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PREDICTION AND GEOGRAPHICAL INFORMATION SYSTEM (GIS) MAPPING OF GROUND MOTIONS AND SITE RESPONSE IN CHARLESTON, SC AND TWO NEIGHBORING COUNTIES: FIRST PHASE DEVELOPMENT OF A GIS FOR SEISMIC HAZARD EVALUATION

Final Report, June 12, 2003

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TECHNICAL ABSTRACT

This study estimates the response of near-surface geologic units in the Charleston area to strong ground motion, and produces results in a GIS coverage. The study area is approximately 1650 km^2 in extent, and includes portions of Charleston, Dorchester and Berkeley counties, south of latitude 33.0N latitude and between 80.25W and 79.75W longitude. The main area of interest is within a 20 km radius of the city of Charleston. Geologic mapping by the U.S. Geological Survey is used to characterize the geologic units of the area. The data used for dynamic site response analysis consists of 281 standard penetration tests and cone penetrometer tests. Direct shear wave velocity measurements at 52 locations from seismic cone penetrometer tests are included. Regression models are developed for shear wave velocity as a function of cone penetrometer tip resistance, effective overburden pressure and lithology. Site specific response is quantified using non-linear dynamic analysis in terms of the ratio of soil surface motion to hypothetical hard rock (pre-Cretaceous) basement outcrop motion. Absolute acceleration response ratios for 5% oscillator damping are computed for 12 oscillator frequencies ranging from 0.1 to 30 Hz and for peak ground acceleration. Scenario earthquake basement motions were developed using the stochastic model. The results of the dynamic analysis are examined for correlation and dependence upon mapped geology and shallow geologic structure. The input data and results are cast as a geographic information system coverage using the ArcGIS software application available from Environmental Systems Research Institute, Inc., Redlands, California.

INTRODUCTION

The city of Charleston, South Carolina and the surrounding area experienced severe damage from a magnitude 7+ earthquake in 1886 (Johnston, 1996). Paleoseismic investigations have shown evidence for several prehistoric liquefaction inducing earthquakes in coastal South Carolina in the last 6000 years (Talwani and Schaeffer, 2001). Ground motion in the future will be influenced by shallow geological conditions. Charleston is situated upon approximately 800 meters of Cretaceous and younger sediments. The Tertiary and Cretaceous sediments are compacted and weakly lithified. Near-surface materials are unconsolidated Quaternary marine and estuarine sands and clays that have low strength and are likely to experience significant non-linear behavior under strong motion.

This study examines the response of near-surface geologic units in the Charleston area to strong ground motion. The study area is approximately 1650 km^2 in extent, and includes portions of Charleston, Dorchester and Berkeley counties, south of latitude 33.0N latitude and between 80.25W and 79.75W longitude. The main area of interest is within a 20 km radius of the city of Charleston.

The study uses previous geologic mapping by the U.S. Geological Survey to characterize the geologic units exposed at the surface. Local engineering firms generously provided geotechnical data consisting of 281 standard penetration tests and cone penetrometer tests. Direct shear wave velocity measurements at 52 locations from seismic cone penetrometer tests are included. Shear wave velocity measurements made in conjunction with testing for new bridge construction at two locations were also provided to us. The suspension log data provide important constraints on shear wave velocity in the depth range 25 to 100 meters in the Tertiary units underlying the study area.

The geotechnical data are used to develop layered soil models for non-linear dynamic analysis. The lithology is taken directly from the standard penetration test (SPT) logs or inferred from the cone penetration test (CPT) results. The shear wave velocity measurements from the 52 seismic cone penetrometer tests (SCPT) are used to develop regression models for shear wave velocity as a function of cone penetrometer tip resistance, effective overburden pressure and lithology. Shear wave velocity models for the SPT sites are derived indirectly, using the regression models and estimates of the mean ratio of CPT tip resistance to SPT blowcounts.

The response at each of the geotechnical exploration sites is calculated using an equivalent linear algorithm implemented by the program SHAKE (Schnabel et al. 1972).

The site specific response is quantified in terms of the ratio of soil surface motion to hypothetical hard rock (pre-Cretaceous) basement outcrop motion. Absolute acceleration response ratios for 5% oscillator damping are computed for 12 oscillator frequencies ranging from 0.1 to 30 Hz and for peak ground acceleration. Scenario earthquake motions for the basement input were developed using the stochastic model. For each site, a series of 20 simulations were made for each of 6 reference basement rock outcrop input motion amplitude levels. The six levels are 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 g peak ground acceleration. The mean site response for a give oscillator frequency is estimated from the mean of the 20 simulations, for each input motion level.

The results of the dynamic analysis are examined for correlation and dependence upon mapped geology and shallow geologic structure. The input data and results are cast in a geographic information system format using the ArcGIS software application available from Environmental Systems Research Institute, Inc., Redlands, California (URL: www.esri.com).

GEOLOGY OF THE STUDY AREA

The study area is within the outer Atlantic Coastal Plain geologic province. This is a seaward thickening wedge of Cretaceous and younger sediments that is approximately 800-850 m thick in the study area. The section consists of unlithified sediments interbedded with weakly lithified units. Units exposed at the surface in the study area include marine, marginal-marine and fluvial-estuarine sediments, ranging in age from Oligocene to Holocene. Most of the surface exposure in the study area is comprised of Pleistocene to Holocene sands and clays, along with artificial fill and spoil. Tertiary units are exposed in small areas in the north and northwest sections of the study area, primarily along stream banks.

Figure 1 is a geologic map of the study area. Table 1 gives a brief description of the Tertiary and Quaternary units present at the surface and in the shallow subsurface. The following discussion is taken from the work of Weems and Lemon (1993, 1988, 1984), McCartan et al. 1984 and Weems et al. 1997. The reader is referred to the extensive work of those authors for detailed descriptions of lithology, geologic profiles and discussion of the geologic history of the study area.

Tertiary Units in the Shallow Subsurface

Tertiary units at shallow depths in the study area are well compacted and in some cases partially lithified. The oldest Tertiary units commonly encountered in geotechnical borings in the shallow subsurface are impermeable limestones of the Cooper Group, which includes the Eocene Parkers Ferry and overlying Oligocene Ashley formations. The Parker's Ferry is not exposed at the surface in the study area, although both it and the Ashley are ubiquitous in the subsurface. It is a dense, sticky lime mudstone. The Ashley formation is a tough phosphatic calcarenite. It is an important unit for foundation embedment of major construction in the study area. It is resistant to erosion and is exposed in the northwestern section of the study area along stream banks in the Ladson and Stallsville quadrangles. The overlying Oligocene Chandlers' Bridge formation is a phosphatic sand that is easily eroded: exposures are sparse. The Pliocene Goose Creek Limestone is a generally soft calcarenite that is easily eroded, with only very minor exposure in the study area.

Quaternary Units

Quaternary deposits are easily eroded unconsolidated sediments deposited in back barrier lagoon, beach-barrier island and shallow marine environments during interglacial high sea-level stands. Five regional Pleistocene beach terrace complexes have been recognized in the South Carolina Coastal Plain. Because of broad crustal uplift during the Quaternary, portions of 4 Pleistocene inter-glacial beach complexes are preserved in the study area, along with the Holocene beach terrace. Younger beach and lagoon deposits generally lie adjacent to the next older terrace deposits, and at lower elevations. Geologic map units and formation definition is largely according to individual terrace complex. The formations have been generally divided and mapped according to 3 facies: fluvial-estuary, beach-barrier island, and marine shelf environments (see, for example, Weems and Lemon, 1988).

The thickness of the Quaternary units in the study area is highly variable, and the units are discontinuous in the subsurface, due to complex spatial variation of depositional environment (e.g., paleochannels, barrier island morphology) as well as post-depositional erosion. Quaternary units exposed at the surface and mapped in the study area include the Penholoway and Ladson formations, the Ten Mile Hill beds, the Wando formation and the Silver Bluff beds.

The Penholoway formation is exposed at the surface and is present in the subsurface only in a small area near the northwestern limit of the study area. This formation forms the Penholoway terrace to the northwest of the study area, with age between 0.75 and 1.25 million years. The Penholoway units in the study area are poorly consolidated, and easily eroded. The beach-barrier island, fluvial-estuarine and shallow marine shelf facies are represented by Qps,Qpc, and Qpf, respectively, in Figure 1 and Table 1.

The Ladson formation underlies the Upper Talbot terrace with age approximately 0.75 to 0.25 million years. The surface exposure and subsurface extent of these units is in the northwestern section of the study area. The mapped facies are indicated by Qls, Qlc and Qpf in Figure 1 and Table 1. Ladson units Qls and Qlc exposed at the surface overlie Penholoway shelf facies units (Qpf) in the subsurface near the northwestern boundary of the study area in the Stallsville and Ladson quadrangles (Weems and Lemon, 1984). Like the Penholoway beds, the Ladson units are easily eroded, unconsolidated sands, clayey sands and clays (Table 1).

The Ten Mile Hill beds form the Lower Talbot terrace in the study area, and were deposited approximately 200 to 240 thousand years ago (0.2 to 0.24 m.a.). Ten Mile Hill beds are exposed at the surface in a belt trending northeasterly across the study area. Generally the fluvial and estuarine facies (Qtc) comprised of clays and clayey sands occurs in the northwestern part of this belt, whereas the beach-barrier island facies (Qts) comprised primarily of extremely well sorted quartz sand is found along the southeastern portion of the belt. The shallow marine shelf facies (fine-grained, fossiliferous and bioturbated sands) are present beneath the southeastern margin of the outcrop belt of the barrier island facies, and in the subsurface slightly further to the southeast beneath the overlying younger beds of the Wando formation which form the next younger (seaward) terrace complex. The clean, well-sorted sands of the beach-barrier island facies (Qtc) near Ten Mile Hill (Charleston airport) exhibited extensive liquefaction during the 1886 earthquake.

The Wando formation forms the Pamlico and Princess Anne terraces in the study area, and is 70 to 130 thousand years old. Three units of the Wando are mapped on the surface. The Qwc unit shown in Figure 1 and listed in Table 1 is the fluvial-estuarine clayey-sand and clay facies, and is exposed at the surface in several areas. Two units marking beach-barrier island facies are mapped: Qws and Qwls. These two sand units are very similar, and are made up of essentially unweathered clean quartz sand to clayey-sands. They cover extensive areas of the Charleston peninsula, James Island, and Mount Pleasant areas. The two units (Qws and Qwls) mark two separate high sea level stands during Wando time. The corresponding fossiliferous shelf sand facies (Qwlf) is in the subsurface in the study area, and is exposed only in a very small area of the northeastern part of the study area. The beach-barrier island sand units of the Wando (Qws and Qwls) experienced liquefaction during the 1886 earthquake.

The Silver Bluff beds form the Silver Bluff terrace (adjacent to the modern beach terrace), and are between 33 and 85 thousand years old. Two facies are mapped in the study area. Estuarine deposits (Qsbc) are silty to sandy clay and clayey sands. The Silver Bluff estuarine deposits are found primarily to the northeast of the Charleston peninsula in the study area, and overlie sandy units of the Wando formation (Qwc, Qwlc).The beach-barrier island facies (Qsbs) to the southeast of the estuarine outcrop is mostly fine-grained quartz sand, but with a small course-grained fraction. Exposures of this facies are found in small patches on Charleston peninsula, James Island, and to the southeast of the Wando units exposed in Mount Pleasant and elsewhere on the Fort Moultrie quadrangle.

Holocene Units

Freshwater stream and swamp deposits (Qhm) of late Pleistocene to Holocene age consist of peat and muck, and are modern to 34 thousand years old. These units are exposed at the surface mostly in small rounded depressions on Ten Mile Hill and Wando depositional surfaces.

Tidal-marsh deposits (Qht) with ages less than 10,000 years are found in extensive areas adjacent to the Ashley and Cooper rivers, and in other low-lying areas between the younger beach terraces. These deposits are clayey sands and clays. They are soft and organic rich, and they support marsh grass.

Holocene alluvium (Qal) consisting mostly of sands is mapped in small areas throughout the study area.

Holocene beach and barrier island deposits (Qhs), consisting of well-sorted quartz sand, fine grained, and light grey in color, form the modern coastal beach complex.

Artificial Fill (af) is represented by sands and clays of diverse origin and used for dams, roads, and landfill. It is less than 300 years old.

Phosphate rich spoil from mining operations is indicated by (ps). Deposits are located to the northwest of Charleston in the vicinity of the Ashley River.

Table 1

Description of Shallow Geologic Units

Unit	**Description***
Qal	Holocene alluvium: sands in drainages.
Qhm	Pleistocene to Holocene freshwater stream and swamp deposits. Thin deposits of peat and muck.
Qhs	Holocene beach and barrier island deposits. Fine grained, well-sorted quartz sand.
Qht	Holocene tidal marsh deposits. Clayey sand and clay, organic rich.
Qsbc	Pleistocene (33-85 ka) Silver Bluff beds. Estuarine deposits, silty to sandy clay and quartz sand.
Qsbs	Pleistocene (35-85 ka) beach and barrier island deposits. Fine-grained with minor course-grained fraction.
Qwc	Pleistocene Wando formation (70-130 ka). Estuarine facies. Clayey sand and clay.
Qws, Qwls	Pleistocene Wando formation (70-130 ka) Beach-barrier island facies. Quartz sand, fine-grained.
Qwlf	Pleistocene Wando formation (70-130 ka) fossiliferous shelf-sand facies, quartz sand, fine to medium grained, phosphatic, bioturbated. Up to 4.5 m thick, and present only in the subsurface.
Qtc	Pleistocene (200-240 ka) Ten Mile Hill beds (informal) clayey sand and clay, fluvial and estuarine deposits. Up to 20 m thick.
Qts	Pleistocene (200-240 ka) Ten Mile Hill Beds (informal) beach and barrier island deposits, fine to medium grained quartz sand. Up to 15m thick.
Qtf	Pleistocene (200-240 ka) Ten Mile Hill beds (informal) fossiliferous sand facies, fine to medium grained, up to 10 m thick. Present in subsurface: exposure limited to stream banks in North Charleston area.
Qlc	Pleistocene (0.25-0.75 ma) Ladson formation, fluvial-estuarine facies. Medium grained, poorly sorted clayey-sands, and clays. Up to 6 m thick.
Qls	Pleistocene (0.25-0.75 ma) Ladson formation, barrier sand facies. Quartz sand, course-grained and poorly sorted. Up to 6 m thick.

Table 1, continued

Description of Shallow Geologic Units

Unit	**Description***
Qlf	Pleistocene (0.25-0.75 ma) Ladson formation, fossiliferous shelf-sand facies. Quartz sand, medium to fine grained, well-sorted, phosphatic, bioturbated. Unit exposed only west of Dorchester Creek and north of Ashley river in northwest section of study area. Up to 5 m thick
Qpc	Pleistocene (0.75-1.25 ma) Penholoway formation, fluvial-estuarine clayey sand and clay facies. Exposed in northwest section of study area. Up to 4m thick.
Qps	Pleistocene (0.75-1.25 ma) Penholoway formation, barrier sand facies. Quartz sand, medium to course grained. Present only in a tiny area in northwest section of study area.
Qpf	Pleistocene (0.75-1.25 ma) Penholoway formation, fossiliferous shelf-sand facies. Fine to medium grained, phosphatic, bioturbated quartz sand. Exposed in northwest section of study area. Up to 12m thick.
Tgc	Pliocene (3.5 my) Goose Creek Limestone. Quartzose and phosphatic calcarenite. Exposed along an unnamed creek bank in the northern section of the study area. Probably less than 3 m thick.
Tcb	Oligocene (28 ma) Chandler Bridge formation. Quartz phosphate sand, very fine to fine grained. Unconformable contact with underlying Ashley formation. Up to 5 m thick. Sparse exposures in stream banks in northwest section of study area.
Ta	Oligocene (30 ma) Ashley formation of Cooper Group. Massive, very fine to fine-grained erosion resistant calcarenite. Exposed in northwest section of study area. Up to 30 m thick.

* Adapted from Weems and Lemon (1993, 1988, 1984), McCartan et al. 1984 and Weems et al. 1997.

VELOCITY MEASUREMENTS

Shallow shear wave velocity measurements at 52 locations were provided by engineering firms in the Charleston, SC area. These measurements were made in the course of seismic cone penetrometer tests (SCPT) for a variety engineering projects. The velocities were measured using a seismic cone transducer. The source for shear waves was at the surface, typically consisting of a horizontal hammer blow applied to the end of a heavy beam anchored to the ground. Shear wave velocity was typically determined at 1 m intervals. Figure 1 shows as red dots the locations of the shallow velocity measurements from the seismic cone penetrometer tests. Forty-six of the profile locations lie outside the Charleston peninsula in figure 1. Only 6 velocity profiles are available for the downtown area. The remaining data points shown in figure 1 for the downtown

Charleston area represent 204 standard penetration tests (SPT) and 6 cone penetration tests without shear wave measurements (CPT).

The majority of the shallow velocity profiles were made to the depth at which the cone encountered the stiff calcarenite unit of the Tertiary (late Oligocene) Ashley formation, locally referred to as the “Cooper marl.” The median maximum depth of the 52 shear wave velocity profiles is 16 m. Twenty-five percent of the profiles terminated at depths less than 10 m, whereas 25% terminated at depths greater than 19m.

Figure 2 shows the minimum, median and maximum interpreted layer shear wave velocities as a function of depth derived from the 52 shallow velocity investigations. The increase in median velocity beginning at a depth of approximately 10 m in figure 2 is due to the velocity increase associated with the transition from soft Quaternary deposits to stiffer deposits of Tertiary age, in particular, the upper Oligocene Ashley formation of the Cooper Group. The depth to this calcarenite varies across the study area. Individual interval velocity profiles typically exhibit a marked velocity increase upon encountering this unit. The apparent smooth increase in the median velocity vs. depth profile shown in figure 2 largely reflects the variable depth to this unit at the different test sites.

Non-linear dynamic analysis requires the specification of lithology, principally a distinction between clay and sand in the sub-surface. We interpreted the shear wave velocity and CPT data provided by the engineering firms in terms of a layered structure using standard geotechnical procedures (e.g., Campanella et al., 1995, Lunne et al., 1997). For example, Figure 3 shows CPT logs and velocities derived for a site in Mt. Pleasant, SC. The cone tip resistance tends to be high for sands and low for clays. Conversely, the friction ratio FR (sleeve friction divided by tip resistance) typically exhibits low values for sands and high values for clays. The pore water pressure and pore pressure ratio are important diagnostics in the study area. The pore pressures are generally higher for clays than sands. The calcarenites of the Cooper Group, in particular the Ashley formation, usually exhibit higher pressures and pressure ratios than typical clays. This behavior, along with an increase in shear wave velocity, characterizes that unit. In Figure 3, we distinguish the sands from clays at shallow depths on the basis of opposing values of tip resistance and friction ratio. Below the water table, at about 3 m in figure 3, the pore pressure is an additional diagnostic with high values indicating clays. The jump in pore pressure and shear wave velocity at approximately 12m is interpreted as the top of the Ashley formation, or “Cooper marl".

Shear Wave Velocities in Tertiary and Older Sediments

Shear wave velocity measurements in the depth range from 17 to 105 meters were made available from investigations using the suspension logging technique. These investigations were made for the new Arthur Ravenel Bridge which will connect the cities of Charleston and Mt. Pleasant along U. S. Highway 17. A suspension log was also made available from the site investigations for the Maybank Highway Bridge replacement project, which connects Charleston to John's Island across the Stono River. Those data provide important information on the shear wave velocity in Tertiary units of the Cooper Group at depths not sampled by the routine shallow geotechnical investigations which comprise the bulk of our data set.

Figure 4 shows the velocity profiles obtained at the Ravenel Bridge site. One profile was obtained at the location of the main pier, in the Cooper River. Another profile was made at the eastern approach to the bridge, near the bank of the Cooper River in Mt. Pleasant. The profiles at the Ravenel Bridge are approximately 0.5 km apart, and show gross similarities, but the velocities differ substantially in detail.

The Maybank Highway profile was located on the opposite (western) side of the Charleston Peninsula. It shows lower velocities in the depth range from 20 to 60 m. The velocity logs at the bridge sites differ in detail, but all exhibit a substantial, systematic increase in velocity from approximately 350 m/s at 50 m to approximately 700 m/s at 100m.

It was necessary to develop a scheme to systematically estimate continuous layered velocity versus depth profiles for each of the 281 sites considered in this study. Only two profiles in the entire data set have continuous S wave velocity logs from the surface to 100 m (Figure 4). Interpolation for the remaining data presents a difficulty, and is uncertain because the 3 deep profiles at the bridge sites demonstrate substantial lateral variability in the velocity profiles at depths between 20 and 100 m. Also, the shear wave velocities from 100 m to the top of the Mesozoic basement at approximately 830 m are not measured from down hole methods.

We have adopted the velocity log from the main pier of the Ravenel Bridge as the "standard" model for the study area for the depth range 20 to 100 m. In cases where the site-specific shallow velocity measurements (or other geotechnical data used to indirectly infer velocity) terminated at a depth of less than 20 m, the intervening data gap was spanned by introducing 5 additional model layers. The velocities of these intervening layers were assigned by linear interpolation between the deepest site-specific velocity determination and that corresponding to the top of the bridge site suspension log profile (424 m/s at 20 m). In the remaining cases where site specific velocity information was available to depths exceeding 20 m, we simply introduced an abrupt transition between the deepest site-specific measurement and the velocity at the same depth from the suspension logs. Examples of both situations are illustrated in Figure 5.

The shear wave velocity profile in the study area for depths greater than 100 meters was inferred from the P wave velocity log determined in the Clubhouse Crossroads core hole, located approximately 40 km to the west of Charleston (Gohn, 1983). Average P wave velocities in the coastal plain sedimentary section are also constrained by vertical seismic reflection profiling and refraction studies near Charleston (Yantis et al., 1983; Ackerman, 1983). The average P/S velocity ratio of 3.06 has been determined by an analysis of micro-earthquake data recorded in the area near Summerville-Middleton Place, approximately 30-45 Km to the northwest of Charleston (Chapman et al., 2003). The P wave velocity profile from the Clubhouse Crossroads well was interpreted here in terms of a 7 layer model. This model defines the velocity structure used at all 281 site locations for the depth range 100 to 830 m. The shear wave velocity assumed for the underlying basement half-space is 3.45 km/sec. This velocity profile is shown in Figure 6.

Prediction of Shear Wave Velocity from CPT Data

Twenty-five of the 281 sites examined in this study have CPT data, but lack seismic velocity measurements. The 52 seismic CPT (SCPT) investigations were used to develop prediction models for shear wave velocity in terms of CPT tip resistance, confining pressure and lithology. This analysis was necessary to utilize data from the 25 sites with only CPT measurements, and for 204 addition boring sites where only standard penetration test (SPT) data are available.

Previous estimates of shear wave velocity Vs in terms of CPT tip resistance q_c include Rix and Stokoe (1991) for sands using field data collected in Italy, and Mayne and Rix (1993) for clays, derived from a world-wide data set. The data set collected for the Charleston area is large enough to provide a statistically robust estimate of Vs in terms of q_c and confining pressure for Quaternary sands and clays, as well as for the upper part of the Tertiary Cooper Group.

The 52 seismic CPT test sites provide 223 Vs- q_c pairs for sands, for effective overburden pressure σ_v' in the range 8 to 205 kPa. For clay, the data set involves 154 Vs-q_c pairs with σ_v' in the range 12 to 171 kPa. For the Cooper Group ("marl"), the data set consists of 93 Vs- q_c pairs with effective confining pressure σ_v' in the range 59 to 239 kPa. Figure 7 shows the distributions of measured Vs for the sand, clays and marl respectively along with estimates for mean log Vs and standard deviation.

The base 10 logarithms of SCPT shear wave velocities in m/s were fit with the following regression models, for sand, clay and Cooper marl.

Sand:

$$Log V_s = (1.476 \pm 0.099) + (0.153 \pm 0.026) Log q_c + (0.147 \pm 0.027) Log \sigma_v' . \quad (1)$$
$$SEE = 0.110, R^2 = 0.293$$

Clay:

$$Log V_s = (1.236 \pm 0.117) + (0.266 \pm 0.033) Log q_c + (0.072 \pm 0.043) Log \sigma_v' . \quad (2)$$
$$SEE = 0.140, R^2 = 0.348$$

Cooper Marl:

$$Log V_s = (1.774 \pm 0.227) + (0.101 \pm 0.058) Log q_c + (0.210 \pm 0.064) Log \sigma_v' . \quad (3)$$
$$SEE = 0.093, R^2 = 0.155$$

where

$$\sigma_v^{'} = g[\rho_s h - \rho_w (h - h_{wt})]/1000\,. \qquad (4)$$

In equations 1 through 3, q_c is measured cone tip resistance in kiloPascal (kPa), and σ_v' is the effective overburden pressure in kiloPascal. In equation 4, g is acceleration of gravity (m/s^2), ρ_s is material bulk density (assumed to be 2000 kg/m^3), ρ_w is the density of water (1000 kg/m^3), h is depth of measurement (m), and h_{wt} is depth of water table. The standard errors of the parameter estimates are given in parentheses: SEE is the regression standard error of estimate.

Figures 8 through 10 show the data and model fits for equations 1 through 3. The shear wave velocity in the sands is about equally dependent upon q_c and σ_v', whereas the velocity for the clays is highly dependent upon q_c, but only weakly dependent upon σ_v'. In contrast to both sands and clays, the measured velocities for the marl show a stronger dependence upon σ_v' than upon $q_{c.}$

Prediction of Shear Wave Velocity from SPT Data

The majority of the geotechnical investigations used in this study are located on the Charleston peninsula. At 204 of those sites, the data consist of geotechnical boring logs, with interpreted lithologic layering and standard penetration test (SPT) blowcounts for each layer.

No direct predictive relations between SPT blowcounts (N), lithology, and Vs have been developed for the study area. Shear wave velocity measurement in the course of CPT testing has only recently become routine practice. Prior to approximately 1995, the standard penetration test was used almost exclusively for routine geotechnical investigation, and shear wave velocity data were not usually collected. Only a few sites have both CPT and SPT measurements.

Our strategy for estimating Vs as a function of depth at the SPT locations involves first determining the ratios of median q_c to median N for sand, clay and marl lithology in the study area. We then indirectly estimate Vs using equations 1 through 3 by converting the measured values of N to estimates of q_c using the ratios of median values.

Figure 11 shows the distributions of q_c and N for the sand, clay and Cooper marl. Note that the CPT and SPT data are from different sites. For q_c in kPa, and N in blows/ft, the data shown in Figure 11 lead to the following estimates: $q_{c/}$/N= 929 for sands, q_c/N = 550 for clay, and q_c/N = 228 for the Cooper marl. These estimates are based on 1737 N values for sand, 1426 N values for clay, and 785 values for marl. Converting N value to q_c and estimating Vs using equations 1 through 3 leads to the distributions shown in Figure 12. A comparison of the results shown in figure 12 with those shown in figure 7 for direct measurement of Vs indicates good agreement in terms of mean values for sand and clay. The mean value of the SPT-inferred Vs for the marl is slightly greater than the mean value in the directly measured data set. This is because the depth to the Cooper marl on the Charleston peninsula is somewhat greater, on average, than at the test sites were the direct velocity measurement were made. This difference in depth, combined with the strong dependence of Vs on σ_v' in equation 3, leads to slightly higher mean estimates for the marl velocity using the N to q_c conversion for those sites.

SHEAR MODULUS AND DAMPING BEHAVIOR AS A FUNCTION OF SHEAR STRAIN

The non-linear behavior of thick sedimentary deposits to strong motion is a subject of much recent interest, but observational and experimental data are limited. Uncertainty remains for geological conditions similar to the study area where a thick sedimentary sequence overlies an extremely high velocity basement. This geological condition is not common in tectonically active environments, and is therefore not well represented in the existing strong motion data base.

Recent laboratory experiments and modeling results indicate that confining pressures at depth in thick deposits mitigate the reduction of shear modulus and increase in damping observed in laboratory tests at confining pressures appropriate for sediment thicknesses on the order of a few tens of meters (Laird and Stokoe, 1993; Assimaki et al., 2000,2001; Hashash and Park, 2001). Until recently, predictive shear modulus reduction and damping models for non-linear dynamic analysis were based on low confining pressure experiments. Such models under-predict surface ground motions in thick deposits.

Confining pressures are particularly important for the dynamic behavior of sands. Clays are less sensitive to confining pressure. Ishibashi and Zhang (1993) developed formulas expressing dynamic shear moduli and damping ratios in terms of cyclic shear strain, mean effective confining pressure and soil plasticity index. Most of their data were obtained at mean effective confining pressures less than 400 kPa, representative of depths approximately 60 meters or less.

We use the Ishibashi and Zhang (1993) model for shallow sands in the study area. The effect of confining pressure at shallow depths is modeled using 6 different relations, for midlayer depths of 1.5, 4.5, 7.5, 10.5, 13.5 and 18.3 meters. We have adopted the Ishibashi and Zhang model for 10 m depth and plasticity index 15, for all shallow clays.

The Ashley formation, uppermost unit of the Cooper Group, is encountered at depths shallower than 24 meters at almost all the sites we study. The thickness of the Ashley is variable, but averages approximately 35 m in the study area. The remaining formations comprising the Cooper Group are the Parker's Ferry and the Harleyville. They are geologically similar to the Ashley, and together, the combined thickness of the Cooper Group is in excess of 75 m at most locations. The suspension logs at the Ravenel Bridge are entirely within the Cooper Group. We assume that the base of the Cooper Group is at

100 meters in the study area, and use experimentally determined shear modulus reduction and damping values to model the dynamic behavior. These results are based on laboratory tests using samples of material from the Ashley (W. Camp, personal communication).

Assimaki et al. (2000, 2001) and Hashash and Park (2001) present models for the dynamic behavior of shear modulus and damping ratio for granular materials at higher confining pressures. These models are based on experiments performed by Laird and Stokoe (1993) to confining pressures of 5 MPa. We have adopted a modified form of the Assimaki et al. model for all materials in the study area at depths between 100 m and the top of the Mesozoic basement, which we assume is at 830 m throughout the study area. Four relationships are used, to cover the depth intervals 100-252, 252-410, 410-510, and 510-830 meters. For each interval, we assume mean effective confining pressures of 1.15, 2.16, 3.04 and 4.38 MPa, respectively, and void ratio equal to 0.3.

The Assimaki et al. (2000, 2001) model predicts very small damping ratios for small strains. For example, at 654 kPa, which corresponds to a depth of approximately 100 m, the model predicts a damping ratio of 4.7×10^{-4} for void ratio 0.3. For comparison with seismological estimates of attenuation at infinitesimal strains, this corresponds to Q of approximately 1050. Abercrombie (1997) cites several studies in California using borehole data recorded from earthquakes that indicate Q for P waves less than 45 and Q for shear waves less than 40 at depths greater than 100 m. Chapman et al. (2003) examined the spectra of microearthquakes recorded in the Summerville-Middleton Place seismic zone just to the north and west of the study area and estimated values of the shear wave attenuation parameter kappa in the range 0.035 to 0.049, for transmission though 775 m of sediments. This implies "path average" Q of 22 to 32.

For analysis, we have modified the Assimaki et al. damping model by introducing a minimum damping ratio value of 5×10^{-3} for strains less than 3×10^{-5}. This corresponds to a Q value of 100, more in line with many previous estimates of shear wave attenuation for thick sediments reported in the seismological literature. Figure 13 shows shear modulus reduction factors as a function of shear strain used for analysis. Figure 14 shows damping ratios as a function of shear strain.

RESPONSE ESTIMATES

Input Ground Motions

We use 6 different levels of input motion intensity to model the non-linear response of the sedimentary section in the study area. The motions are distinguished by peak acceleration values.

A point-source stochastic model (e.g., Boore, 1983, Boore and Atkinson, 1987, Atkinson and Boore, 1995) was used to simulate the outcrop motions of pre-Cretaceous basement rock. Table 2 lists the parameters of the stochastic model used to make the simulations. The scenario earthquake in all cases is at an epicentral distance of 30 km, and at a depth of 10 km. This scenario is consistent with a source in the area of maximum shaking intensity in 1886, centered approximately 30 km to the northwest of Charleston in the vicinity of Summerville (Dutton, 1889). The motions generated for 0.1, 0.2 and 0.3g peak acceleration are simulated using moment magnitude M = 6.4, 6.7 and 7.1, respectively. Twenty acceleration time series were simulated for each peak ground acceleration (PGA) level. Because PGA is a random variable, a mean estimate for the 20 simulations at each magnitude level was calculated. The 20 time series were then scaled such that the mean peak acceleration of the 20 simulations was equal the to the desired mean peak acceleration value.

The upper range of estimates of the moment magnitude M of the 1986 earthquake is 7.5 (Johnston, 1996). We used M=7.5 to generate the time series for the 0.4, 0.5 and 0.6g acceleration levels.

Table 2

Parameters of the Stochastic Model Used to Generate Basement Outcrop Motion for Dynamic Response Analysis.

epicentral distance:	30 km
focal depth:	10 km
crustal velocity:	3.5 km/sec
crustal density:	2.6 gm/cm3
stress parameter:	100 bars
crustal quality factor:	$Q=680\ f^{0.36}$
free surface factor:	2.0
radiation pattern:	0.55
component partition factor:	0.707

Moment magnitude	mean PGA*	Scaling factor**
6.4	0.169	0.591 for 0.1g
6.7	0.218	0.917 for 0.2g
7.1	0.300	1.000 for 0.3g
7.5	0.436	0.917 for 0.4g
7.5	0.436	1.147 for 0.5g
7.5	0.436	1.376 for 0.6g

* mean peak ground acceleration (PGA) from 20 realizations of the stochastic model
** scaling factor applied to each of 20 simulations for use in response analysis

Site Conditions and General Site Response Characteristics

The 52 seismic cone penetrometer tests provide the highest quality data used in this study. To examine these velocity data for any obvious correlation with surface geology, we have calculated mean velocity of material above the interpreted depth of the top of the Copper Group, or "top of marl". Figure 15 shows these values, plotted versus the interpreted depth to the top of marl. Different symbols are used in figure 15 to indicate different mapped geologic units. The mean velocity here is determined by summing the vertical shear wave traveltimes of each Quaternary layer interpreted in the SCPT profiles, and then dividing that sum by the sum of the layer thicknesses. Inversion of the result gives a measure of the shear wave velocity for the entire sequence.

Figure 15 shows no obvious correlation of mean Quaternary material velocity with mapped surface geologic unit. The four measures of velocity on artificial fill are all less than 200 m/s, but otherwise the lack of geological correlation of these average velocity data suggest that mapped surface geology does not provide an easily interpreted diagnostic for potential variation of mean Quaternary material velocity. Although the data set is very small for most of the individual units, the velocities for the Quaternary as a whole appear to cluster tightly about a central value of 200 m/s, suggesting that as a whole, the sediments are relatively uniform in terms of shear moduli.

The mean velocities of the Quaternary material at the 52 SCPT sites fall between 150 and 250 m/sec. The small range of variation of mean velocity (+/- 50 m/s) about a central value of 200 m/sec has implications for site response prediction. Because of this small variation of average velocity, the vertical time of shear wave propagation through the Quaternary section at these sites depends largely upon the variable thickness of the section. As shown in figure 15, thickness varies between about 5 and 30 meters for the 52 sites with SCPT data.

There is a correlation of depth to marl and mapped surface geology in the study area. Tertiary units are generally near the surface in the northern and northwestern parts of the study area, and are exposed in stream banks in those areas. The Tertiary units lie at greater depths beneath the progressively younger beach terrace complexes that roughly parallel the coastline. Hence, Quaternary sediments of the Ladson formation (Qlc) are relatively thin in the northwestern section of the study area, whereas sites on the younger Ten Mile Hill beds typically overly a somewhat deeper Tertiary-Quaternary contact, and sites in the Wando, Silver Bluff and modern terrace complex generally overly the Tertiary units at still greater depths. However, the Tertiary-Quaternary contact is an irregular surface. Depth to that surface depends on ground surface elevation, as well as the complex erosion and depositional history of the study area. Figure 15 shows that the depth to the marl is less than 20 m at most sites in the Ladson and Ten Mile Hill surface exposure areas. Several of those sites exhibit depth to marl of less than 10 m. Sites closer to the coast, on the Wando, Silver Bluff and modern beach terrace complex are typically at depths exceeding 15m. Depth to marl exceeds 20 m at several sites in downtown Charleston on Wando and Silver Bluff sand units Qws and Qsbs. Because the beach and barrier island deposits tend to form the highest ground surface elevations in the study area, depth to marl is generally largest under areas where those units are mapped at the surface.

The amplitude of the site response is determined by the impedance contrasts between the basement and coastal plain sedimentary sequence, and between geologic units within the sedimentary section. The contrast in velocity between the Quaternary and Tertiary units in the study area is substantial. Figure 16 plots the SCPT shear wave velocities for the Tertiary units. The velocities of the "Cooper marl" average approximately 400 m/s, with most measurements in the range 300 to 500 m/s. As a result, we can expect that for an average site in the study area, the Quaternary-Tertiary impedance contrast will typically be approximately 2, based on mean velocities of 400 and 200 m/s, for the uppermost Tertiary units (Cooper marl) and Quaternary material at the SCPT sites.

Figure 17 shows estimates of layer-over-half space fundamental resonance frequency for vertically incident shear waves, for the SCPT sites. Site fundamental frequency is given by V'/4h, where h is depth to marl and V' is mean Quaternary velocity. The curve is constructed for V' = 200 m/s. Various symbols refer to sites in mapped geologic units shown in Figure 1 and described in Table 1.

The results in Figure 17 indicate that site resonance frequency is largely dependent upon the depth to the Tertiary Cooper Group. Because of spatially complex erosion and depositional processes, this depth varies considerably in the study area. In general, we expect ground motion amplification of approximately a factor of 2 in the frequency band from 2 to 10 Hz, due to the velocity contrast between Tertiary and Quaternary units.

An important characteristic that is common to all sites in the study area is the major impedance contrast at the base of the Coastal Plain sedimentary section. This occurs at a depth of approximately 830 meters at Charleston. As shown in figure 6, we model the Pre-Cretaceous basement rock with shear wave velocity of 3.45 km/sec (density 2.6 gm/cm3), and the overlying Cretaceous sediments with velocity 822 km/sec (density 2.0 gm/cm3) inferred from a P wave velocity log at the Clubhouse crossroads well. This results in an impedance contrast of 5.46. This is the largest impedance contrast likely to exist along the path from earthquake source to ground surface in the study area, and it has a major effect on the predicted site response.

Figure 18 is constructed to illustrate the main geological effects on site response. These are 1) the impedance contrast and single layer effect of the entire Coastal Plain sequence, and 2) the impedance contrast and single layer effect of the Quaternary sequence. All sites in the study area exhibit these characteristics to variable degrees. Figure 18 shows the response of a single layer over half-space model representing the entire coastal plain sequence, where the impedance contrast is 5.46 and the vertical traveltime is 1.25 seconds. Also shown is a single layer response for a impedance contrast of 2.0, and vertical traveltime of 0.075 seconds. This is rough approximation of the individual response (surface motion amplitude spectrum divided by amplitude spectrum of half-space outcrop motion) due to the total Coastal Plain section and the Quaternary section, respectively. The responses shown in Figure 18 are for linear behavior and quality factors Q=100. Also shown in figure 18 is the combined effect of both response functions, which models to a first approximation the major features of site response in the Charleston area.

Figure 18 illustrates, in simplified form, that the two main geological features produce very distinctive site response features. The effect of the entire Coastal Plain sequence is to introduce site amplifications at frequencies of approximately 0.2, 0.6, 1.0, 1.4, 1.8, etc., or at odd harmonics of 1/4T where T is the one-way shear wave travel time of approximately 1.25 seconds through the section. The effect of the Quaternary section is the due to the same physical process, but resonance frequencies occur, as modeled in this example, at frequencies of 3.3, 9.9, 16.5 … Hz, due to the much smaller traveltime of shear waves through that sequence. The combined effect of the two layers is also shown in figure 18.

The results of this study show the 5 percent damped SA response spectral ratios for the ground surface motion to that of an outcrop of hard (Pre-Cretaceous) basement rock. The calculations incorporate much more detail than the simple examples shown in figure 18, and involve as many as 30 different layers for some sites. In each case, we take into account non-linear behavior of the sediments, so that the computed responses depend on the peak acceleration levels of the input motions. However, in most cases, the general characteristics of site response shown in figure 18 can be recognized in the results derived for the individual sites, regardless of site location and input motion level.

RESULTS

For each site shown in figure 1, we have calculated the ground surface to basement outcrop SA response spectral ratio, as well as the ratio of PGA amplitudes. This has been done for 6 basement half-space input motions, ranging in amplitude from 0.1g PGA to 0.6g PGA. The results have been incorporated into a GIS format, (ArcGIS version 8.1). The following discussion summarizes the main results.

An overview of the results is shown in Figure 19. Figure 19 plots the SA spectral ratios for the 52 SCPT sites, for input motions of 0.1, 0.3 and 0.5 g. We note that the spectral ratios of the various sites are similar at the lowest frequencies (0.2 Hz) and that they diverge with increasing frequency to a maximum dispersion amounting to approximately a factor of 3 at approximately 5 Hz. The frequency band 1 to approximately 10 Hz corresponds to the band in which the difference in site response due to variability of the Quaternary section thickness, and to a lesser degree, the velocity layering within that sequence, is most important. At higher frequencies (greater than 10 Hz), the SA spectral ratios at these sites converges to within a factor of 2 at 30 Hz. At the low frequencies, the sites exhibit spectral modulation corresponding to the first few harmonics of the total Coastal Plain sequence (0.2, 0.6 and 1.0 Hz), an effect that is common to all the sites in the study area.

For 0.1g input motion amplitude, the median maximum response is 3.5, and occurs in the frequency range from 1 to 3 Hz. The site conditions in the study area amplify 0.1g

PGA input motion in the frequency band from 0.2 Hz to 10 Hz at almost all sites. As the input motion amplitude increases, the frequency band in which amplification occurs narrows, and the high frequency motions become attenuated. For example, at 10 Hz, the median response for 0.1 g input motion is 1.7, for 0.3g it is 0.65 and for 0.5g, the median response is 0.35.

Variability of Site Response

The variability of response at the different sites examined in this study is rather small. This is due to the homogeneity of the shear wave velocity in the Quaternary materials. Appreciable variation from the typical condition is found for some sites on artificial fill. As an example, figure 20 shows the results for 0.1g for SCPT sites on fill and on beach and barrier island facies. In this example, response at two sites in the low frequency range 0.5 to 2 Hz is substantially larger than predicted for sites on beach and barrier island facies. However, the average PGA ratio for 0.1g input amplitude on fill (96 sites) is no different from the average value of PGA ratio for the 145 sites on beach and barrier island facies: both ratios average 1.5 for the entire data set. This result points to the fact that although variation of a factor 3 or more in site response can be found between individual sites in the frequency band 1 to 10 Hz, there does not appear to be a strong, systematic geologic predictor of site response characteristic. The thickness of the Quaternary section is perhaps the single most important factor, as described below for the case of PGA.

Correlation of PGA with Thickness of Quaternary Section and V30

The average shear wave velocity in the upper 30 meters (V30) has been used as a diagnostic for site response characteristics in many previous studies. The Cooper Group is present beneath all sites at a depth of 30 meters or less, and the mean velocity in the upper 30 meters will be largely determined by the thickness of the Quaternary section. In estimating the mean velocity in the upper 30 meters for the sites studied here, we have assumed that the shear wave velocities in the Cooper Group are those measured on the suspension log at the Ravenel bridge (main pier). Figure 21 plots the peak ground acceleration ratio (ground surface divided by basement outcrop) for all 281 sites in the study versus V30 (average velocity of the upper 30 meters) as well as versus the "Depth to Marl" (depth to the top of the Tertiary Cooper Group). The results show that the behavior of PGA is loosely correlated with the thickness of the Quaternary section. Because the mean velocities of the Quaternary sediments are quite similar at the different sites, the velocity of the upper 30 meters of material is in general inversely related to the thickness of the Quaternary section. We observe that PGA ratios tend to be the large (for a given input motion level) on sites with higher V30 values: these sites tend to be sites where the depth to marl is small.

GIS Coverage

The results are incorporated into an ArcGIS coverage. The response calculations have been installed in 6 layers, each layer involving site calculations for one of 6 different basement outcrop input motion levels. The attributes of each layer include site identifier, latitude, longitude, spectral response ratio at 0.1, 0.2, 0.5, 0.75, 1.0, 2.0, 3.3, 5.0, 7.5, 10, 20, 30 Hz, PGA ratio, mapped surface geologic unit, depth to marl, V' (mean Quaternary shear wave velocity) and V30 (mean velocity in the upper 30 meters). The data can be queried for a variety of combinations and values of these attributes. For example, figure 22 shows an example from the Charleston peninsula. A query has been built for 0.2g input motions, for sites located on the Silver Bluff beach and barrier island deposits Qsbs, with calculated values of the PGA ratio greater than 1.0. The blue dots in figure 22 show the sites matching these conditions, and an table is displayed that gives the values of all attributes for a selected site.

The interested reader can extract from the GIS coverage specific results for all 6 input motion levels and query the database for various correlations between site location, depth to marl, average velocity in the upper 30 meters, and surface geology at each of the 281 sites investigated. The GIS coverage is available by contacting the authors, or by direct download at the following website.

http://vtso.geol.vt.edu/outreach/vtso/charlestongis/

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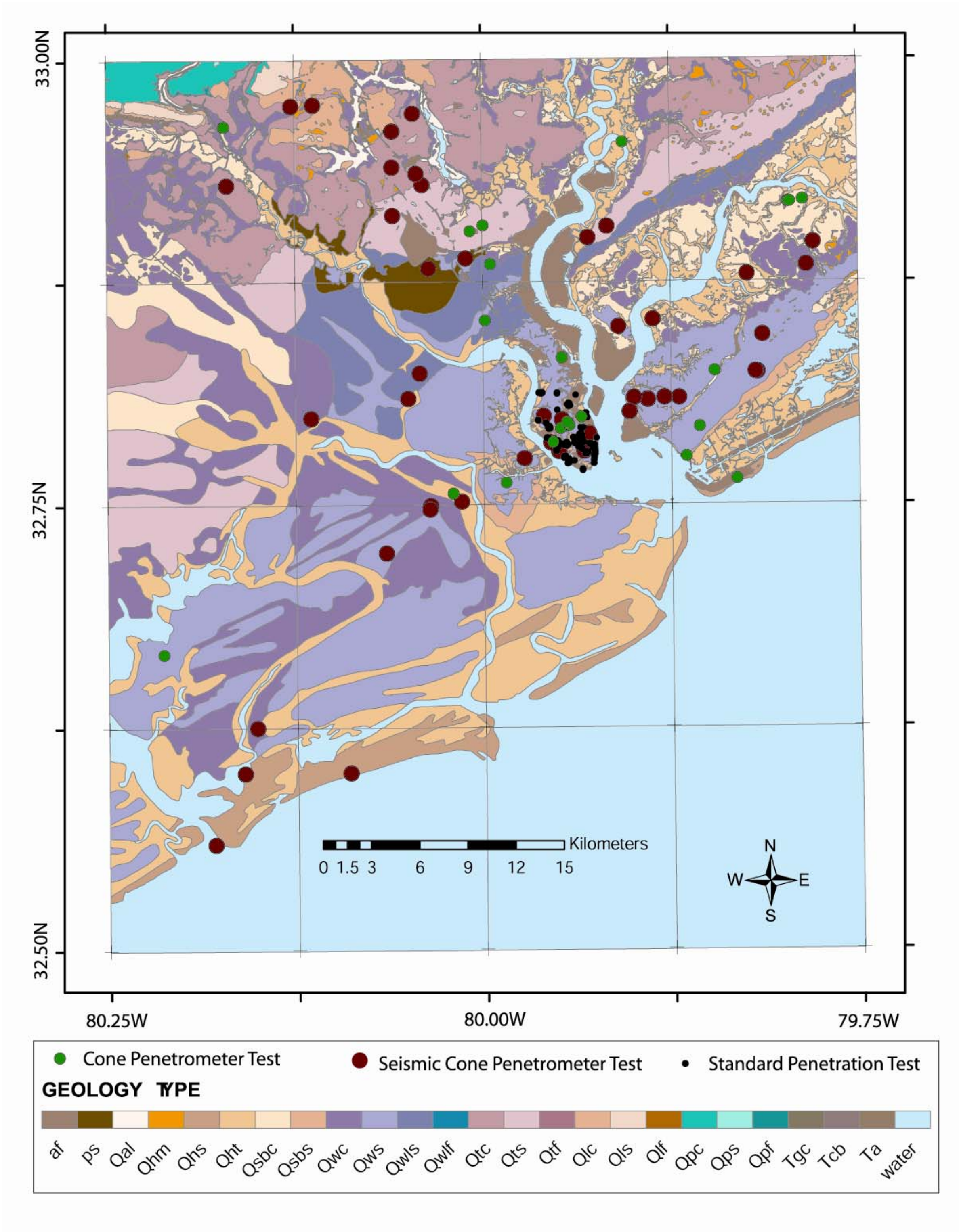

Figure 1. Geologic map of the study area with locations of geotechnical tests shown as filled circles. The geotechnical data include cone penetration tests, seismic cone penetration tests, and standard penetration tests. The geological map is derived from Weems and Lemon (1994,1993, 1988), McCartan et al. 1984 and Weems et al. 1997. Table 1 lists the geological descriptions of the various mapped units.

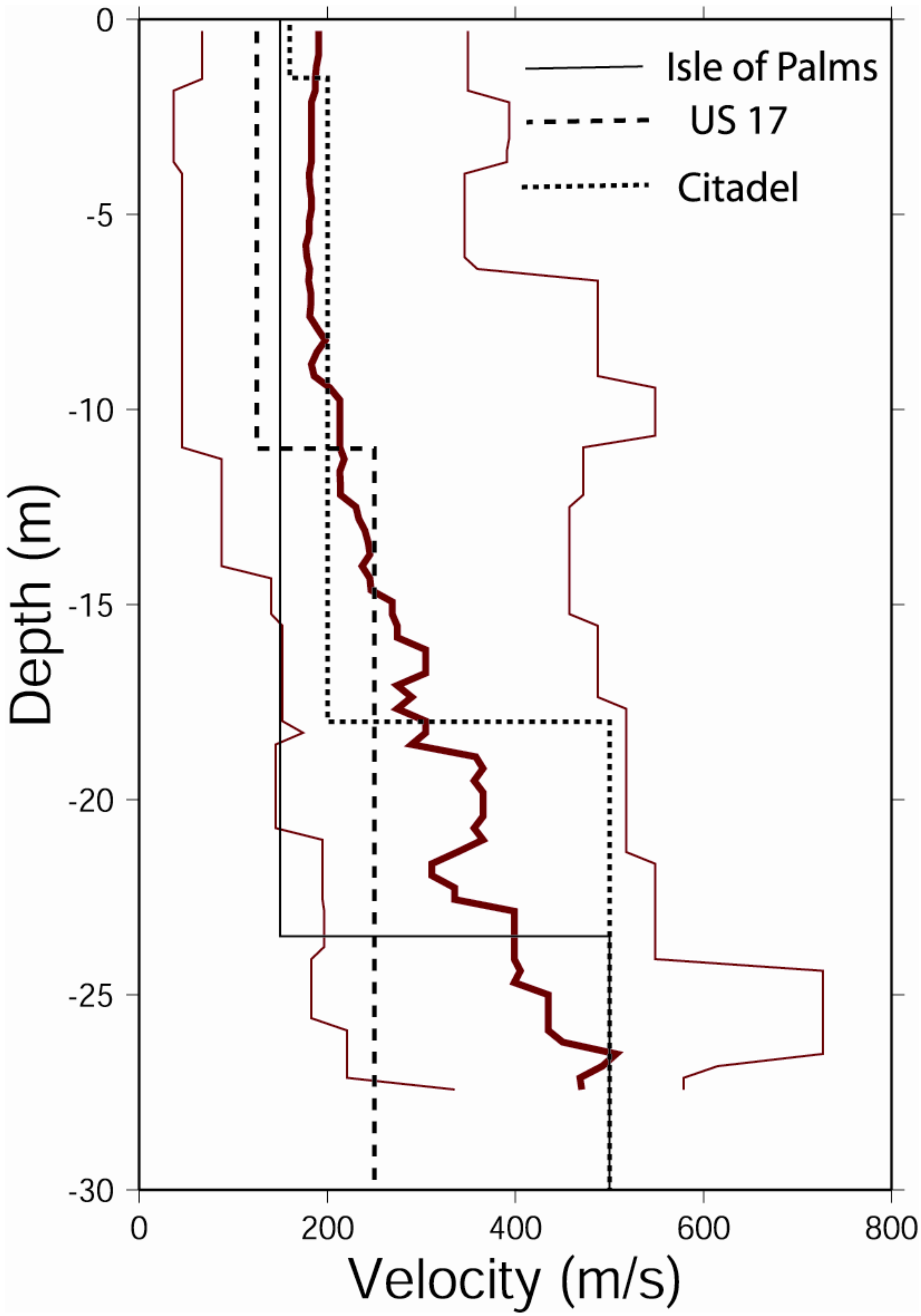

Figure 2. Red lines show the minimum, median and maximum shear wave velocities obtained from 52 shallow shear wave velocity profiles in the study area. Velocity profiles from refraction experiments by Williams et al. (2000) are also indicated.

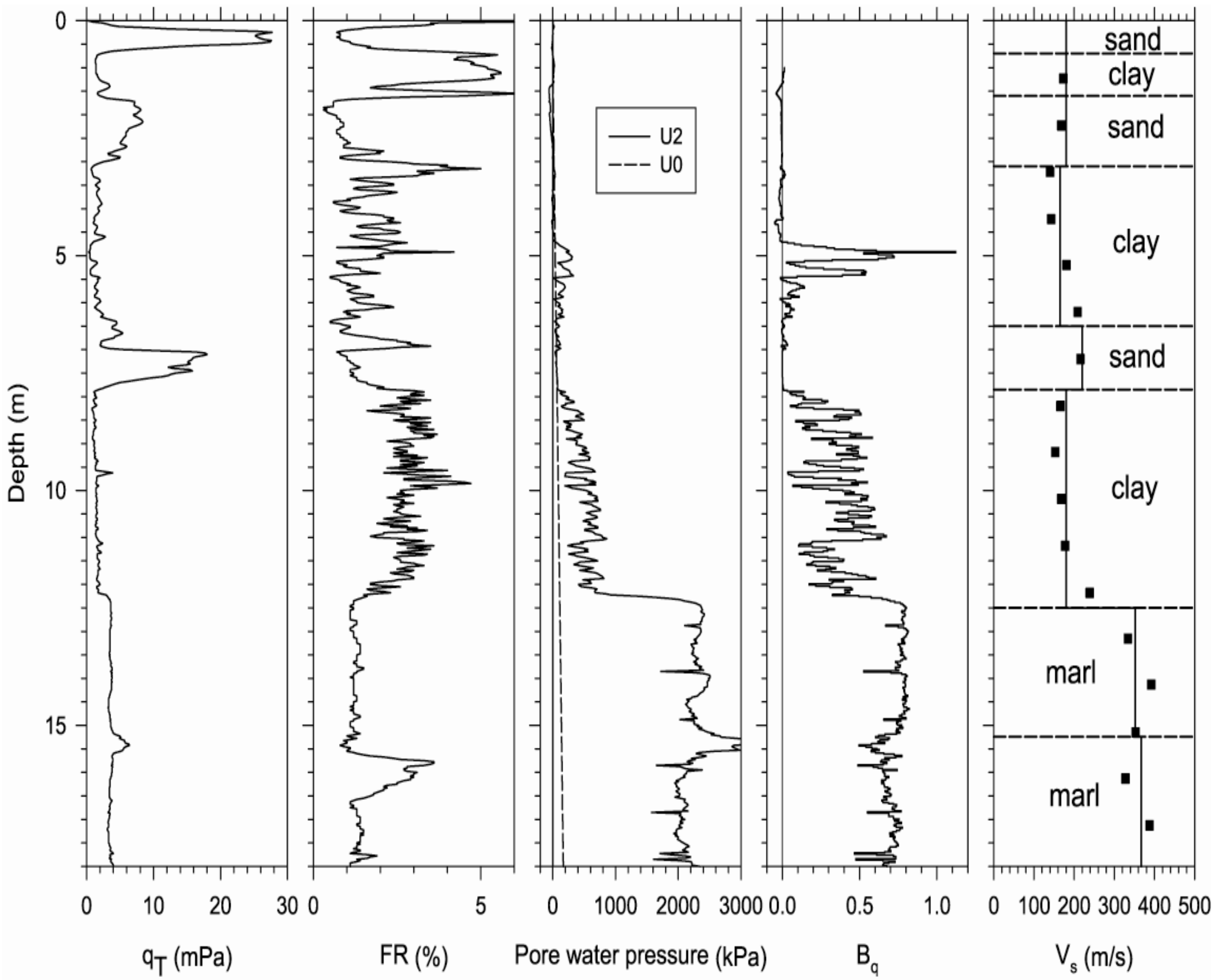

Figure 3. Left to right: q_T is corrected cone tip resistance, FR is the ratio of sleeve friction to tip resistance, U0 is hydrostatic pressure, U2 is measured pore pressure during penetration, Bq is the pore pressure ratio, (U2-U0)/ (q_T-σ_{vo}), where σ_{vo} is the total vertical confining pressure. The square symbols at right indicate measured shear wave velocities, and the dashed and solid lines distinguish interpreted soil types and layer velocities.

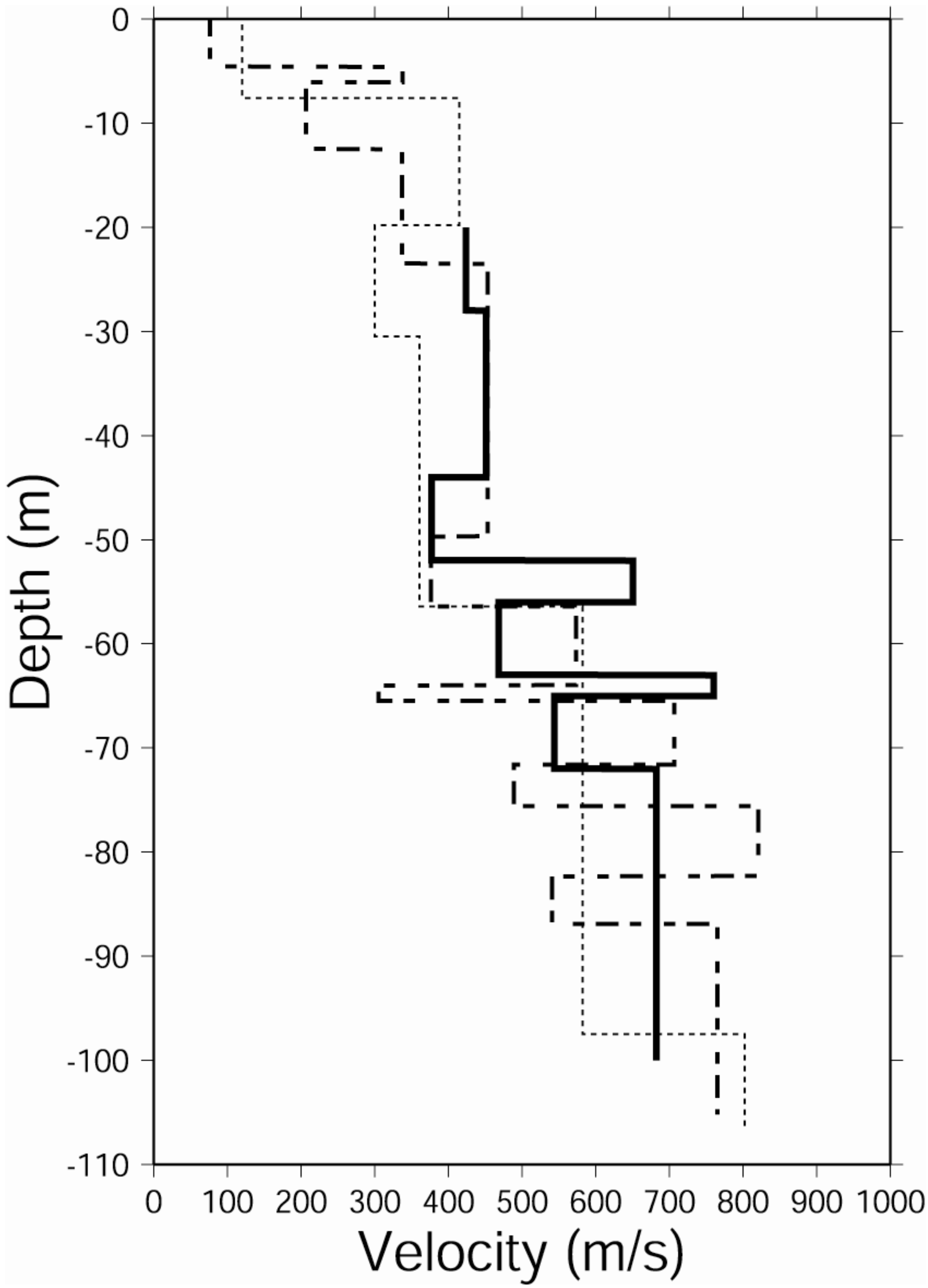

Figure 4. Left: shear wave velocity profiles penetrating the Cooper Group at 3 locations, derived from suspension logs. Thin dashed line: Maybrook highway bridge site, Johns Island, SC. Heavy dashed line: Arthur Ravenel bridge site, eastern approach, Mt Pleasant, SC. Heavy solid line: Arthur Ravenel bridge, main pier, Cooper River.

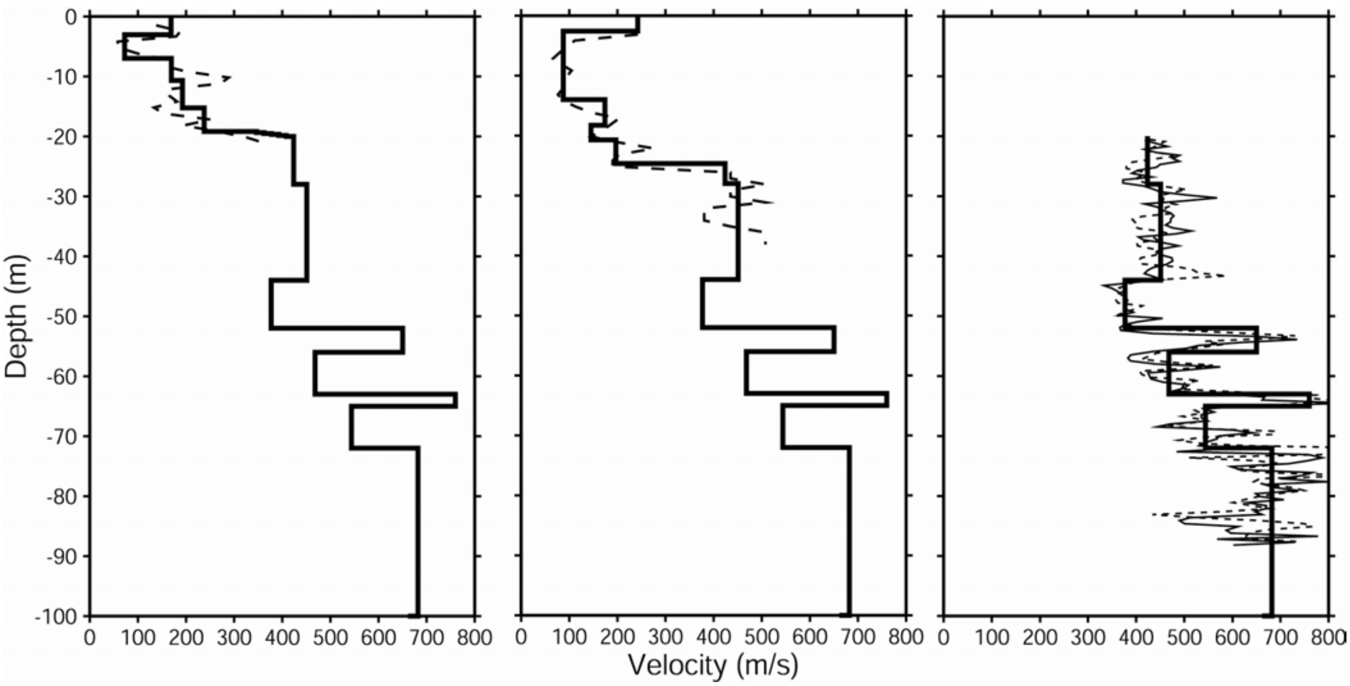

Figure 5. Left: shear wave velocity profile developed for a site where the maximum depth of geotechnical investigation was less than 20 m. Center: profile corresponding to the situation where the depth of geotechnical investigation exceeded 20 m. In both cases, the dashed lines indicate measured shear wave velocity at shallow depth. Right: thin dashed and thin solid lines show shear wave velocity profiles obtained by suspension logging at the main pier of the Ravenel bridge. The thick solid lines show the corresponding interpreted layered velocity structure used for dynamic analysis.

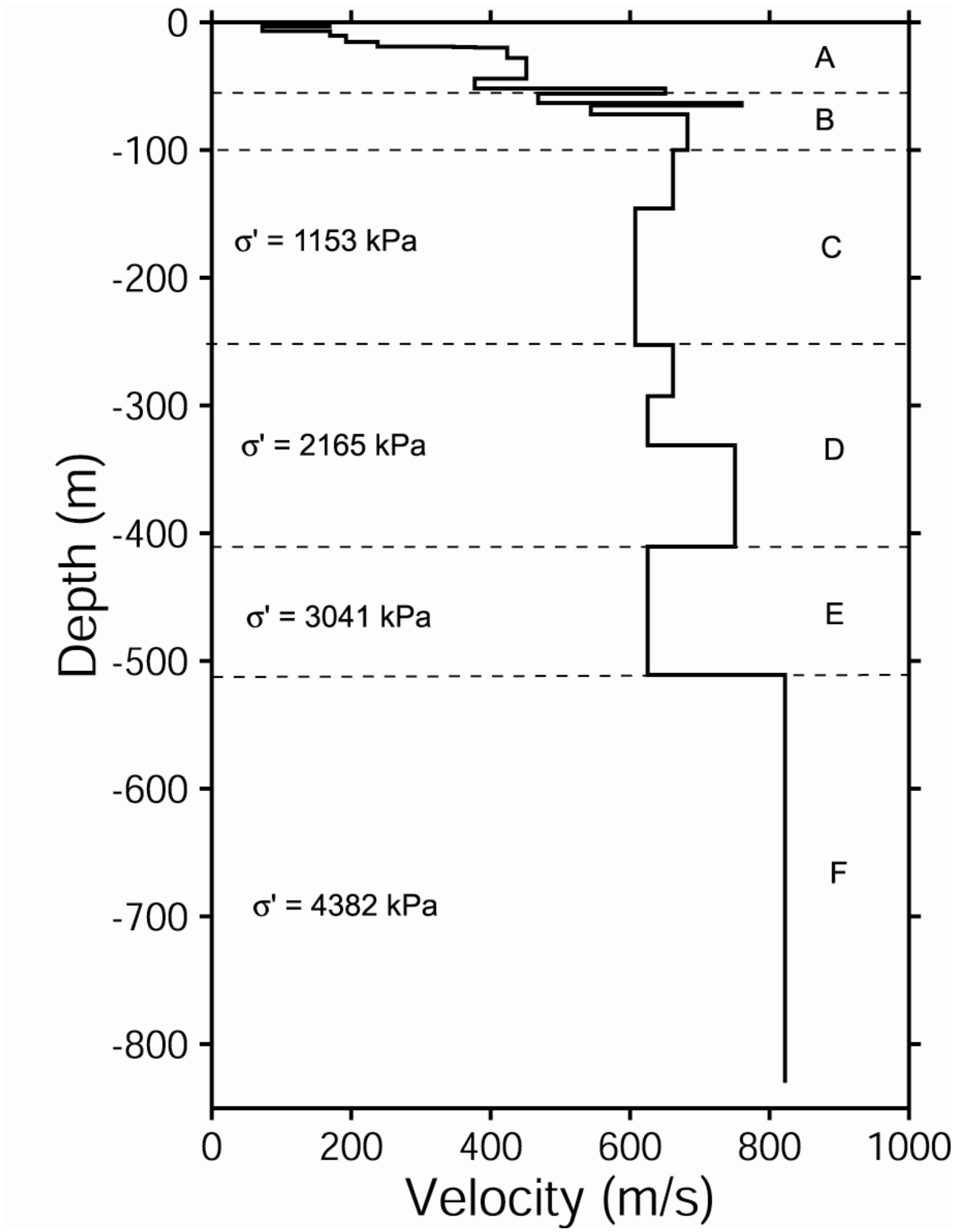

Figure 6. Typical shear wave velocity profile for the study area. Velocities in the upper part of region A (0 to 56 m) are defined on the basis of site-specific geotechnical investigation. Strain dependent modulus and damping degradation is defined on the basis of site-specific lithology and confining pressure. Velocity in region B (56 to 100 m) is inferred from velocity logs at the Ravenel Bridge site. The modulus and damping degradation is that derived from experimental data for the Ashley formation (W. Camp, personal communication). Velocity in regions C, D, E and F is inferred from the P velocity log at the Clubhouse Crossroads corehole site. The modulus and damping degradation models for regions C, D, E and F are taken from Assimaki et al. (2000, 2001) and are functions of mean effective stress σ', assuming a compaction ratio of 0.3.

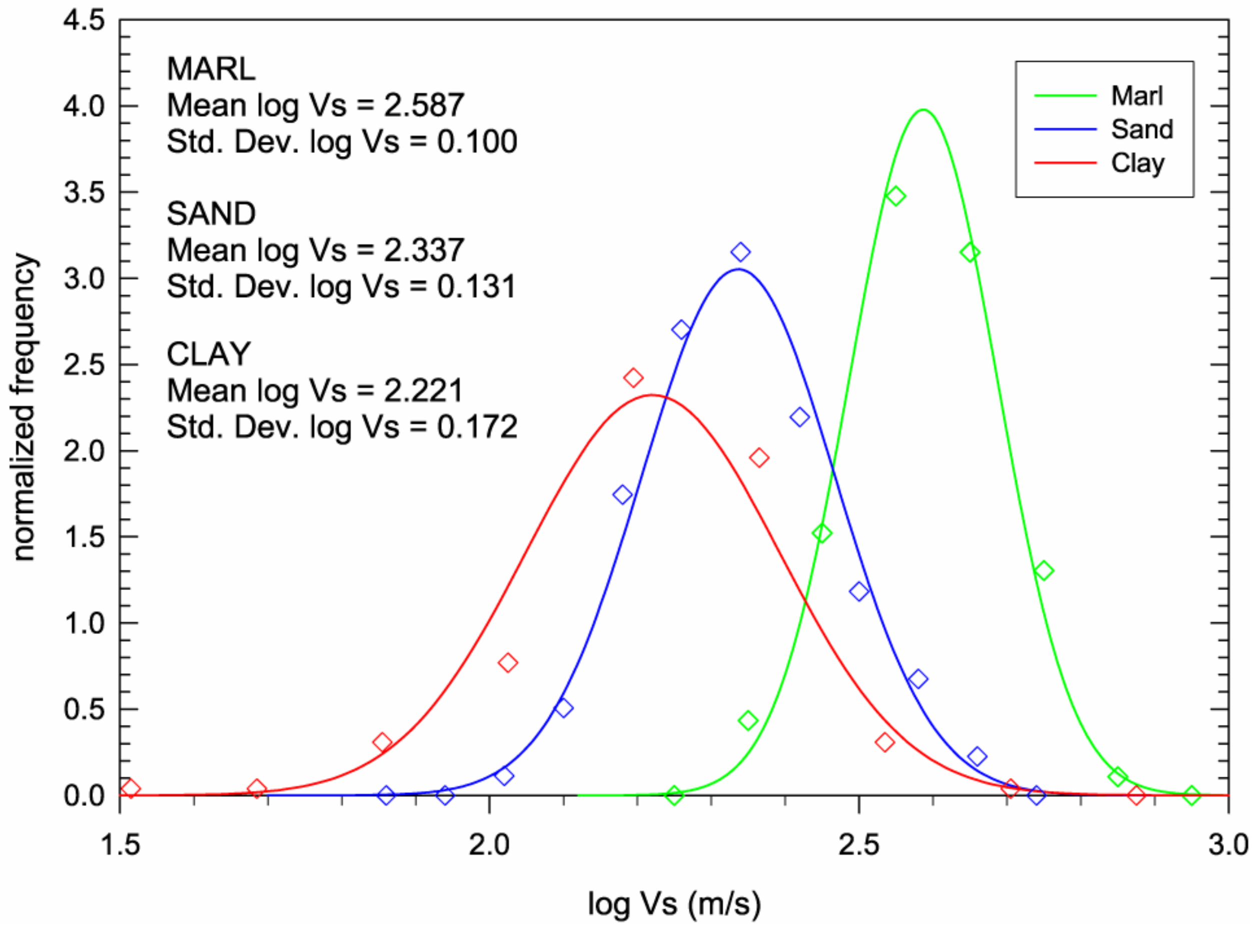

Figure 7. Distribution of measured shear wave velocity.

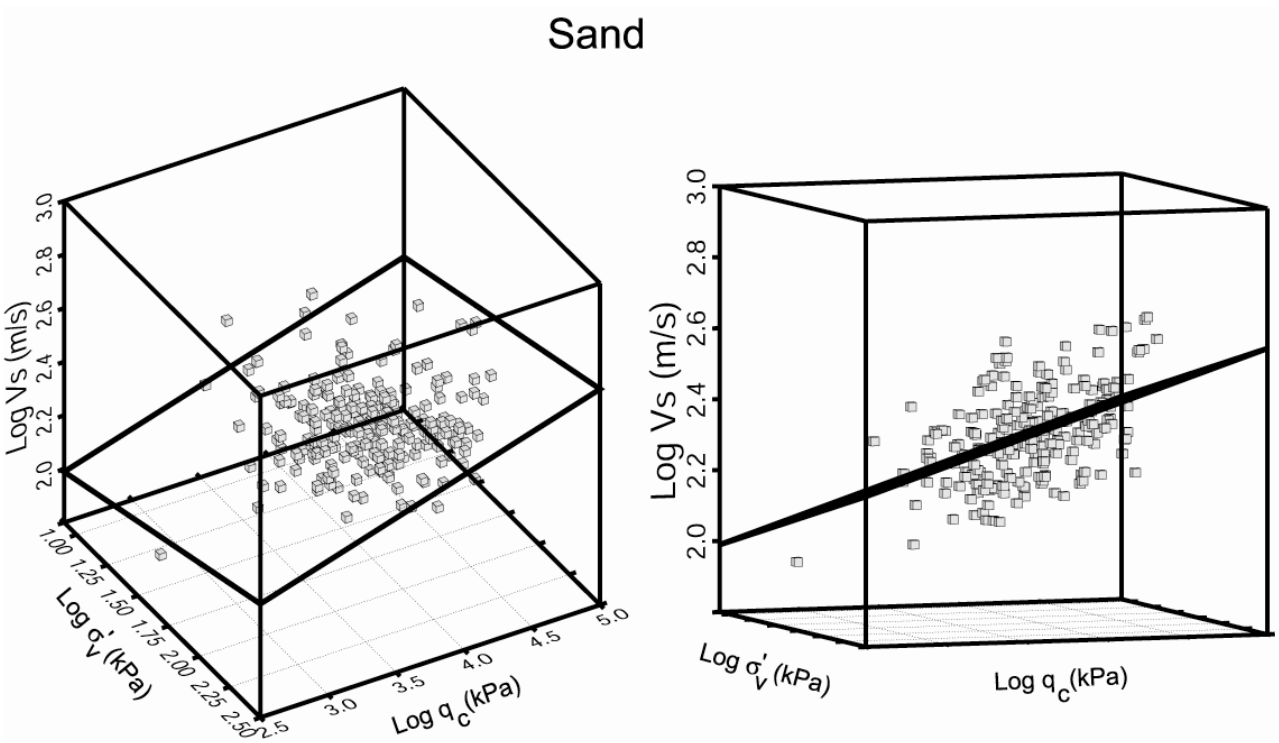

Figure 8. Regression model for sands, using data from 52 seismic cone penetrometer tests (SCPT). Measurements are indicated by the small filled cubes. The model prediction is indicated by the plane enclosed within the large cube.

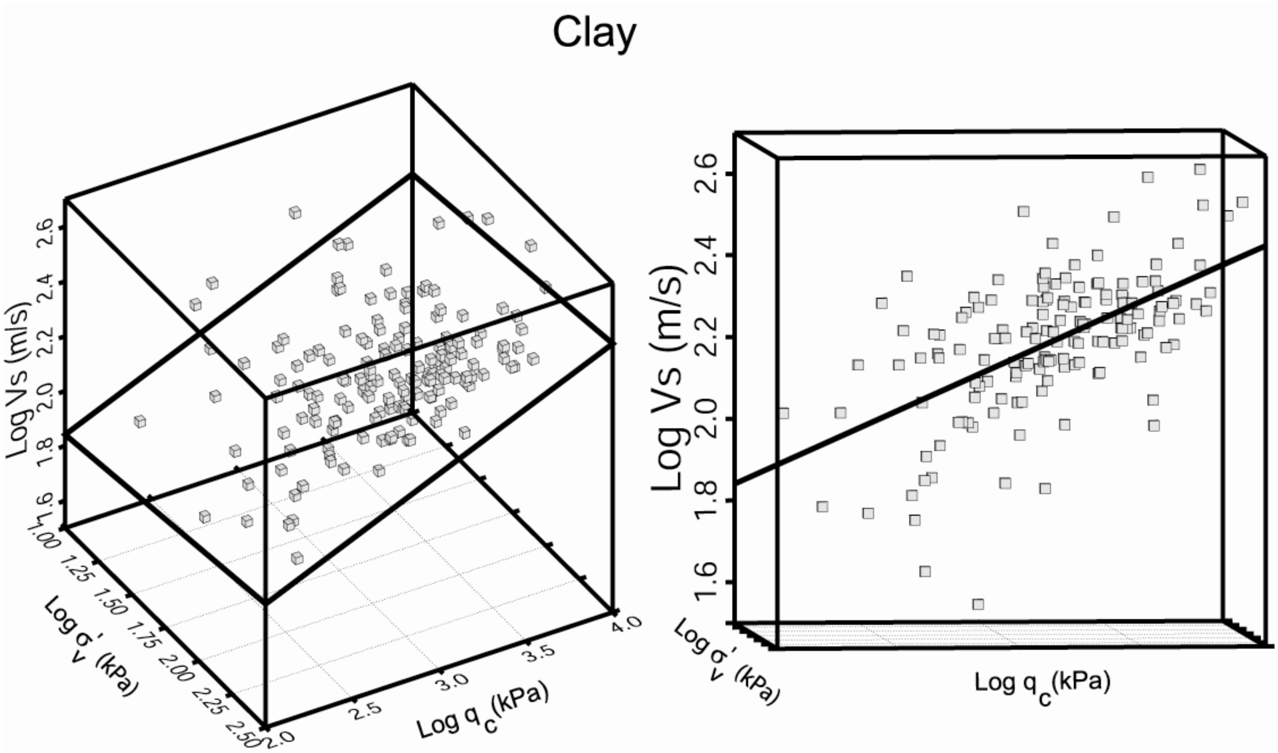

Figure 9. Regression model for clays, using data from 52 seismic SCPT investigations. Measurements are indicated by the small filled cubes. The model prediction is indicated by the plane enclosed within the large cube.

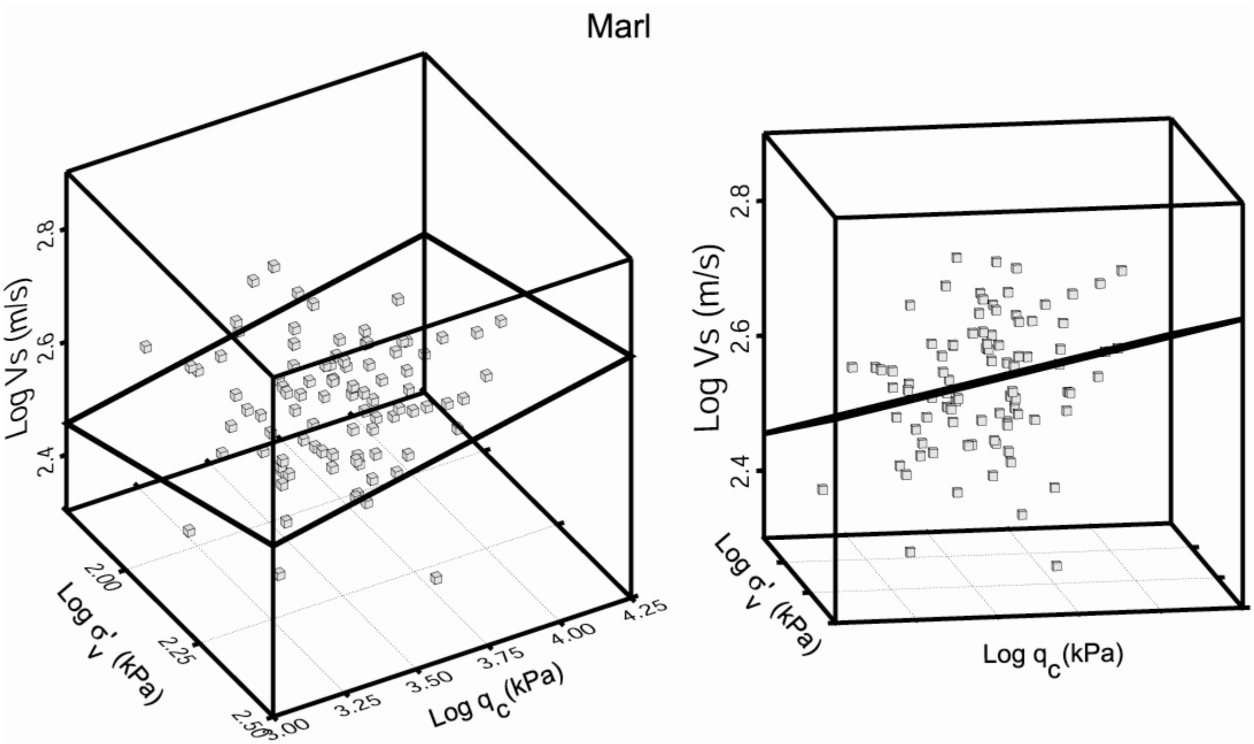

Figure 10. Regression model for Cooper marl, using data from 52 seismic SCPT investigations. Measurements are indicated by the small filled cubes. The model prediction is indicated by the plane enclosed within the large cube.

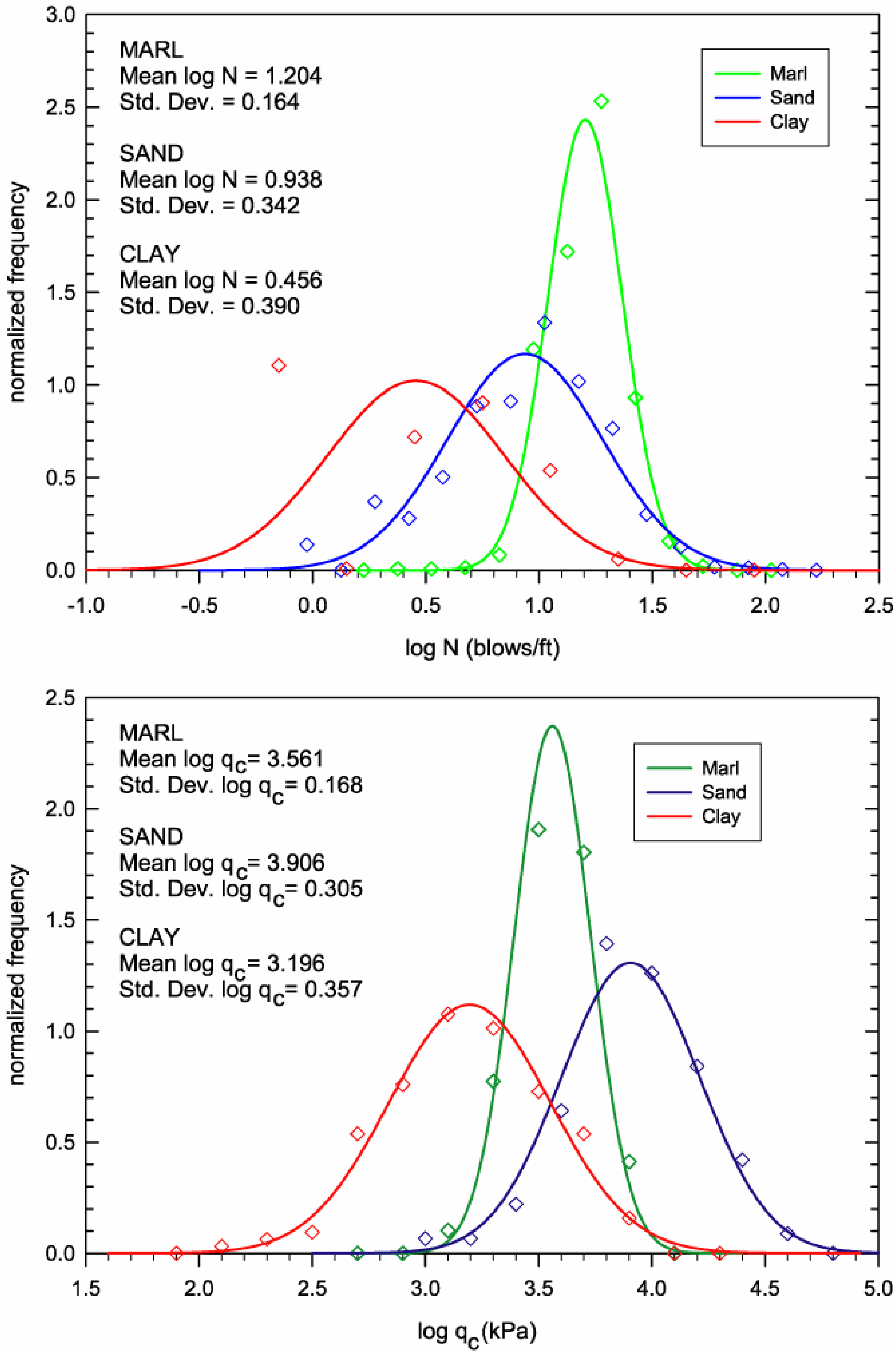

Figure 11. Distribution of SPT blowcounts N (upper) and CPT tip resistance q_c (lower).

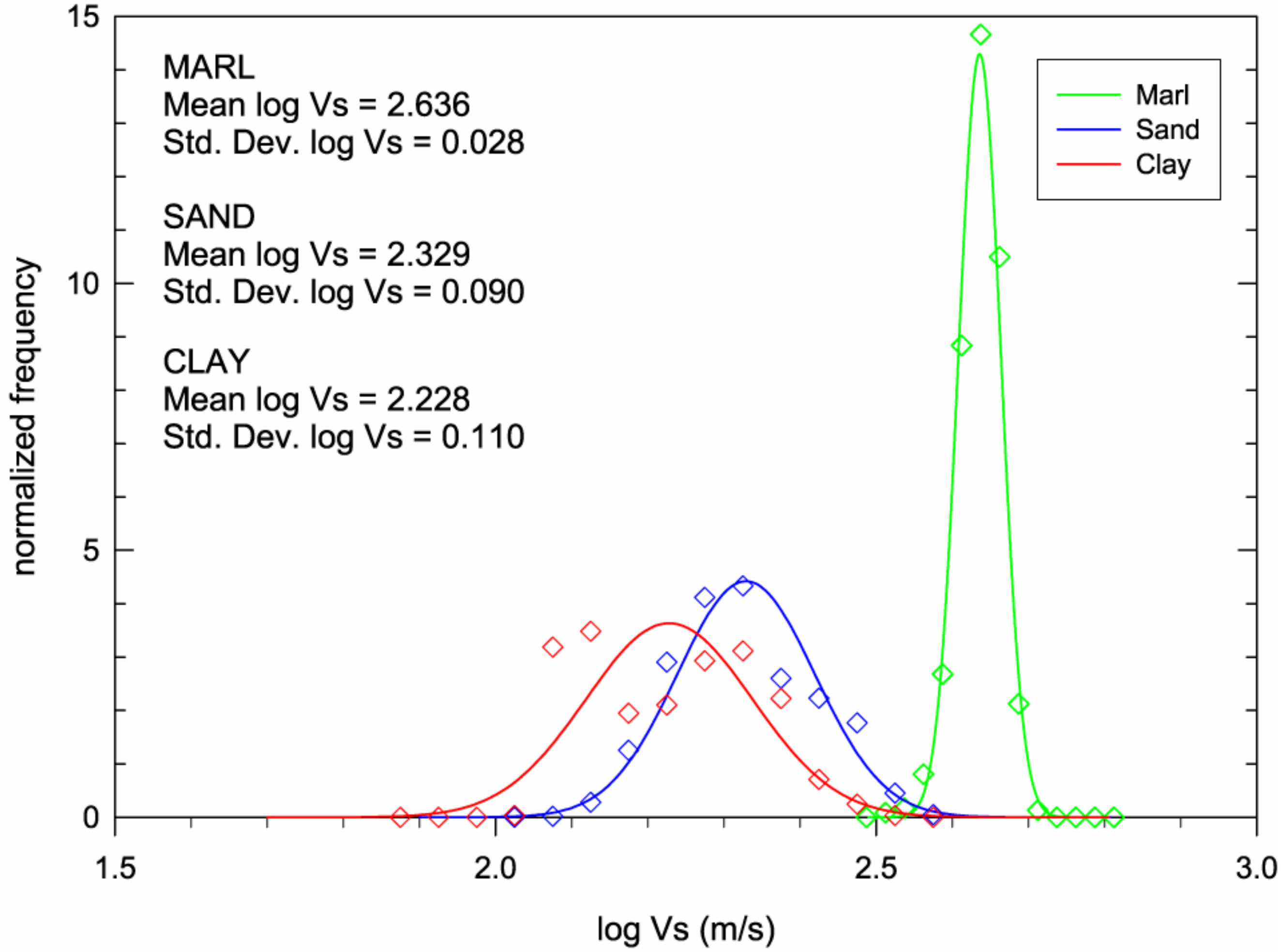

Figure 12. Shear wave velocity Vs indirectly inferred from standard penetration test N values at 204 locations on the Charleston peninsula.

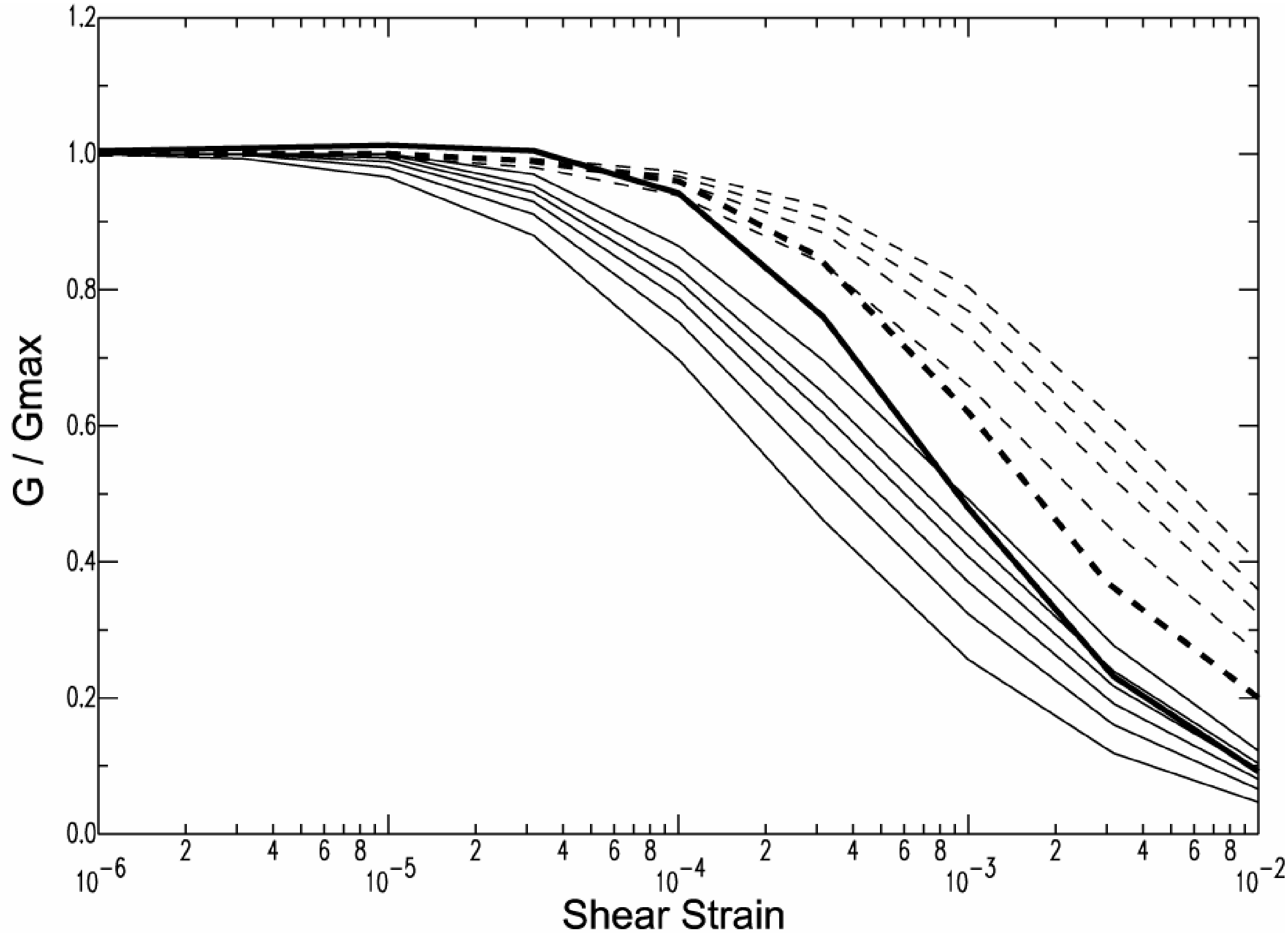

Figure 13. Shear modulus (G) reduction factors as a function of shear strain. Gmax is maximum shear modulus, at infinitesimal strain. Thin solid lines are for sands with mid-layer depths of 1.5, 4.5, 7.5, 10.5, 13.5, and 18.3 m. The thick solid line is the model for clay at depths less than 20 m. The thick dashed line is for the Cooper Group, in the depth range 20 to 100 m. The thin dashed lines are for materials beneath the Cooper Group, in the depth ranges 100-252, 252-410, 410-510, and 510-830 m.

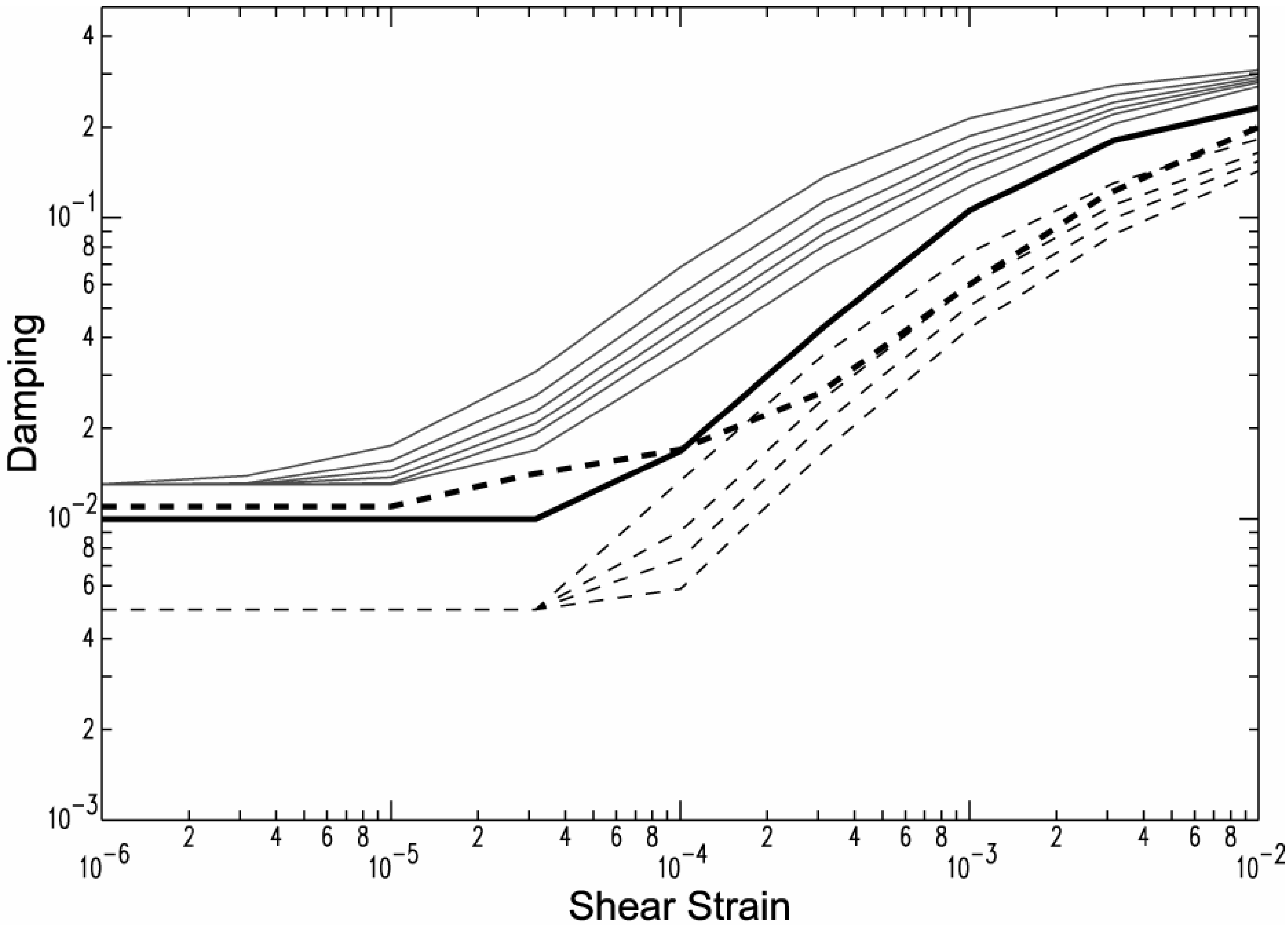

Figure 14. Material damping as a function of shear strain. Thin solid lines are for sands with mid-layer depths of 1.5, 4.5, 7.5, 10.5, 13.5, and 18.3 m. The thick solid line is the model for clay at depths less than 20 m. The thick dashed line is for the Cooper Group, in the depth range 20 to 100 m. The thin dashed lines are for materials beneath the Cooper Group, in the depth ranges 100-252, 252-410, 410-510, and 510-830 m.

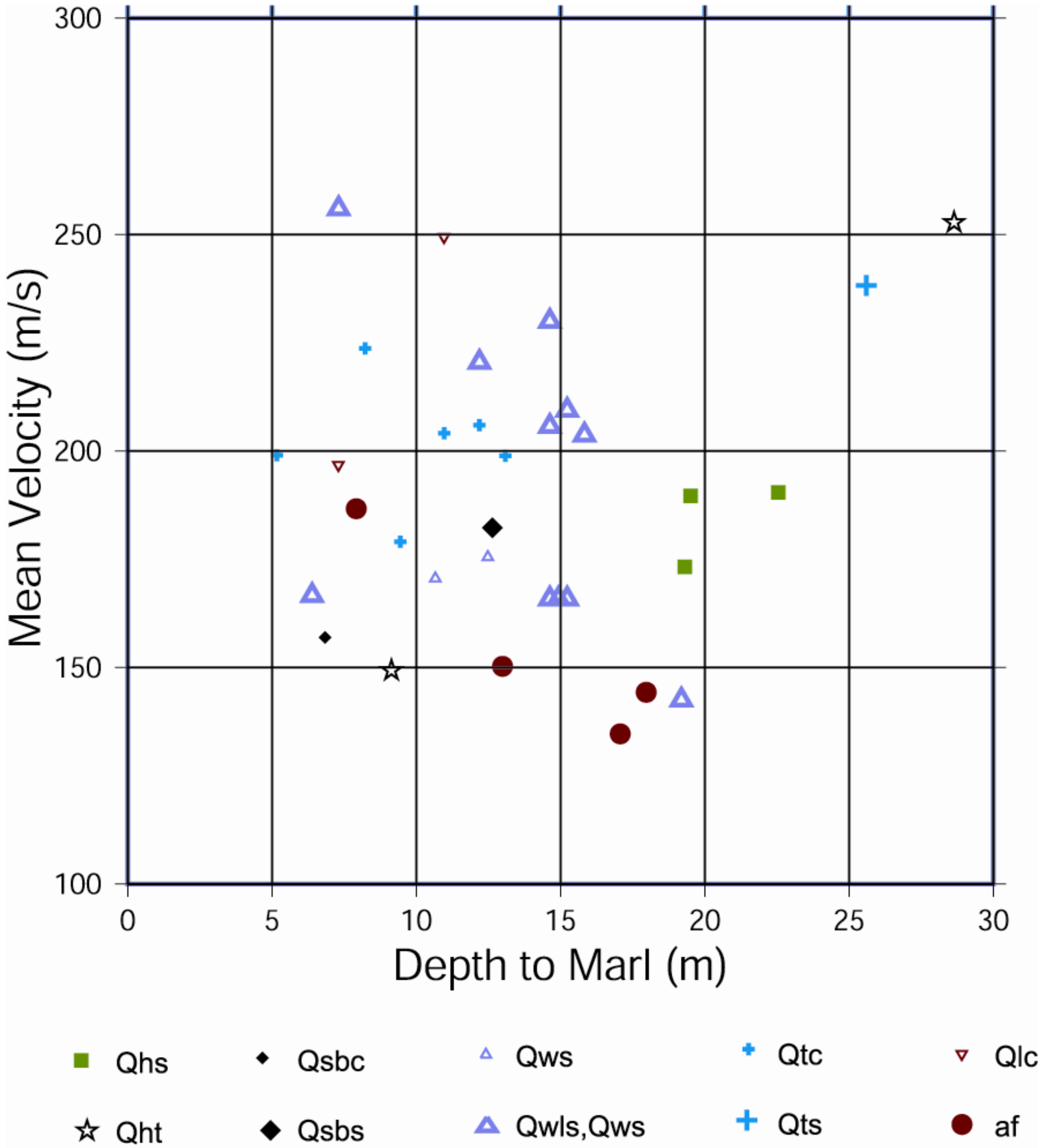

Figure 15. Average shear wave velocity of Quaternary sediments above the Tertiary Cooper Group (Cooper marl), derived from seismic cone penetrometer tests. Symbols refer to geologic units mapped in Figure 1 and described in Table 1.

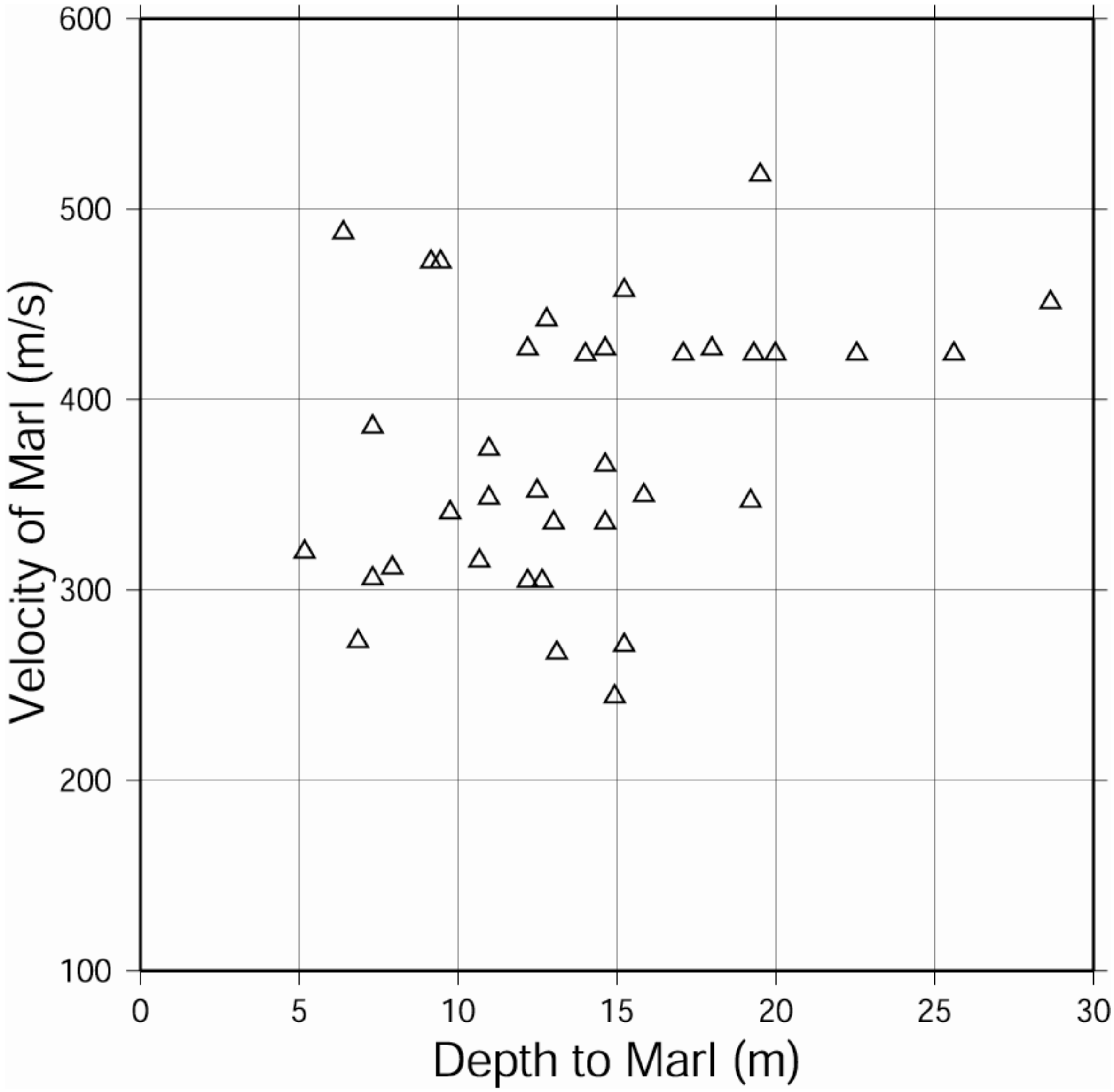

Figure 16. Shear wave velocity measurements of material immediately below the top of the Tertiary Cooper Group (Cooper marl), derived from seismic cone penetrometer tests.

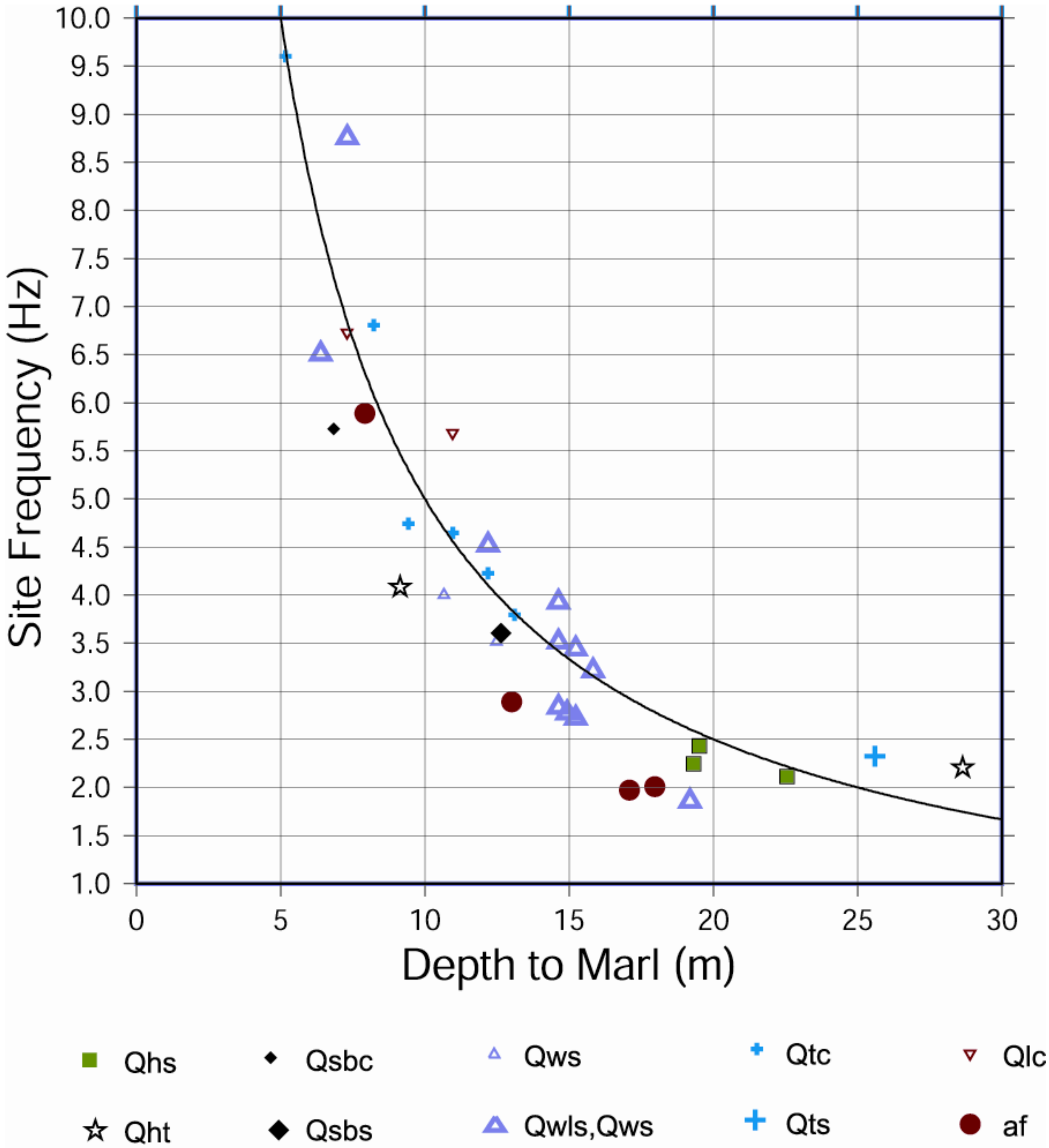

Figure 17. Fundamental resonance frequency for a single layer over half space, for vertically incident shear waves. The symbols refer to different geologic units shown in Figure 15. The curve is constructed for V' = 200 m/s.

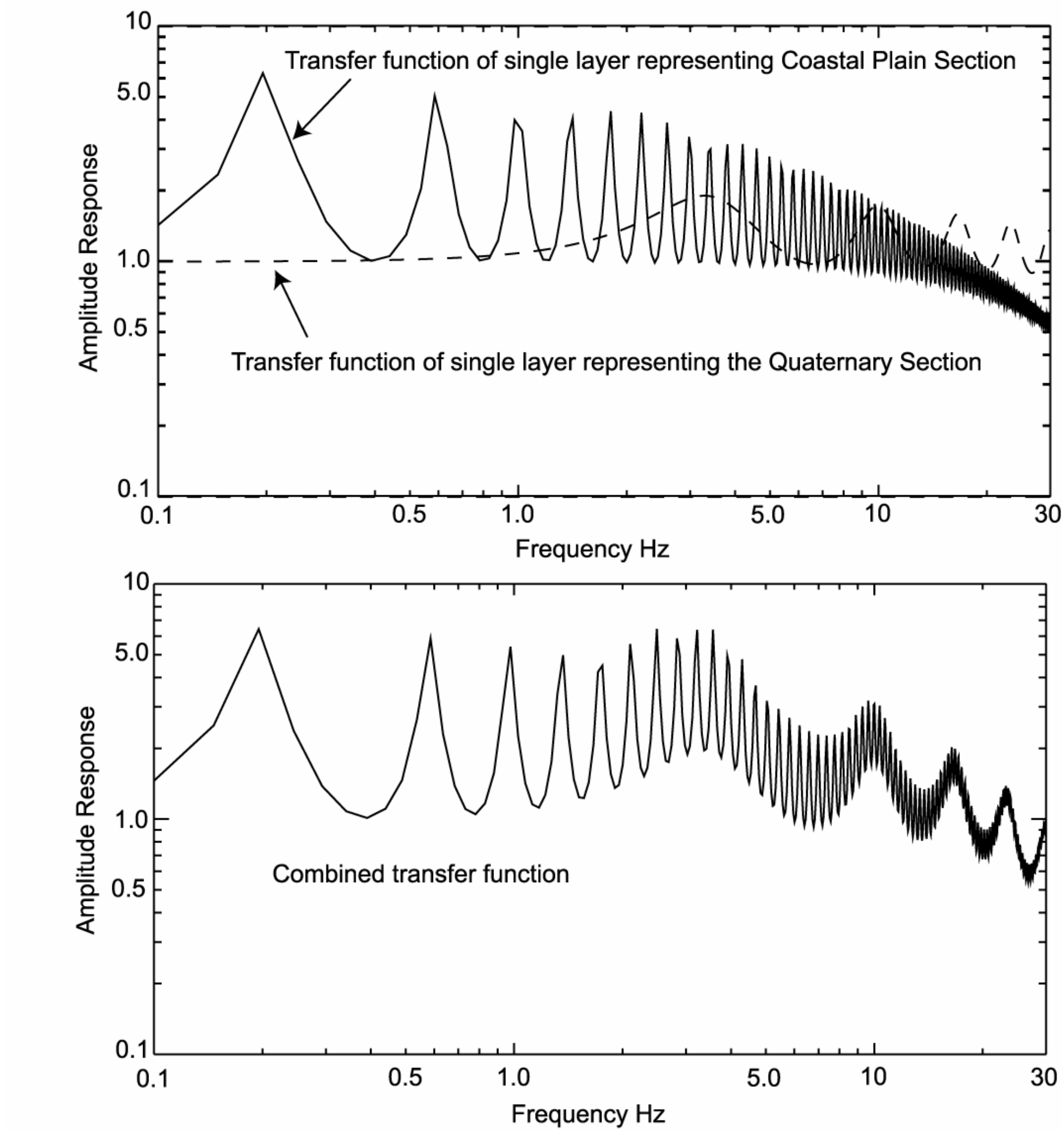

Figure 18. The upper plot shows the Fourier amplitude spectra of single-layer-over-half-space transfer functions representing the total Coastal Plain section (solid line) and the Quaternary section (dashed line). The lower plot shows the combined effect of both geologic features on the Fourier amplitude spectrum of site response. The figure is a gross simplification of the response at any specific site.

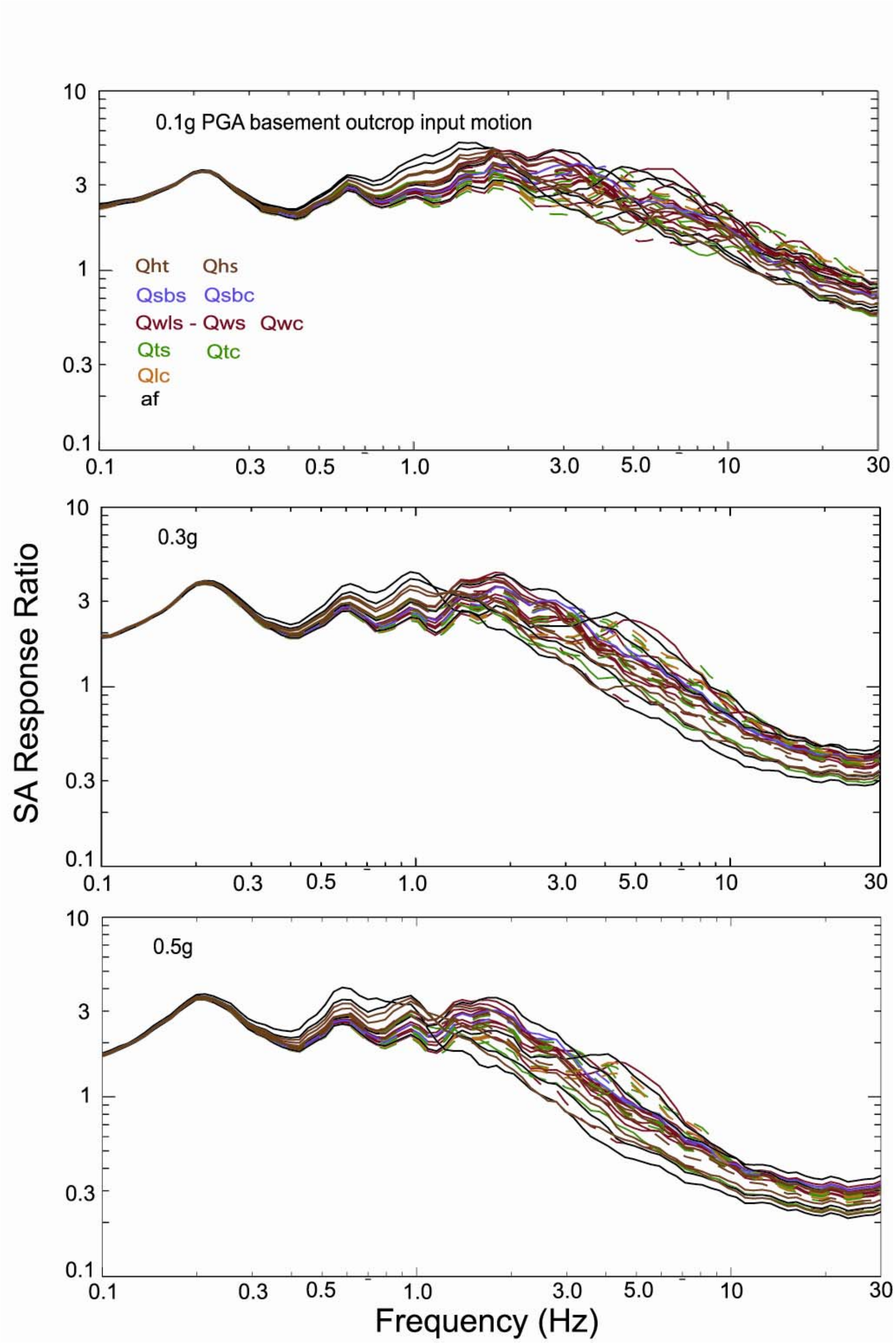

Figure 19. SA response spectral ratios (ground surface divided by basement rock outcrop) for 0.1g, 0.3g, and 0.5g peak acceleration basement rock outcrop input motions. The different colors refer to sites on different geologic units, described in Table 1. Only locations of SCPT investigations are shown.

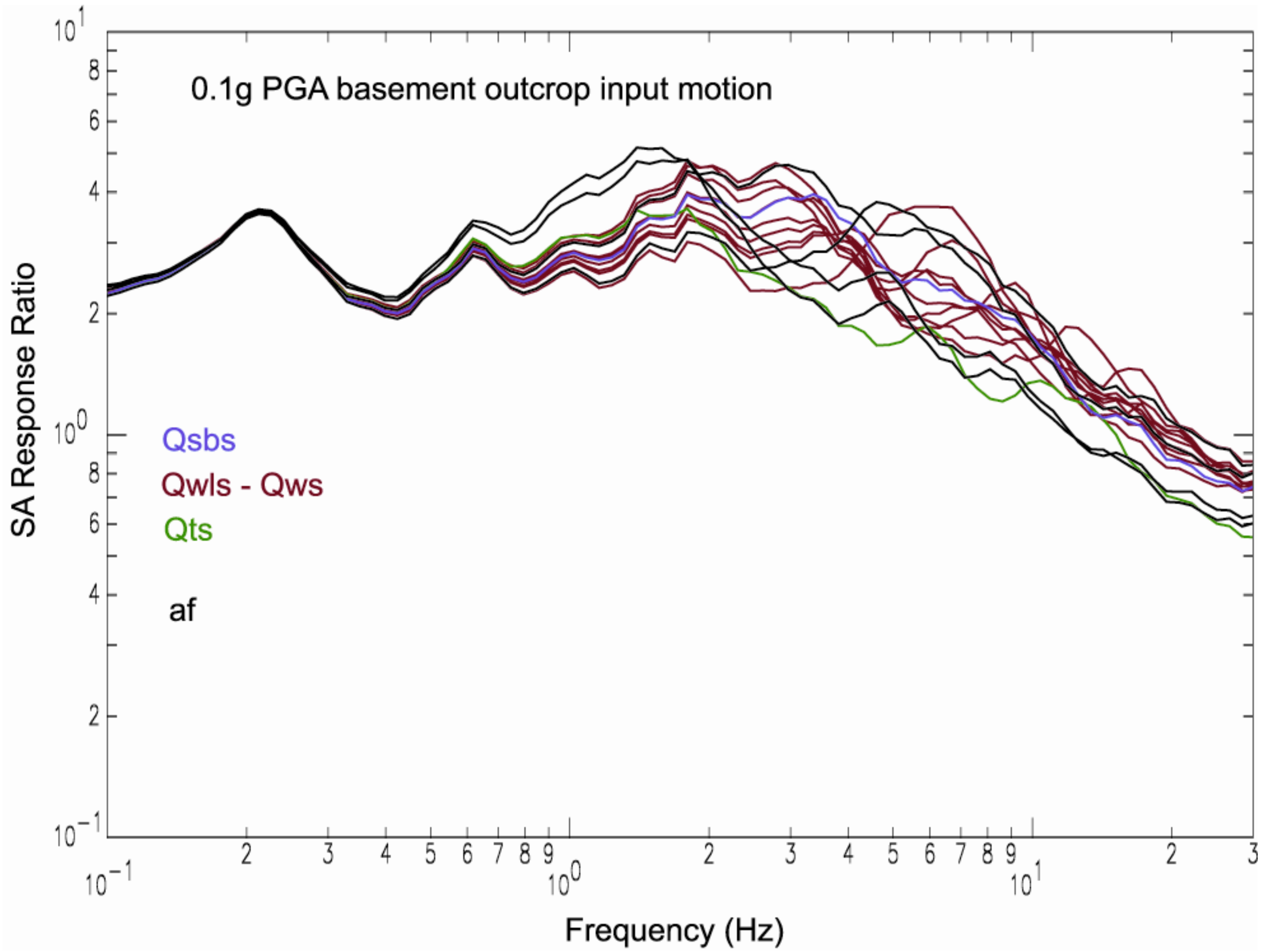

Figure 20. SA response spectral ratios for 0.1g basement outcrop input motion. SCPT sites on beach, barrier-island facies (Qsbs, Qwls, Qws, Qts) and on artificial fill (af).

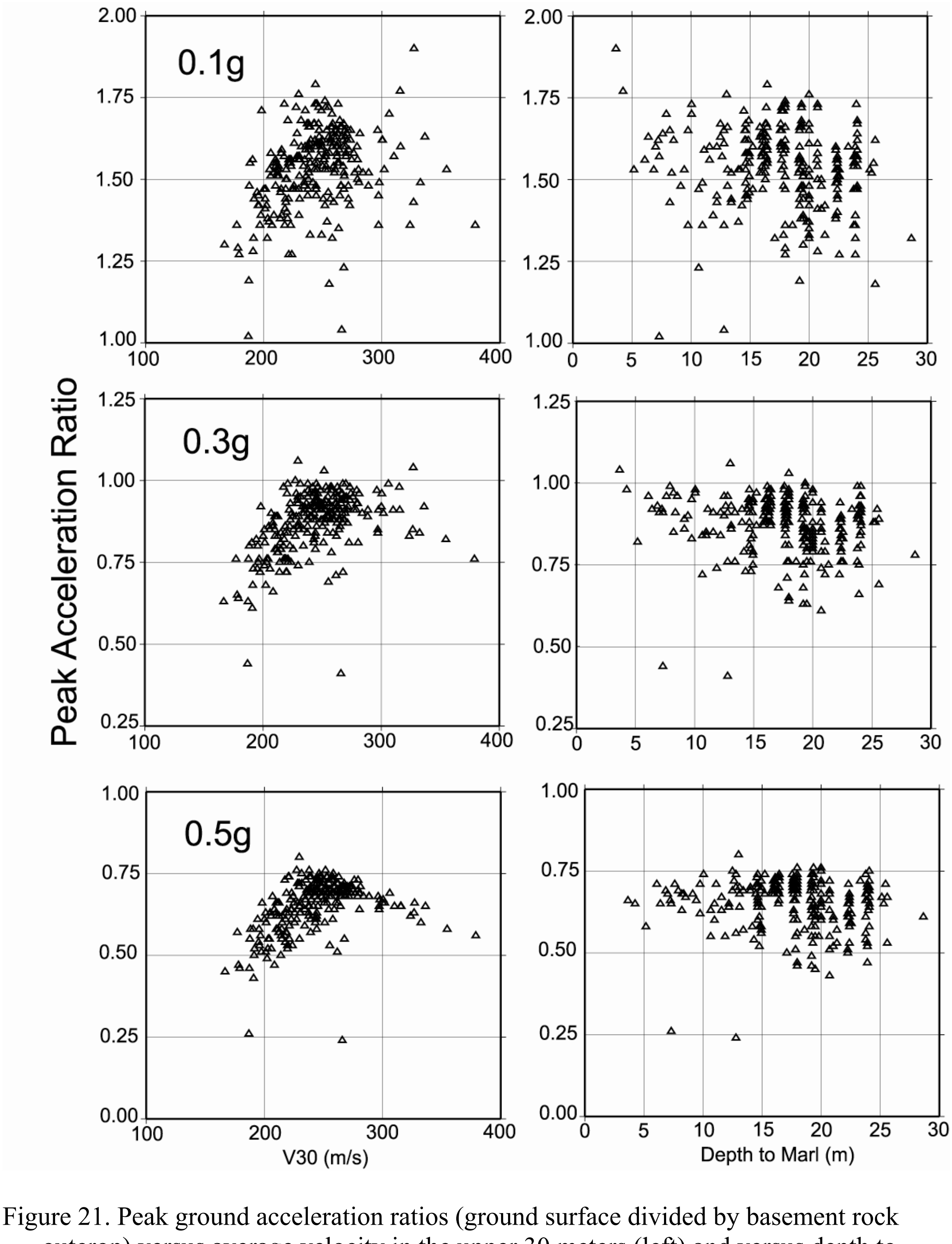

Figure 21. Peak ground acceleration ratios (ground surface divided by basement rock outcrop) versus average velocity in the upper 30 meters (left) and versus depth to marl, or thickness of Quaternary section, (right). The plots are constructed for basement rock outcrop input motion of 0.1g, (top) 0.3g (middle) and 0.5g PGA (bottom).

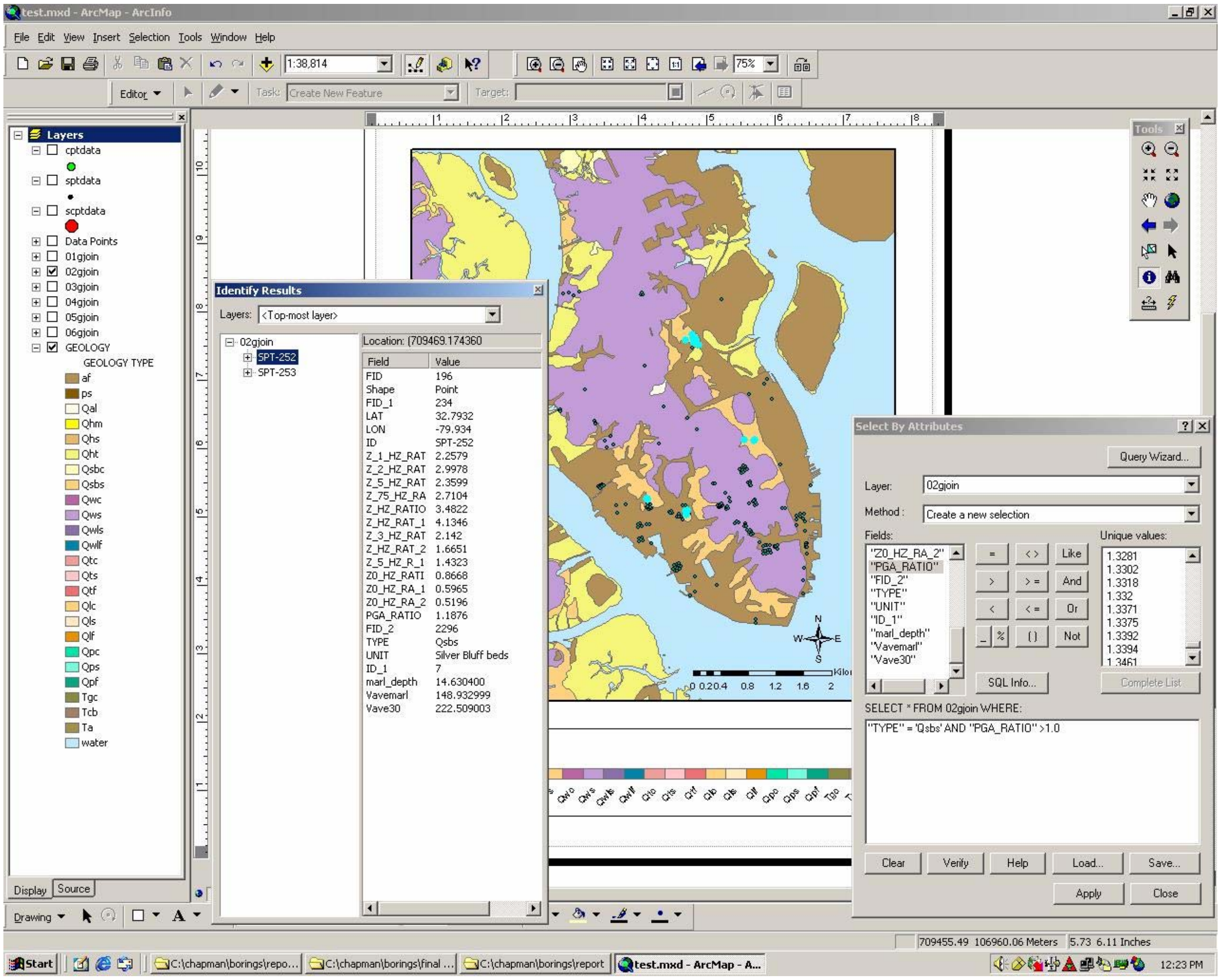

Figure 22. Example of a GIS query. The blue filled circles indicate the sites matching the following conditions: input motion 0.2g, site geologic unit Qsbs, PGA ratio greater than 1.0. The drop-down table on the left shows attribute values for one selected site, and the table on the right shows the query definition.