logarithmic conversion of V_S values, the originally log-normally distributed data are transformed to normally distributed and corresponding parameters are obtained accordingly. Based on the χ^2 values, all V_S data sets are equally or better represented by the log-normal distribution, except for the fill data set that is better represented by the normal distribution. Because 9 of the 10 data sets are equally or better represented by the log-normal distribution that distribution is preferred in this study.

The probability density function of the log-normal distribution is given by:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Ln(x) - \mu}{\sigma} \right)^2 \right] \qquad \text{for } 0 < x < \infty \qquad (2)$$

where x is the considered variable, and μ and σ are the two parameters defining the distribution. Here the variables x is V_S, and the parameters μ and σ are mean and standard deviation values of $Ln(V_S)$, respectively. The probability density functions of V_S for the six units within the top 25 m are generated according to Equation (2) and plotted in Figs. 4(a)-4(f) to compare with the histograms. It can be seen that the plotted probability density functions match the histograms well, with the possible exception of the fill data set.

Mean values of V_S in the top 25 m based on log-normal distribution are 141 m/s, 108 m/s, 190 m/s, 178 m/s, 309 m/s and 393 m/s for the man-made fills, the Holocene and late Pleistocene deposits, the Wando Formation, the Ten Mile Hill beds, the Penholoway Formation and Daniel Island beds, and the Tertiary sediments, respectively. These mean V_S values are plotted as vertical lines in Figs. 2(a)-2(f) for the depth ranges of plotted data.

For the Tertiary sediments within the depth intervals of 25-55 m, 55-75 m, 75-100 m, and 100-110 m, mean values of V_S based on log-normal distribution are 436 m/s, 553 m/s, 670 m/s and 822 m/s, respectively. These mean V_S values are plotted as vertical lines in Figure 3.

Table 1. Chi-square test results, mean values, and standard deviation ranges for V_S measurements from six geologic units.

Geologic Unit	No. of V_S Values	Normal Distribution				Log-Normal Distribution			
		Degrees of Freedom	Total χ^2	Mean V_S (m/s)	One Standard Deviation Range of V_S (m/s)	Degrees of Freedom	Total χ^2	Mean V_S (m/s)	One Standard Deviation Range of V_S (m/s)
Man-made fills	91	4	13	152	93-205	4	33	141	95-211
Holocene and late Pleistocene	238	4	11	116	72-162	4	12	108	74-158
Wando Fm.	538	4	36	195	148-242	4	3.0	190	151-239
Ten Mile Hill beds	73	4	8.3	184	131-238	4	1.2	178	136-232
Penholoway Fm. and Daniel Island beds	88	4	20	328	202-453	4	4.5	309	221-431
Tertiary sediments									
0 – 25 m	383	4	280	417	175-660	4	23	393	288-537
>25 – 55 m	443	4	39	440	360-526	4	23	433	362-525
>55 – 75 m	61	4	20	564	445-683	4	11	553	454-637
>75 – 100 m	52	4	4.1	679	561-797	4	1.8	670	565-793
>100 – 110 m	4	3	2.3	822	691-952	3	2.3	814	689-961

It is interesting to note that mean V_S increases with age in the natural sediment deposits, with the exception of the Ten Mile Hill beds. The Ten Mile Hill beds were deposited in an environment similar to the Wando Formation, but about 100,000 years earlier. One possible explanation for lower V_S values in the Ten Mile Hill beds is that the corresponding test sites are located in north Charleston, which is closer to the 1886 epicenter and fault rupture than the test sites corresponding to the Wando Formation measurements. Greater number of liquefaction sand boils and ground failures were observed in north Charleston following the 1886 earthquake (Bollinger 1977). It is possible that the sediments closer to the 1886 energy release were so disturbed from the intense ground shaking and liquefaction that their aging clocks were reset, thus lowering the V_S values in the older Ten Mile Hill beds.

The statistical results presented above can be used to generate approximate V_S profiles for sites where only the geologic profile is known. When combined with the geologic map and cross-sections of Weems and Lemon (1993), the results provide required information to accurately assessed ground shaking hazard in the Charleston area.

SITE RESPONSE PARAMETRIC STUDY

To illustrate the effects that V_S and thickness of the Quaternary section have on seismic ground response, the dynamic response of several generalized soil/rock models typical of some locations in the Charleston quadrangle are analyzed in this section using two input ground motions.

Soil/Rock Models

Selected generalized soil/rock models considered in the parametric study are illustrated in Figures 6(a)-6(d). The models illustrated consist of 0 m, 10 m, 20 m, and 30 m of Quaternary sediment, respectively, with mean V_S values of 110 m/s or 190 m/s. Additional soil/rock models considered, but not illustrated in Figure 6, consist of 7 m, 13 m, 15 m, and 17 m of Quaternary sediment. The models with mean V_S of 110 m/s for the Quaternary section represent the range in thickness of Holocene and late Pleistocene deposits in Charleston. The models with mean V_S of 190 m/s for the Quaternary section represent the range in thickness of the Wando Formation deposits.

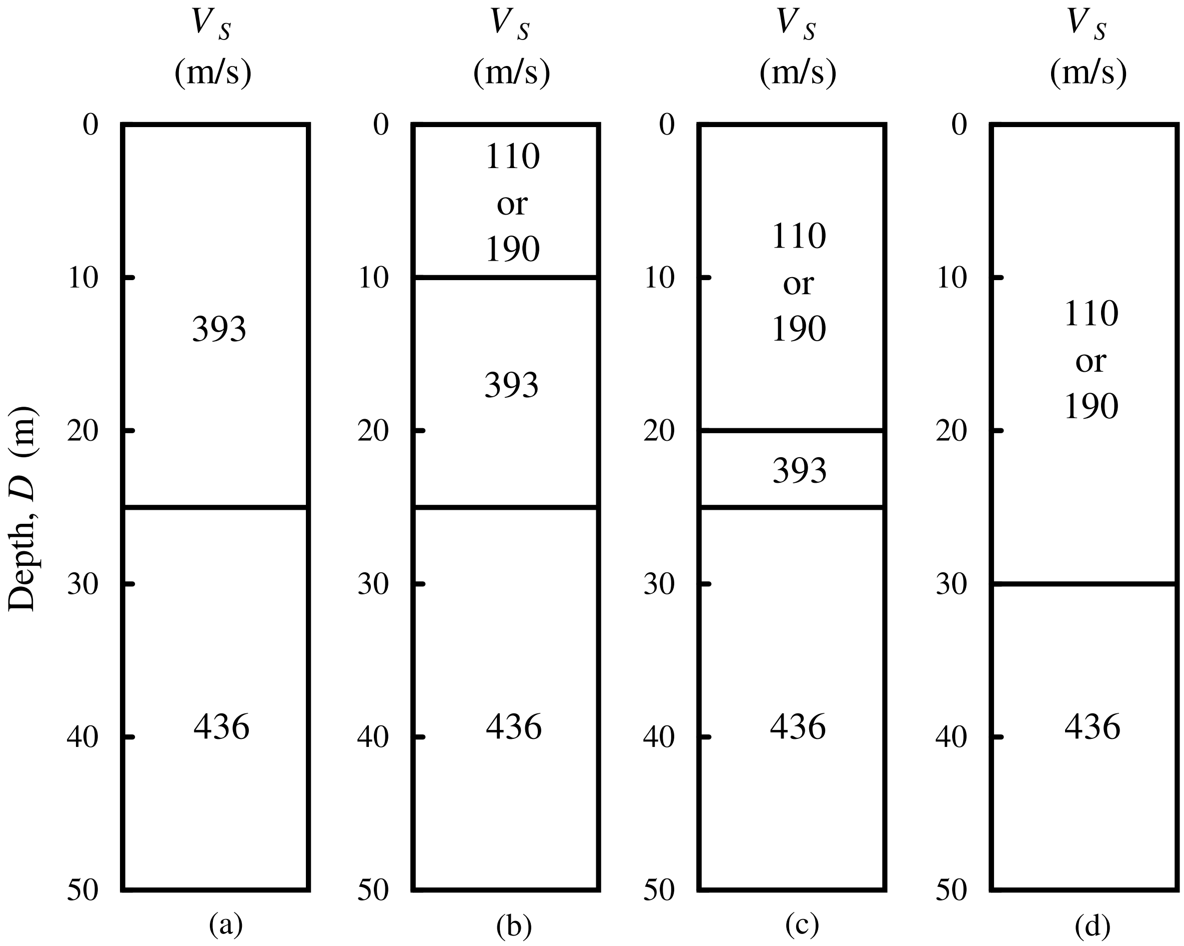

Figure 6. Velocity profiles of top 50 m used in site response parametric study, assuming thicknesses of Quaternary sediment are: (a) 0 m, (b) 10 m, (c) 20 m, and (d) 30 m.

A total of 27 soft-soil to soft-rock layers are assumed in all models analyzed. Specific engineering properties assumed for the soil/rock model with mean V_S of 190 m/s in the top 10 m are given in Table 2.

It should be noted that no direct V_S measurements are currently available below a depth of 110 m in the Charleston area. The values of V_S below a depth of 100 m given in Table 2 are based on earlier approximate models. Wheeler and Cramer (2000) suggested a linearly increasing profile from a depth of 110 m to a depth of 808 m, where V_S is 1300 m/s at 808 m. Silva et al. (2003) assumed V_S increases from about 762 m/s at 152 m to about 914 m/s at 213 m, and remains constant until a depth of 1219 m. A similar profile was assumed by Chapman et al. (2003), but a smaller constant V_S value was used for the depths between 510 m and 830 m. For this study, the deep V_S profile is assumed to increase linearly from 800 m/s at 100 m to 914 m/s at 808 m. This profile is then placed on top of pre-Cretaceous basement rock, which is represented by a uniform half-space with V_S of 3.5 km/s, as suggested by Chapman et al. (2003).

The groundwater table in Charleston is shallow, and assumed to be 1.5 m below the ground surface for mean effective stress (σ'_m) calculations. Also assumed is a coefficient of at rest earth pressures (K'_0) of 0.5 for all layers.

Normalized Shear Modulus and Material Damping Relationships

Small-strain shear-wave velocity is directly related to small-strain shear modulus (G_{max}) by:

$$G_{max} = \rho {V_S}^2 \tag{3}$$

where ρ is the mass density of soil (or total unit weight of the soil divided by the acceleration of gravity). At moderate to high strains, the secant shear modulus (G) is used to represent the average soil stiffness. It is common practice to normalize G by dividing by G_{max}. A plot of the variation of G/G_{max} with shear strain (γ) is called a normalized shear modulus reduction curve.

Table 2. Generalized soil/rock model for a selected area in Charleston, South Carolina.

Layer No.	Thickness (m)	V_S (m/s)	Total Unit Weight (kN/m^3)	σ'_m (kPa)	USCS Soil Type	G/G_{max} and D Curves Used
1	1.5	190	18.2	15	SP-SC	Quaternary, *PI*=15
2	1.5	190	18.2			
3	2.0	190	18.2	50	SP-SC	Quaternary, *PI*=15
4	2.0	190	18.2			
5	3.0	190	18.2			
6	5.0	393	18.5	150	CH	Tertiary and older, *PI*=50
7	5.0	393	18.5			
8	5.0	393	18.5			
9	5.0	436	18.5			
10	5.0	436	18.5			
11	10.0	436	18.5			
12	10.0	436	18.5	400	CL	Tertiary and older, *PI*=15
13	10.0	553	18.9			
14	10.0	553	18.9			
15	10.0	669	18.9			
16	15.0	669	18.9			
17	20.0	803	19.6	900	Limestone	Tertiary and older, *PI*=0
18	20.0	806	19.6			
19	20.0	810	19.6			
20	40.0	816	19.6			
21	40.0	823	22.5	2500	Sand	Tertiary and older, *PI*=0
22	80.0	835	22.5			
23	80.0	848	22.5			
24	100.0	864	22.5			
25	100.0	881	22.5	5000	Sand	Tertiary and older, *PI*=0
26	100.0	897	22.5			
27	108.0	914	22.5			
28	Half-space	3500	22.5	--	Rock	--

Normalized shear modulus and material damping ratio curves used in the parametric study are based on the predictive relationships developed by Zhang et al. (2005). These relationships were developed using resonant column and torsional shear test results for 8 Quaternary and 66 Tertiary and older soil specimens from primarily the South Carolina Coastal Plain. Variables used in the relationships for G/G_{max} are: shear-strain amplitude, confining stress, and plasticity index (PI). The material damping ratio (D) relationships are expressed in terms of a polynomial function of G/G_{max} plus a minimum damping ratio. The minimum damping ratio depends on confining stress and PI. In general, Quaternary soils exhibited more linearity (i.e., G/G_{max} values are closer to 1.0 at higher shear strain levels) than older soils. Soils from both age groups exhibited significant variations with confining stress, and moderate variations with PI.

Ideally, G/G_{max} and D curves would be calculated for each layer. However, this would mean having unique curves for all 27 layers and require more input data-entry time. Based on evaluations of laboratory data and analytical studies, Stokoe et al. (1995) suggested that the estimated field σ'_m should be within about ±50 % of the actual values when selecting curves for design. Therefore, the approach used in this parametric study is to divide the soil/rock models into several major units. Average values of σ'_m for each major unit are calculated and compared with σ'_m values calculated for each layer within the unit. If the σ'_m value for each layer is within ±50 % of the average value for the major unit, then the average σ'_m is assigned to all layers within the unit. Otherwise, the unit is subdivided and new average σ'_m values are calculated. According to this approach, the generalized soil/rock model can be divided into seven major units. The corresponding average σ'_m values for the seven major units are listed in Table 2.

The seven sets of G/G_{max} and D curves used to characterize the normalized shear modulus and material damping relationships for the 27 layers above pre-Cretaceous basement rock summarized in Table 2 are plotted in Figures 7 and 8, respectively.

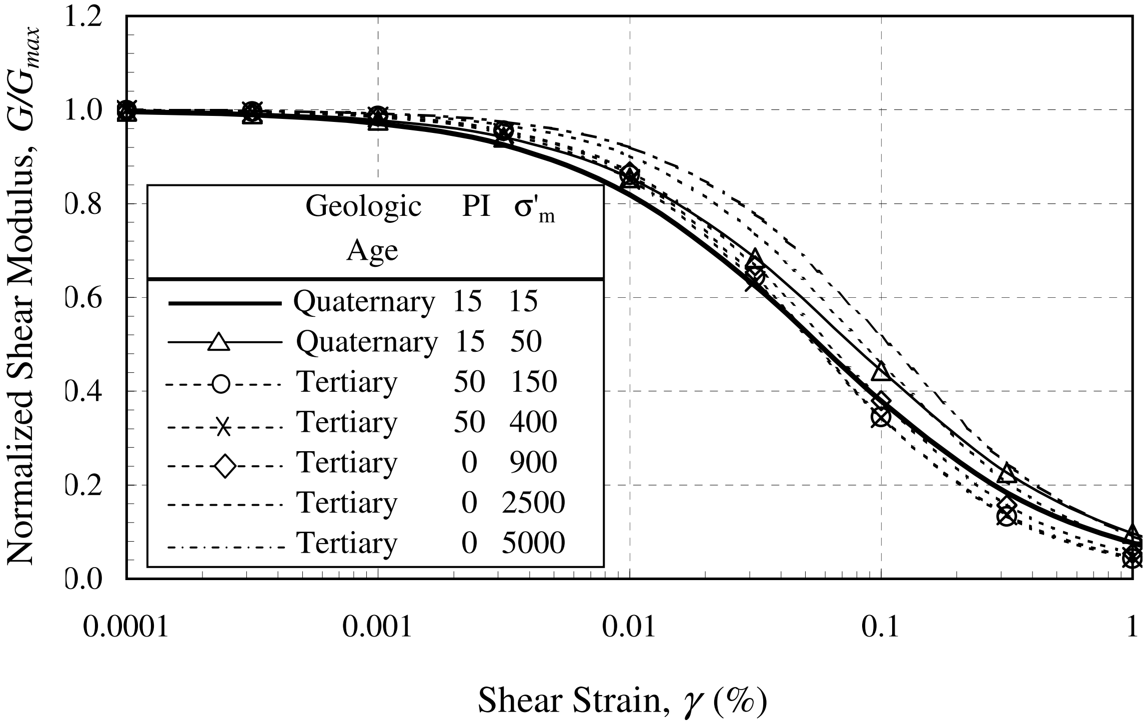

Figure 7. Selected G/G_{max} - log γ curves used in site response parametric study.

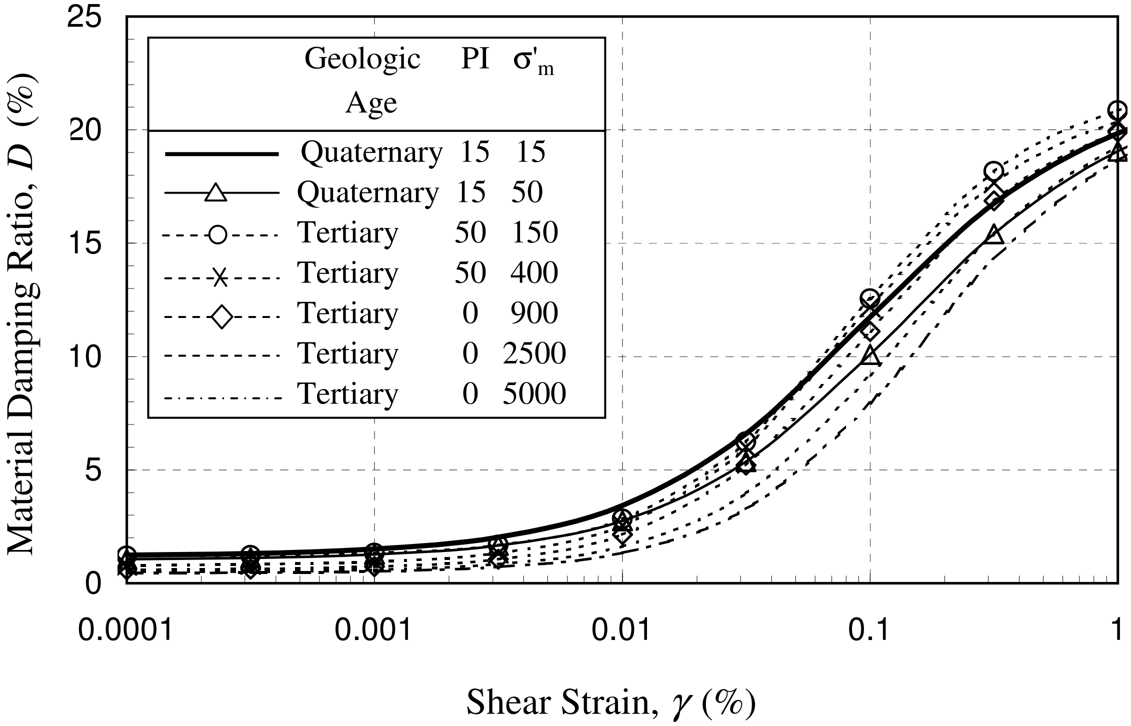

Figure 8. Selected D - log γ curves used in site response parametric study.

Input Rock Outcrop Motions

The two rock outcrop motions used in the site response parametric study are generated from a computer program provided by Dr. Martin C. Chapman of Virginia Polytechnic Institute and State University (written communication, August 2003). Dr. Chapman's program is based on a point-source stochastic model that simulates hard-rock outcrop motions for South Carolina. The specific site location (latitude = N 32.78583, longitude = W -79.93626) assumed for the motions is the intersection of King Street and Calhoun Street in downtown Charleston. Also assumed for both motions is an earthquake magnitude of 7.3, the dominant magnitude in the deaggregated seismic hazard matrix for the region.

The first rock outcrop motion is plotted in Figure 9(a), and is for a 2 % probability of exceedance in 50 years. This acceleration time history exhibits a peak value of 0.30 g. It should be noted that a peak ground acceleration of 0.30 g is significantly less than the peak of 0.83 g provided by the U.S. Geological Survey 2002 seismic hazards maps for a similar exposure time (http://eqhazmaps.usgs.gov/). The difference in peak ground accelerations provided the U.S. Geological Survey seismic hazard maps and Dr. Chapman's ground motion prediction program may be the result of different assumptions made in the development of both methods, including such factors attenuation relations, stress drop, source regions, and V_S and layering of rock. A peak ground acceleration of 0.30 g is close to the values predicted to have occurred in the old city district of Charleston during the 1886 earthquake (Silva et al. 2003), and is considered adequate for use in this parametric study.

The second rock outcrop motion is shown in Figure 9(b). It is for a 10 % probability of exceedance in 50 years. This acceleration time history exhibits a peak value of 0.08 g, which is also significantly less than the peak ground acceleration of 0.18 g provided by the U.S. Geological Survey 2002 seismic hazards maps for a similar exposure time (http://eqhazmaps.usgs.gov/). The second motion is selected to evaluate the effects of lower intensity input motion on site response.

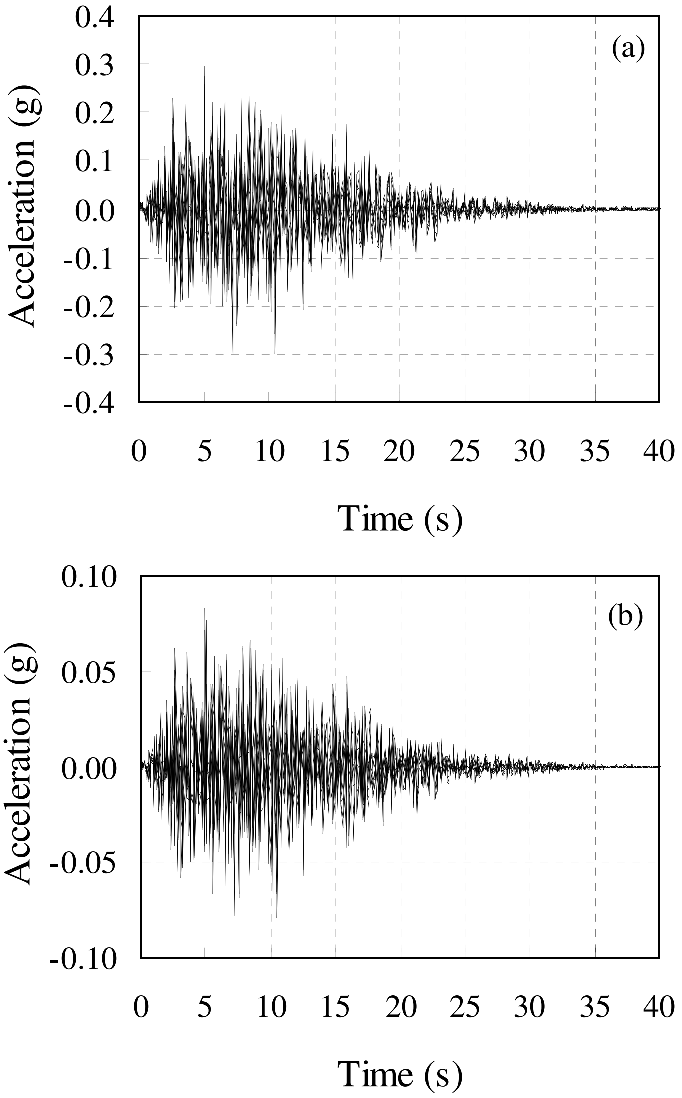

Figure 9. Input rock outcrop motions generated by Dr. Martin Chapman's program for (a) 2 % and (b) 10 % probalility of exceeding in 50.

Analysis Method

The analysis is conducted using computer program SHAKE (Schnabel et al. 1972), specifically the SHAKE91 version (Idriss and Sun 1992) with the pre and postprocessor routines of SHAKE2000 (Ordóñez 2000). SHAKE is based on the equivalent linear approach and assumes vertically propagating seismic waves. It is considered adequate for this study because the ground surface in Charleston is fairly flat, and the computed ground accelerations and shear strains computed in most of the models are < 0.4 g and < 2 %, respectively, the approximate limits suggested by Kramer and Paulsen (2004).

The computed maximum accelerations for each layer do not exceed 0.35 g in any of the soil/rock models. The computed maximum shear strains for each layer are all less than 2 %, except in layers near the base of the Quaternary section having a mean V_S of 110 m/s when shaken by the larger input motion. Maximum shear strains computed for these soft lower layers vary from 2 % to 7 %.

Results

Plotted in Figure 10 are calculated peak ground surface accelerations for the selected soil/rock models shaken by the two input motions. Peak ground accelerations for the model sites shaken by the 2 % in 50 years motion are 0.56 to 1.14 times the peak acceleration of the input rock outcrop motion, indicating deamplification of ground motions at some sites and amplification of ground motions at other sites. On the other hand, peak ground accelerations for the model sites shaken by the 10 % in 50 years motion are 1.76 to 2.91 times the peak acceleration of the input rock outcrop motion, indicating significant amplification at all model sites. These results are generally consistent with the observations of Idriss (1990), who concluded that peak accelerations at soft soil sites are likely to be greater than on rock sites at low to moderate acceleration levels (less than about 0.4 g).

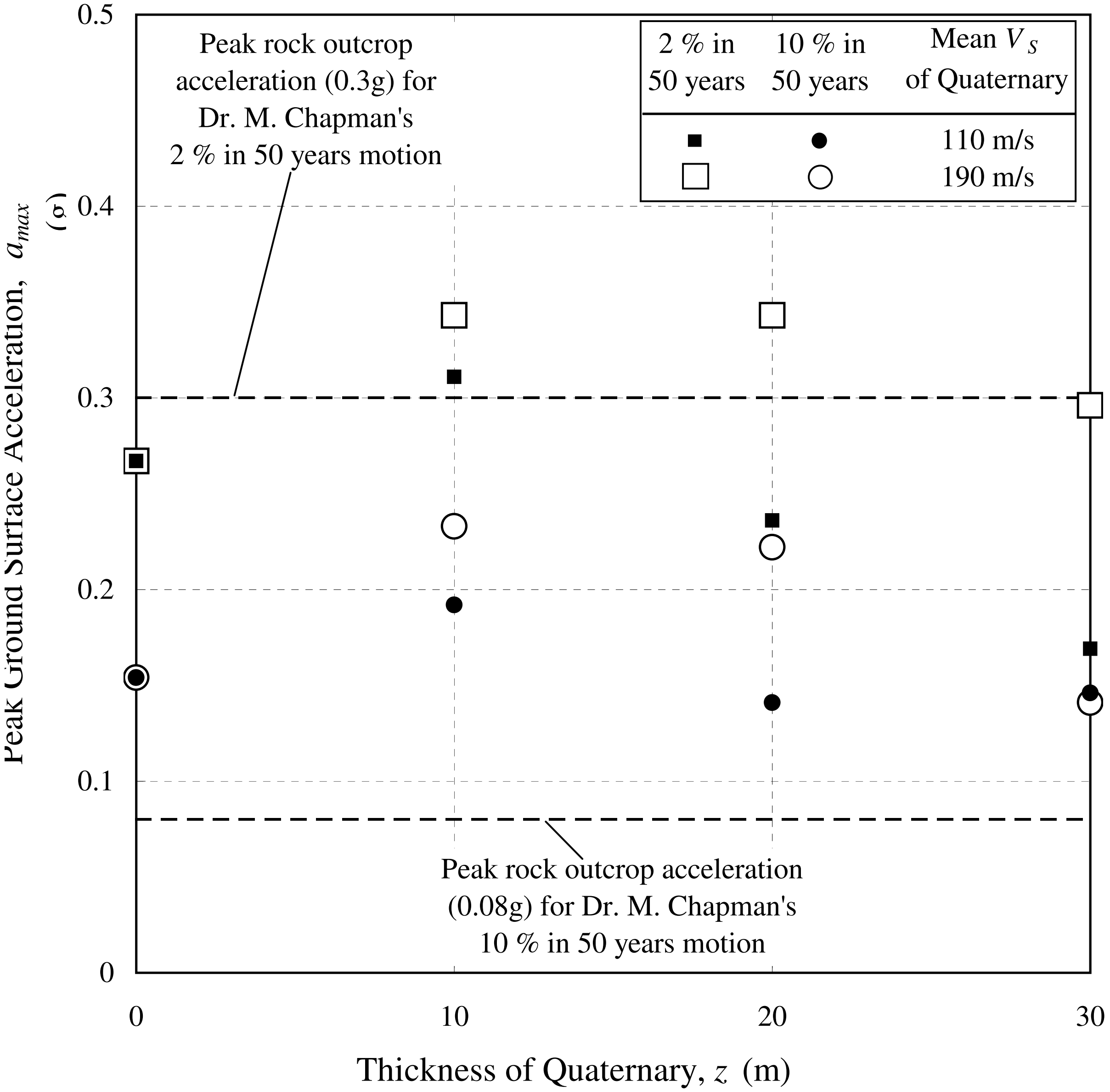

Figure 10. Comparison of input peak rock outcrop acccelerations with predicted peak ground surface accelerations.

It is interesting to note that the calculated ground surface accelerations are generally greater for sites having Quaternary sections with higher mean V_S (i.e., 190 m/s). This finding is in general agreement with the site response study conducted by Chapman et al. (2003). Chapman et al. (2003, page 17) observed that ratios of computed peak ground surface acceleration to peak rock outcrop acceleration tend to be larger (for a given input motion level) on sites with higher average V_S in the upper 30 m, and these sites tend to be sites where the depth to the Cooper Marl is small.

Acceleration response spectra for a single-degree-of-freedom structure at the ground surface determined using the 2 % in 50 years rock motion are shown in Figures 11(a) and 11(b). As can be seen in Figure 11(a), only one of the response spectra for the selected model sites with the Quaternary section having mean V_S of 110 m/s exhibits a major peak spectral acceleration above 0.8 g. The range of periods for this peak is 0.9 s to 1.5 s. This response spectrum is for the profile with 10 m of Quaternary sediment. In Figure 11(b), the response spectra for the model sites with Quaternary sediments having mean V_S of 190 m/s and thickness of 10 m, 20 m and 30 m are presented. The spectra exhibit major peaks at about 0.31 s, 0.78 s, and 1.5 s, respectively. These results illustrate the variations in predicted spectral accelerations that can occur, depending on V_S and thickness of the Quaternary section.

Shown in Figures 12(a) and 12(b) are acceleration response spectra determined using the 10 % in 50 years rock motion. None of the response spectra for the selected model sites with the Quaternary section having mean V_S of 110 m/s plotted in Figure 12(a) exhibit a pronounced resonant peak. Of the model sites with the Quaternary section having mean V_S of 190 m/s, only the response spectrum shown in Figure 12 (b) for the model with 10 m of Quaternary sediment exhibits a pronounced resonant peak. This resonant peak occurs between periods of 0.2 s and 0.35 s.

The results of this seismic response parametric study are somewhat different from the earlier study by Elton and Martin (1989). Elton and Martin (1989) estimated dynamic site periods of about 0.5 s to 1.0 s for areas in Charleston with stiffer (i.e., mean V_S of 190 m/s) Quaternary sections; and 1.0 s to over 2.0 s for areas with softer (i.e., mean V_S of 110 m/s) Quaternary sections. The differences between estimated site periods may be explained by the improved nonlinear soil properties and V_S measurements used in this study, that were not available at the time of Elton and Martin's (1989) study.

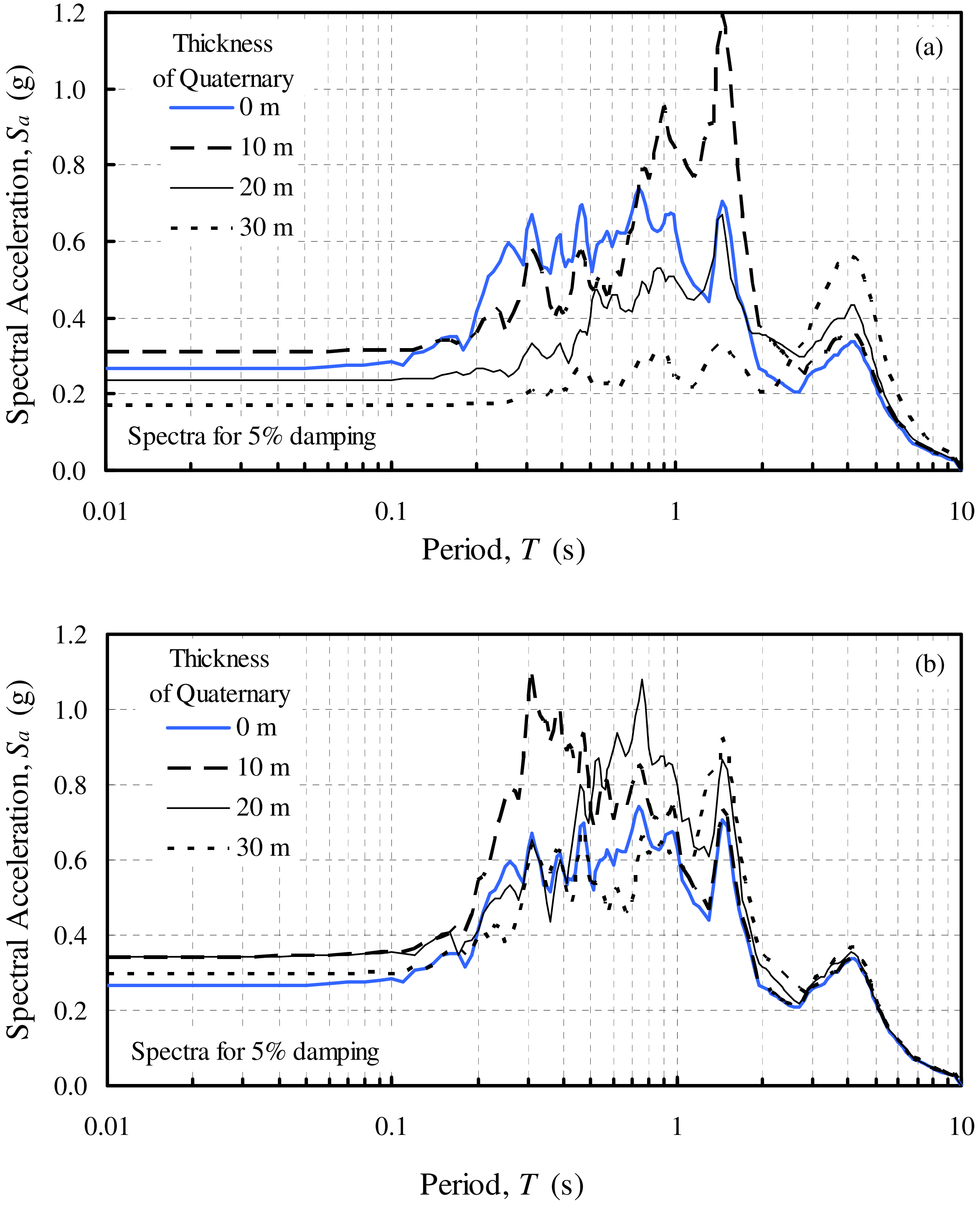

Figure 11. Variations in spectral acceleration for sites with Quaternary sediment having mean V_S of (a) 110 m/s and (b) 190 m/s shaken by Dr. Martin Chapman's 2 % in 50 years ground motion.

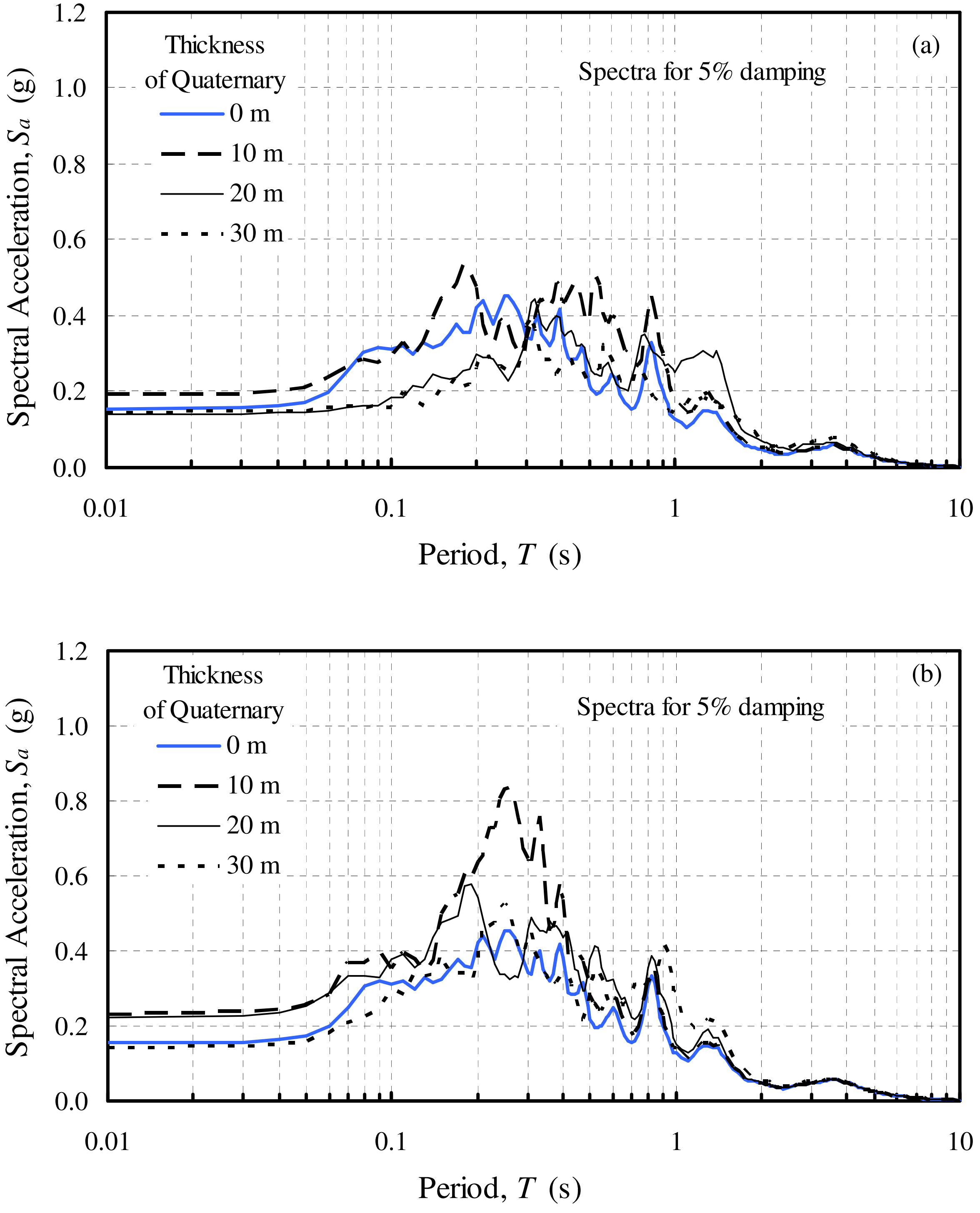

Figure 12. Variations in spectral acceleration for sites with Quaternary sediment having mean V_S of (a) 110 m/s and (b) 190 m/s shaken by Dr. Martin Chapman's 10 % in 50 years ground motion.

PRACTICAL SIGNIFICANCE

Greater building damage is expected to occur where the fundamental site period matches the fundamental building period. This condition is called “double resonance.” According to the International Code Council (ICC 2000), the approximate fundamental period of a building (T_{bldg}), in seconds, can be determined from:

$$T_{bldg} = C_T h_n^{3/4} \tag{4}$$

where C_T is the building coefficient, and h_n is the height above the base to the highest level of the building in meters.

Many of the existing buildings in the old city district of Charleston are the same ones heavily damaged during the 1886 earthquake, only repaired. They are of brick and/or wood construction. For these buildings, the ICC (2000) recommended value for C_T is 0.049. Current zoning regulations for the city restrict the height of buildings (Zoning Ordinances Section 54.306) to preserve the historic skyline of the city. For example, along King Street between Broad Street and Calhoun Street all new buildings are required to be no shorter than 9.1 m and no taller than 16.8 m (Michael J. Cain, Department of Public Services, City of Charleston, June 21, 2005). Assuming this range of heights for h_n, the estimated range of T_{bldg} for many of the historic and recent buildings in the old city district is 0.26 s to 0.41 s.

Based on T_{bldg} range of 0.26 s to 0.41 s and the results of the site response parametric study presented in the previous section, double resonance is predicted to occur where the Quaternary section has mean V_S around 190 m/s and thicknesses between about 7 m and 15 m (see Figure (11b)). These Quaternary sections are typical of the slightly higher ground in Charleston where surficial sediments are of the Wando Formation. The prediction of double resonance occurring at sites where surficial sediments are the Wando Formation is supported by damage that occurred in 1886. Some of the greatest structural damage observed occurred in the three- and four-story brick masonry buildings constructed on the Wando Formation in the commercial district of Charleston (e.g., Dutton 1889; Robinson and Talwani 1983; Lindbergh 1986; Peters and Herrman 1986). Thus, the results of the seismic response parametric study provide strong evidence that local site conditions and double resonance were contributing factors to building damage in the 1886 earthquake.

CONCLUSIONS

Using in situ V_S measurements from 91 test sites in the greater Charleston area, the stiffness of six major geologic units are characterized. The six major geologic units are: 1) man-made fills; 2) Holocene and late Pleistocene deposits; 3) the Wando Formation; 4) the Ten Mile Hill beds; 5) the Penholoway Formation and Daniel Island beds; and 6) Tertiary sediments. Values of V_S for each unit are found to be equally or better modeled by the log-normal distribution than by the normal distribution, except for the V_S values from the fills that are better modeled by the normal distribution. In addition, it is found that the V_S values from the top 25 m separated by geology exhibit little or no depth dependencies, when the data are considered as a whole.

Assuming log-normal distributions and no depth dependencies, calculated mean V_S values in the top 25 m for the six geologic units are 141 m/s, 108 m/s, 190 m/s, 178 m/s, 309 m/s and 393 m/s, respectively. For the Tertiary sediments in the depth intervals of 25-55 m, 55-75 m and 75-100 m, calculated mean V_S values are 433 m/s, 553 m/s, and 670 m/s, respectively. The results indicate that mean V_S generally increases with age in the natural sediments, with the exception of the Ten Mile Hill beds. One possible explanation for the somewhat lower V_S values is in the Ten Mile Hill beds is that test sites used to characterize this unit are located closer to the 1886 fault rupture where greater shaking and soil disturbance occurred.

To evaluate the effects that V_S and thickness of the Quaternary section have on spectral accelerations, a seismic response parametric study is conducted assuming several generalized soil/rock profiles and two input ground motions. Fundamental site periods of 0.31 s, 0.78 s, and 1.5 s are determined for the profiles with Quaternary sections with mean V_S of 190 m/s and thickness of 10 m, 20 m, and 30 m, respectively, using an input ground motion with peak acceleration of 0.3 g. These fundamental site periods are somewhat lower than periods of 0.5 s to 1.0 s predicted by Elton and Martin (1989). The improved nonlinear soil properties and V_S measurements used in this study may explain the difference between predicted fundamental site periods.

Many of the historic and new buildings in the old city district of Charleston have fundamental periods between about 0.26 s and 0.41 s. At locations where site periods match these building periods, greater intensity shaken and damage occurred in 1886 and is expected to occur in future earthquakes. The double resonance condition commonly exists in areas where surficial sediments are of the Wando Formation and buildings are three and four stories high.

When combined with available 1:24,000 geologic cross-sections, the results can be used to develop generalized cross-sections of V_S of the Charleston area. Additional work is needed to better characterize V_S of the sediment facies within and to delineate the lateral extent of the six major geologic units.

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APPENDIX

COMPACT DISK WITH ELECTRONIC COPIES OF THE FINAL REPORT, THE PAPER BY ZHANG ET AL. (2004), AND THE DATA REPORT BY FAIRBANKS ET AL. (2004)