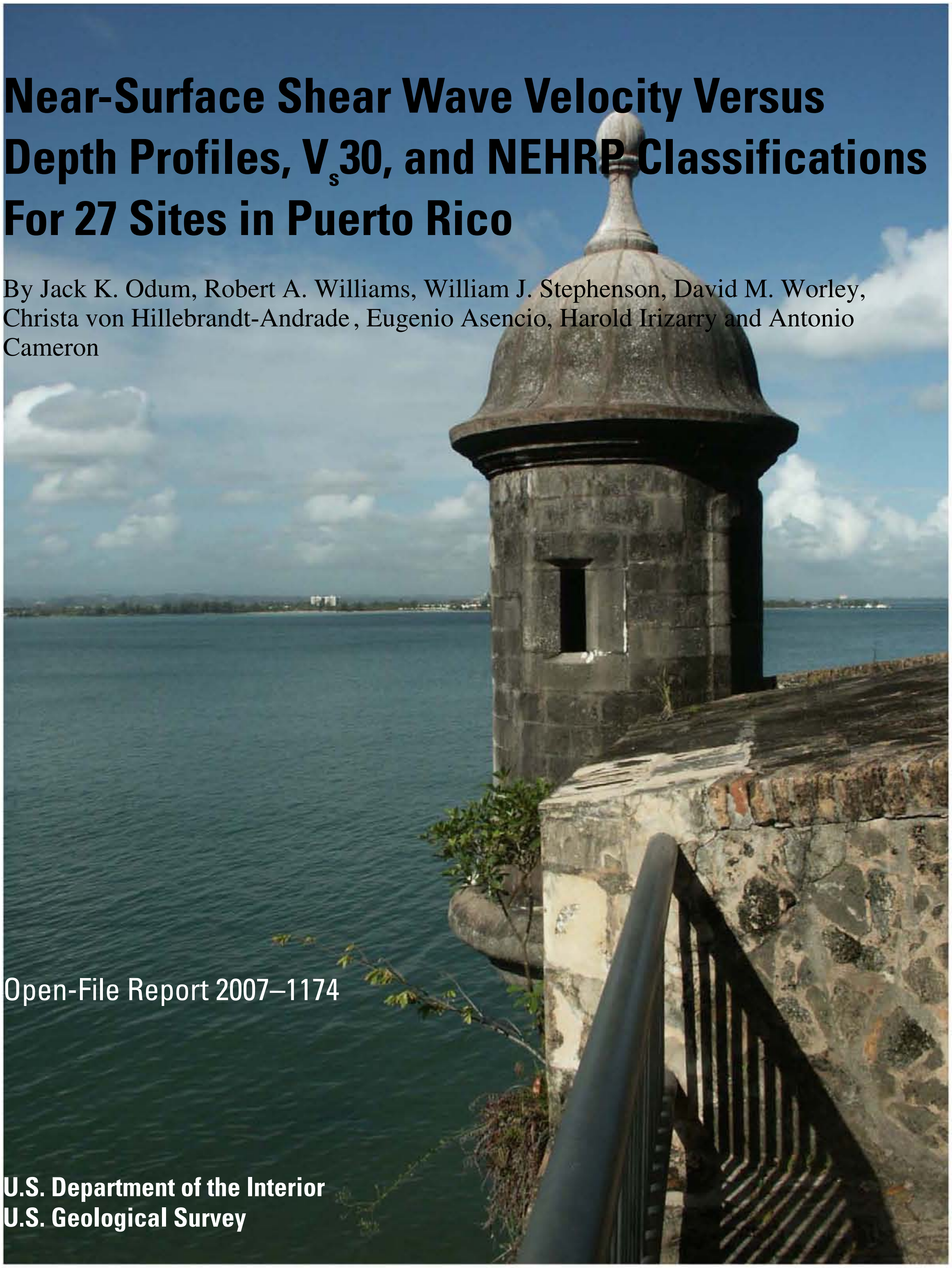

Near-Surface Shear Wave Velocity Versus Depth Profiles, V_s30, and NEHRP Classifications For 27 Sites in Puerto Rico

By Jack K. Odum, Robert A. Williams, William J. Stephenson, David M. Worley, Christa von Hillebrandt-Andrade, Eugenio Asencio, Harold Irizarry and Antonio Cameron

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This report has not been reviewed for stratigraphic nomenclature.

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Abstract

In 2004 and 2005 the Puerto Rico Seismic Network (PRSN), Puerto Rico Strong Motion Program (PRSMP) and the Geology Department at the University of Puerto Rico-Mayagüez (UPRM) collaborated with the U.S. Geological Survey to study near-surface shear-wave (Vs) and compressional-wave (Vp) velocities in and around major urban areas of Puerto Rico. Using noninvasive seismic refraction-reflection profiling techniques, we acquired velocities at 27 locations. Surveyed sites were predominantly selected on the premise that they were generally representative of near-surface materials associated with the primary geologic units located within the urbanized areas of Puerto Rico. Geologic units surveyed included Cretaceous intrusive and volcaniclastic bedrock, Tertiary sedimentary and volcanic units, and Quaternary unconsolidated eolian, fluvial, beach, and lagoon deposits. From the data we developed Vs and Vp depth versus velocity columns, calculated average Vs to 30-m depth (V_s30), and derived NEHRP (National Earthquake Hazards Reduction Program) site classifications for all sites except one where results did not reach 30-m depth. The distribution of estimated NEHRP classes is as follows: three class “E” (V_s30 below180 m/s), nine class ”D” (V_s30 between 180 and 360 m/s), ten class “C” (V_s30 between 360 and 760 m/s), and four class “B” (V_s30 greater than 760 m/s). Results are being used to calibrate site response at seismograph stations and in the development of regional and local shakemap models for Puerto Rico.

Introduction

The Caribbean region has a long prehistoric and historic record of high magnitude earthquakes that are responsible for large numbers of deaths and property destruction. Currently, over 50 million people live within the North American-Caribbean plate boundary zone, and projections are for the population to double by 2050 (Mann, 2005). With a population of approximately 4 million people occupying an island that measures

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170 by 60 km, Puerto Rico has a population density (433 persons/km^2) comparable to Japan and Taiwan (Mann, 2005). As a result of the island's rugged interior terrain, the largest urban centers have developed primarily on the relatively flat, low-lying coastal plains, alluvial plains, and terraces along major rivers (fig.1); all these areas tend to be vulnerable to intense earthquake ground shaking, liquefaction, and landslides. As is true for most developing countries, these most densely populated areas are the location for the rapid construction of everything from well engineered high-rise buildings to large numbers of one- and two-story, poorly built concrete block houses.

Numerous studies over the last few decades have clearly established that Vs in the upper 30 to 60 m can greatly influence the amplification and duration of earthquake ground motions observed at the surface (for example, Borcherdt and Gibbs, 1976; Joyner and others, 1981; Seed and others, 1988). The determination of near-surface seismic velocities is also motivated by their use in the code provisions that place a special significance on shallow Vs (BSSC, 1997). V_S30 data are also a key element in the development of shake maps for Puerto Rico. Future earthquakes are unpreventable, so it is of utmost importance to gather and disseminate the scientific data that will help mitigate at the local level, to the extent that is economically feasible, the effects of these future events.

Generalized Tectonic and Geologic Setting

The geologic and tectonic history of the rocks that make up the island of Puerto Rico spans at least 150 million years. Puerto Rico is part of a shallow subareal platform of the easternmost bank of islands forming the Caribbean Greater Antilles island-arc. This island group lies along the northeastern edge of the Puerto Rico-Virgin Islands microplate, which is located within the active plate boundary created by the convergence, and principally left-lateral translation, of the North American and Caribbean plates (Mann and others, 2002; McCann, 1985). In the Puerto Rico region, it is estimated that the north edge of the Caribbean plate is moving eastward in a strike-slip fashion at a rate of 2 cm/yr along the Puerto Rico trench boundary (Dillon and others, 1999) as the eastern edge of the Caribbean plate overrides the North American plate. Based upon the regional tectonic framework, Puerto Rico is subject to a high degree of seismicity and has a history of large earthquakes. Examples of historical events include a magnitude 7.5 (1946) centered to the northwest, and magnitude 8.1 and 6.9 (1946 and 1953) events centered north of Hispaniola (Dillon and others, 1999). Other large historical events are the 1787 (**M** ~8.1) event, which is believed to have an epicenter in the Puerto Rico Trench area, and the 1767 (**M** ~7.5) event, with an epicenter near the Anegada trough (Dillon and others, 1999). The USGS National Hazard Map estimates that the probability of damaging ground motion for Mayagüez in western Puerto Rico is equivalent to that of Seattle, Washington; other Puerto Rico cities also have substantial risk (Dillon and others, 1999; Frankel and others, 1996).

A generalized geologic map showing the distribution of principle lithologic groups and the location of major faults is presented in figure 2. The island's rugged central core, including portions of the northeast and southeast margins (approximately 44 percent (3,700 km^2) of the surface area), primarily is composed of Late Jurassic to Paleocene and Eocene age sedimentary rocks (volcaniclastic sandstone, siltstone, ash-flow tuff, breccia and conglomerate) and Late Cretaceous and Eocene intrusive plutonic rocks (granodiorite, quartz monzonite, and syenite (Bawiec, 2001)). The developing urban areas of Caguas and Cayey occupy intermountain alluvial valleys that overlie volcanic and volcaniclastic rocks.

The relatively flat-lying northern coastal plain, which extends from the northwestern coastline nearly to the eastern coast, is visible on the SLAR (side-looking airborne radar) mosaic image (fig. 1). A similar, but smaller, coastal plain lies along most of the southwest half of the island. These flat regions consist primarily of Oligocene and younger sedimentary rocks that unconformably overlie the older volcanic and vocaniclasitic rocks (Zapp and others, 1948). Coastal plain rocks (approximately 17 percent (1,500 km^2) of the land surface) are predominantly composed of massive to interbedded sandstone, calcareous clastic rocks, and limestone (Bawiec, 2001). The relatively flat coastal plains are locally modified by karst solution structure and drainage incision as a result of relatively recent island uplift and sea level lowering.

Quaternary deposits cover approximately 24 percent (2,100 km^2) of the exposed land surface and consist of beach, swamp, alluvial fan, plain and terrace, and weakly consolidated to laterized eolian blanket sands at higher elevation. The largest urban developments in Puerto Rico (San Juan and Arecibo on the northern coastal plain, Mayagüez on the west coast, and Ponce and Guayama on the south coast) are situated predominantly in areas of extensive Quaternary deposits that overlie Tertiary clastic and carbonate rocks. A detailed description of the geologic history and lithologic assemblage of each terrain block of Puerto Rico can be found in Bawiec (2001).

Seismic Data Acquisition and Processing

Shear-wave data were recorded using a linear array of 60 4.5-Hz horizontal-component geophones spaced 1.5 m apart. Geophones are single component and oriented perpendicular to the profile direction. The shear-wave seismic source consisted of a wooden timber with steel caps, oriented at right angles to the direction of the profile (parallel to the geophone orientation) placed on pavement or soil beneath the wheels of a vehicle. Reversed-polarity seismic energy was produced by striking opposite ends of the timber with a 4-kg sledgehammer. A set of reversed seismic S-wave profiles at least 87 m in length was collected at each site. The shear-wave profile lengths typically result in a maximum survey depth range of about 30 to 50 m. Where space permitted, a full 87-m-offset shot-point record was obtained at one and or both ends of the profile. All data were used in the construction of the depth versus velocity profiles. In cases where reversed profiles (looking from opposite ends of the profile) are different, two depth versus velocity profiles are plotted and labeled. Differences in interpreted depth and velocity in these situations are generally the result of dipping strata. Similar studies to characterize near-surface materials using surface seismic methods have been conducted by Williams and others (1998, 1999, and 2003) and Odum and others (2003).

Compressional-wave data were recorded using an in-line spread of 60 8-Hz, vertical-component geophones at 1.5-m spacing. Energy for P-wave investigations was generated

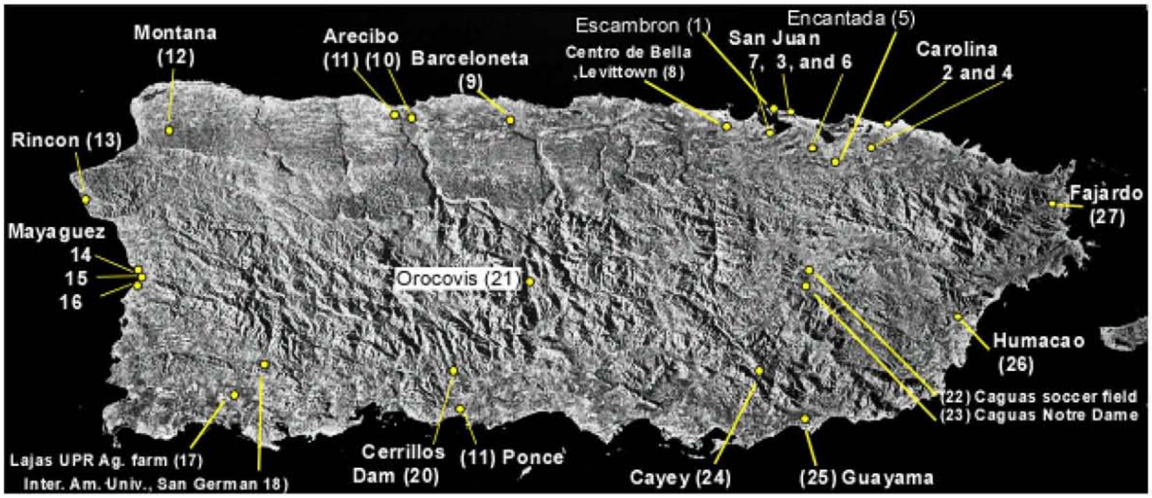


Figure 1. Cartographically accurate high-resolution side-looking airborne radar (SLAR) mosaic image of Puerto Rico. Visible on the image is the extent of the rugged interior terrain that dominates much of the island and the relatively flatter coastal plain platform that extends along most of the northern and south-central portions of the island. Most major urban centers are located along the island margins. Names and numbers refer to city locations and ID site numbers on table 3. Base map modified from Bawiec (2001).

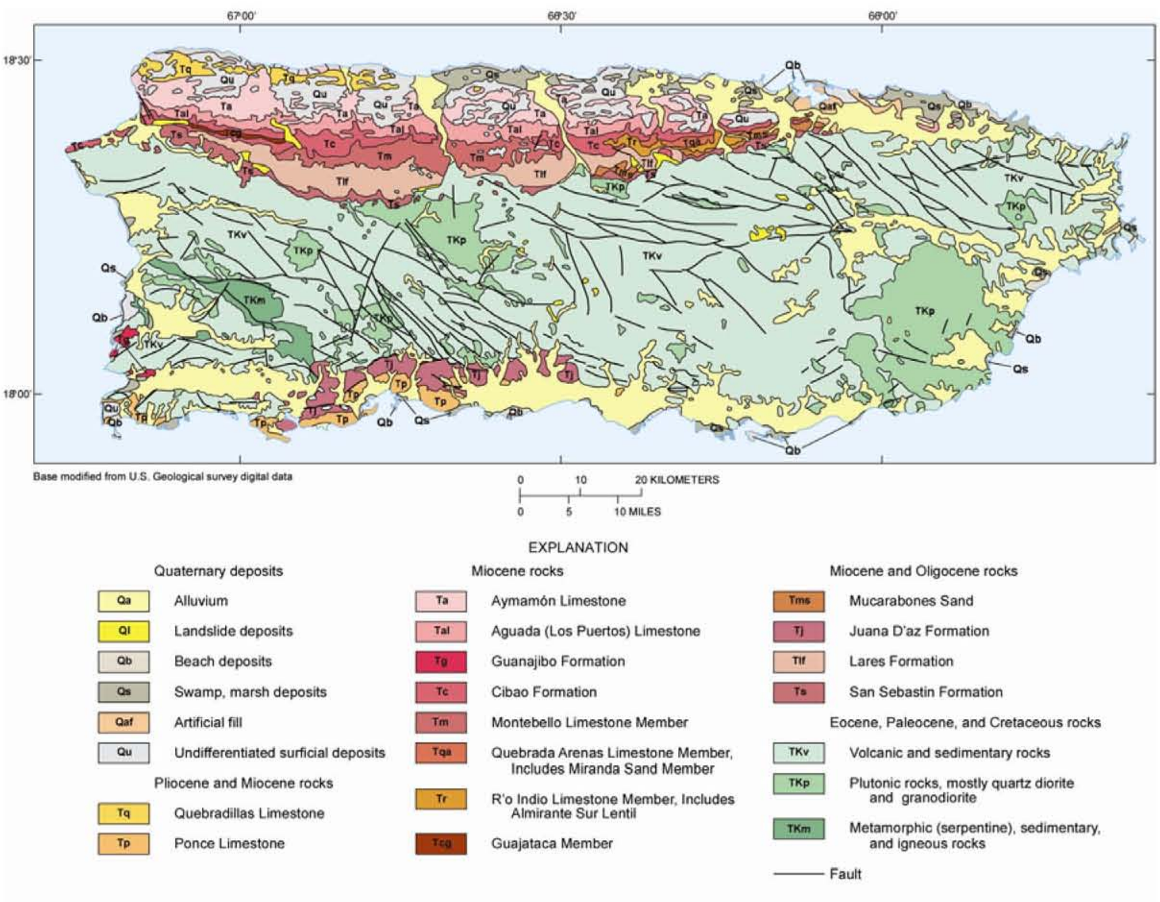


Figure 2. Generalized geology of Puerto Rico from Renken and others (2002).

by vertically striking a steel plate with a 4-kg sledgehammer. Recording parameters for both S- and P-wave surveys are listed in table 1.

Table 1. Seismic-refraction-reflection data recording parameters.

Recording system	Geometrics Strata Visor 24-bit seismograph (60 channels)
Sampling interval	0.001 seconds
Record length	1 second
Recording format	SEG-2
Geophones	60 4.5-Hz horizontal or 8-Hz vertical
Geophone array	Linear with single phones at 1.5-m intervals
Source	4.0-kg sledgehammer on wood timber (S-wave) or steel plate (P-wave)
Source array geometry	Linear, 87-m array lengths

Seismic Data Interpretation

We interpreted refraction data from both the S-and P-wave surveys using the slope-intercept method described by Mooney (1984). Data interpretation generally produced a profile column consisting of 2- to 5- distinct velocity layers for each site. In cases where no additional layers were detected below about 20 m by refraction methods, the maximum imaging depth was approximated by assuming that a higher velocity layer would have been detected on the next geophone beyond the end of the profile (Mooney, 1984). Velocity versus depth profiles and interpreted geology structure columns are presented for each site in the discussion section of this paper. Using the results from the velocity versus depth profiles we calculated the average Vs to a depth of 30 m (V_s30) at each site. According to NEHRP guidelines, V_s30 is determined by

$$V_s30 = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \qquad (1)$$

where d_i is the thickness of the *i*th layer between 0 and 30 m and V_{si} is the velocity of the *i*th layer. The NEHRP building code assigns one of six soil-profile types to a site, from hard rock (type A) to soft soils (types E or F), based on the V_s30 (table 2). These soil profile categories, which are determined for each site in this study, are also part of the International Building Code adopted in 2001 (IBC, 2002).

Discussion of Site Velocities

In this discussion section, sites are grouped by geographical areas as indicated on figure 1. Beginning with the San Juan area on the northeast coastal platform, sites will be discussed in a counterclockwise fashion around the perimeter of the island ending with the sites on the east coast.

TABLE 2. Site categories in NEHRP provisions (BSSC, 1997).

Soil profile type	Rock/soil description	Average S-wave velocity (m/s) top 30 m
A	Hard rock	> 1,500
B	Rock	760 – 1,500
C	Very dense soil/soft rock	360 – 760
D	Stiff soil	180 – 360
E	Soft soil	< 180
F	Special soils requiring site-specific evaluation	

For each site we present a single-page discussion, which contains a depth versus Vs and Vp velocity plot, sometimes a photograph showing the survey lay out, location and NEHRP classification code. Because Vs layer velocities and thicknesses are important to the engineering community and for seismological modeling of site response, a geologic interpretation column correlated to Vs layer plot is also presented. The discussion section of each page primarily will focus on the lithologic units correlations with the Vs depth versus velocity profiles. Table 3 summarizes the velocity information obtained from the velocity versus depth profiles and provides additional information on site location, surficial geologic map-unit symbols, major subsurface geologic units thought to be surveyed, highest velocities recorded in the survey regardless of depth, calculated V_s30 and NEHRP site classification codes (see table 2 for explanation). Geologic names and symbols shown on the interpreted geologic columns are taken from geologic quadrangle maps and may differ from what is shown in the generalized geologic map (fig. 2). There is no correlation between colors shown in columns and the generalized map units in figure 2.

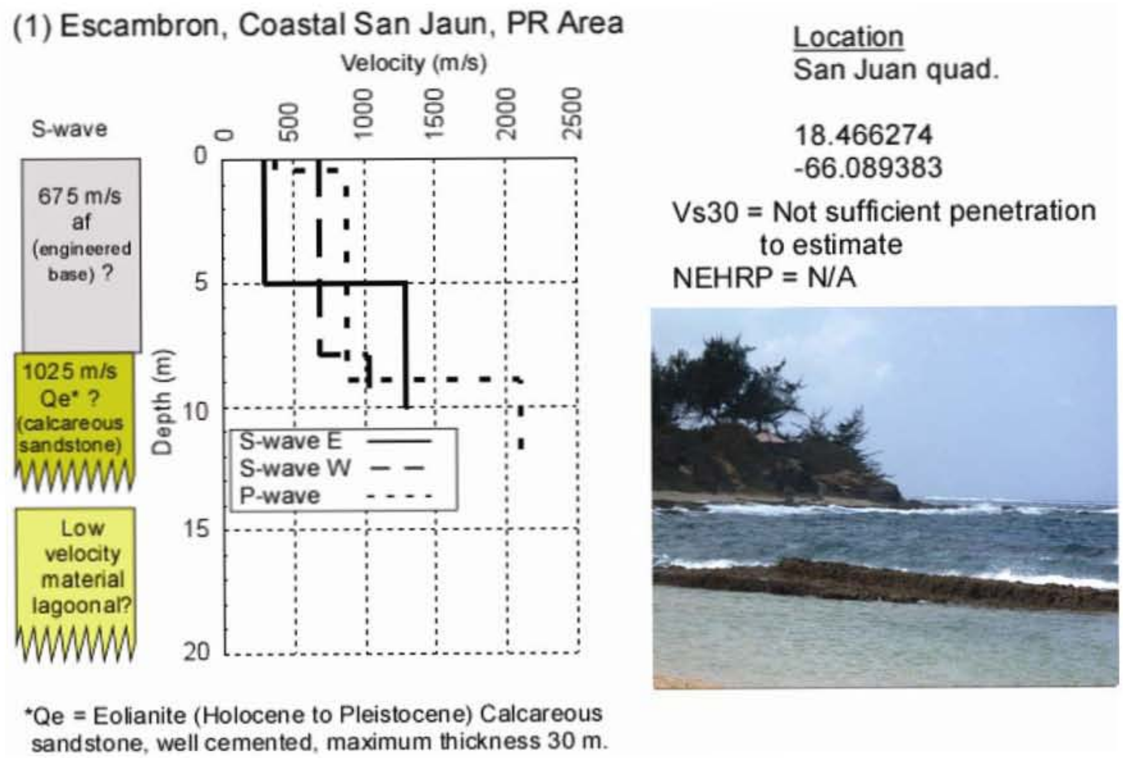
Some of the sites studied in urban areas are located within the infield areas of track stadiums or in other urban settings where the original ground surface has been modified by the addition of artificial fill (af) and/or one or more layers of engineered compacted soil and aggregate. These near-surface layers are seen in the raw seismic data as low-velocity direct arrivals and refracted phases that are the first arrivals near the seismic source position. Shown in many of the velocity versus depth columns are one or two thin layers 1 to 3 m thick with velocities faster than the underlying undisturbed geologic materials. For the higher-velocity surface layers, we roughly estimate the thicknesses because only one or two data points are available to define them, and the thicknesses of these layers are not well constrained when a higher velocity layer does not immediately underlie the artificial layer. The total thickness of these surface layers is probably less than what is calculated. In this study all calculated velocity layers are used in the calculation of V_s30 and NEHRP site classification.

Table 3. Site locations of investigations, surficial geology, V_s30 velocity, NEHRP site classification Code, and geologic unit information for seismic refraction-reflection surveys in Puerto Rico.

Site name	V_s30 (m/s)	NEHRP soil type	Highest recorded Vs (m/s)	Highest recorded Vp (m/s)	Imaged(?) geologic units	Description	Site location
(1) Escambron, San Juan, coastal	See text	* ?	1,025 @ 5 m	2,085 @ 9 m	Qe Qs Tay?	Eolianite-calcareous reef lagoon bay mud? Aymamon Limestone?	N 18°27' 59" W 66° 05' 22"
(2) Carolina Beach, San Juan	290	D	290 @ 1 m	1,645 @ 2 m	Qb Tay	Beach deposits (sand) Aymamon Limestone	N 18°26' 53" W 65° 59' 56"
(3) Barbosa Ocean Park, San Juan, coastal	285	D	545 @ 38 m (?)	2,030 @ 7 m	Qb/Qss QTt Tay	Beach sand (thin) Older alluvial deposits Aymamon Limestone	N 18°27' 05" W 66° 02' 57"
(4) Carolina, UPR track, San Juan area	515	C	1740 @ 12 m	3,324 @ 12 m	Qal/QTt Kf	Alluvium, older alluv. Frailes Fm. Upper Cret.	N 18°23' 14" W 65° 57' 23"
(5) Encantada, San Juan area	1,410	B	2212 @ 10 m	4,214 @ 9 m	Qal Tg	Alluvium, older alluv. Guaracanal (Andesite)	N 18°21' 22" W 65° 59' 37"
(6) San Juan Univ. track, San Juan	415	C	440 @ 1.5 m	1,870 @ 12 m	Qt Tay Ta	Alluvium-terrace Aymamon Limestone Aguada Limestone	N 18°24' 32" W 66° 02' 44"
(7) Estadio P. Cepeda, San Juan area	173	E	535 @ ~52 m	1,821 @ 5 m	Af-Qa Qs/Qa Tay	Artificial fill alluvium Swamp-older alluvium Aymamon Limestone	N 18°26' 15" W 66° 07' 31"
(8) Centro de Bellas Artes, San Juan area	305	D	450 @ 15 m	1,865 @ 10 m	Qal/Qt Tay	Alluvium-terraces Aymamon Limestone	N 18°26' 15" W 66° 10' 38"
(9) Barceloneta	170	E	460 @ 22 m	1,790 @ 9 m	Qal Tay	Alluvium Aymamon Limestone	N 18°27' 30" W 66° 32' 23"
(10) Arecibo airport	433	C	*630 @ 23 m	1700 @ 3.0 m	Qal/Ql QTb Tay	Lagoonal deposits Blanket deposits Aymamon Limestone	N 18°26' 55" W 66° 40' 28"
(11) Arecibo, college track	378	C	570 @ 33 m	3,324 @ 10.0 m	QTb Tcu	Blanket deposit Camuy Fm.	N 18°26' 55" W 66° 40' 28"
(12) Montana	985	B	1220 @ 8 m	1,700 @ 2.5 m	Qc/QTb Tay/Ta	Colluvium-Blanket dep. Aymamon/Aguado Ls.	N 18°21' 03" W 66° 06' 13"
(13) Rincon	1,045	B	2385 @ 16 m	3,690 @ 14 m	af Tv	Artificial fill Tertiary volcanic rock	N 18°21' 02" W 67° 16' 08"
(14) Mayagüez, El Seco ball field	212	D	445 @ 38 m	1,833 @ 8 m	Qal Ky	Alluvium Yauco Fm-saprolite	N 18°12' 47" W 67° 09' 34"
(15) Mayagüez, UPR track	200	D	2400 @ 18 m	4,400 @ 11.5 m	Ky	Yauco Fm-saprolite	N 18°21' 30" W 67° 16' 06"

Site name	V_s30 (m/s)	NEHRP soil type	Highest recorded Vs (m/s)	Highest recorded Vp (m/s)	Imaged(?) geologic units	Description	Site location
(16) Mayagüez, Candelaria	200	D	355 @ 18 m	1,980 @ 3.5 m	Qal Ky ?/ Kmr ?	Alluvium Yauco Fm-saprolite	N 18º 11' 42" W 67º 04' 22"
(17) Lajas, Agri-culture Station	435	C	1675 @ 31 m	2,735 @ 15 m	Qaf Kl?/ Kc?	Alluvial fan Volcanics weathered-Cotui Limestone	N 18º 02' 03" W 67º 9' 02"
(18) San German, Inter. Am. Univ.	650	C	1,320 @ 6 m	3050 @ 6 m	Kjs	Serpentinite	N 18º 04' 58" W 67º 02' 56"
(19) Ponce, Univ. Catolica track	163	E	505 @ 26 m	1,580 @ 3.5m	Qaf Tp Tje	Alluvial fan deposit Ponce Limestone-calcareous sandstone	N 17º 59' 58" W 66º 37' 10"
(20) Cerrillos Dam, mountains	925	B	1,545 @ 13 m	3,640 @ 15.0 m	Tm	Monderrate Fm	N 18º 04' 33" W 66º 34' 46"
(21) Orocovis, central mountains	225	D	1,470 @ 34 m	2500 @ 10 m	Ql bedrock	Landslide deposits Cret. volcanic rock	N 18º 10' 31" W 66º 25' 59"
(22) Caguas, soccer field	285	D	1910 @ 42 m	1,820 @ 6 m	Qt Kn	Older alluvial deposits Los Negros Fm.-volcanic tuff	N 18º 15' 16" W 66º 2' 28"
(23) Caguas, Notre Dame	395	C	660 @ 22 m	2,125 @ 4 m	Qa? Qt Kgc	Older alluvial deposits Granodiorite	N 18º 13' 57" W 66º 1' 38"
(24) Cayey, Observatory	285	D	800 @ 100 m?	1,645 @ 7 m	Qal Ka	Alluvium-colluvium Volcanic flows-breccia	N 18º 6' 42" W 66º 8' 56"
(25) Guayama	460	C	1675 @ 25 m	3,685 @ 16 m	Qaf Ka	Alluvial fan Volcanic flows-breccia	N 17º 58' 39" W 66º 8' 56"
(26) Humacao, CUH track	330	C	775 @ 25 m	2,825 @ 22 m	Qa/Qaf Klg	Alluvium-fanglomerate Granodiorite	N 18º 08' 45" W 65º 50' 06"
(27) Fajardo, Airport ball field	425	C	920 @ 45 m	2,985 @ 37 m	Qal Kftu	Alluvium Fajardo Fm.	N 18º 18' 54" W 65º 39' 49"

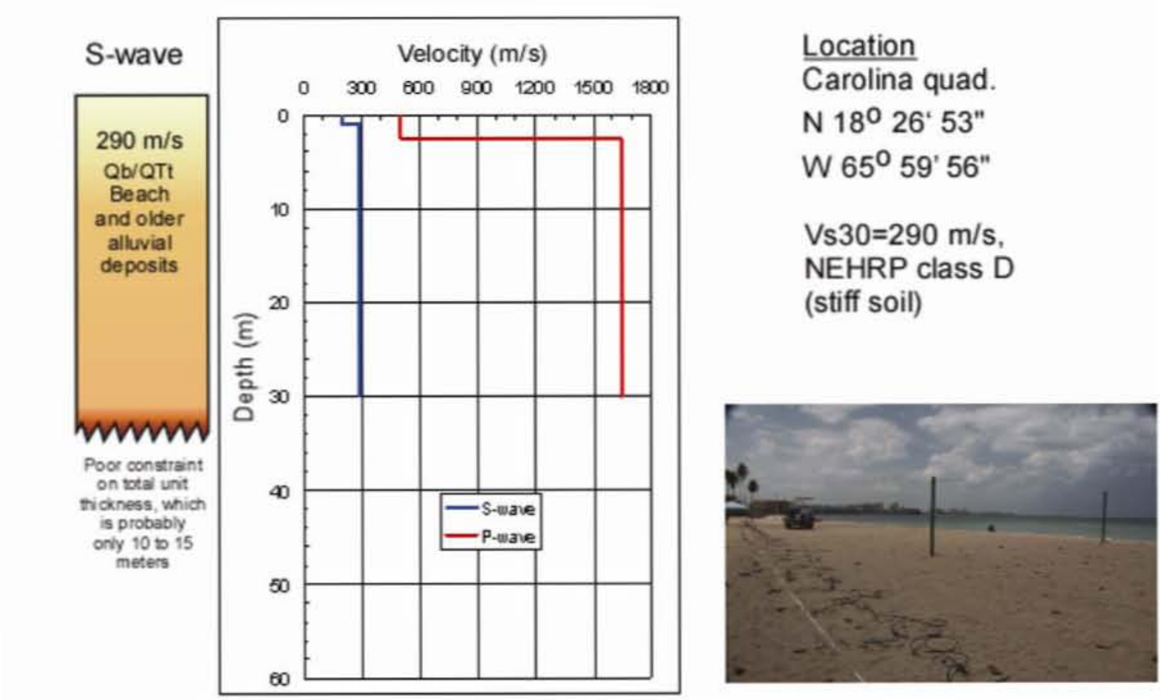
See figure 1 for site approximate locations. Surficial map units and geologic unit abbreviations are taken from 1:24,000 quadrangle maps and might not correlate with the generalized geologic units on figure 2. Q – Quaternary; T– Tertiary; K – Cretaceous; J – Jurassic. (*) See text discussion for this site.



The location of this site is within 30 m of the ocean front in an area that has been artificially filled for construction (fig. 1). Acquisition conditions were poor due to a high level of cultural noise and limited working area, which prevented off-end shots needed for deeper imaging. All plotted layer depths are poorly constrained and therefore represent only rough estimates of the true layer thickness.

The depth versus velocity curves show two distinct velocity layers in the upper 10 m. Difference in “S-wave E” and “S-wave W” (indicating data records recorded looking east and west along the geophone array) profiles is attributed to dipping strata. Based on a first-break phase termination of the P- and S-wave first arrivals, we suspect that there is a low-velocity zone underlying the high-velocity layer. Our data suggest that the thickness of the high-velocity (Vs=1,025 m/s) layer is at least 2 meters, but, unfortunately, say little about the low-velocity layer. We interpret the first layer (Vs=675 m/s) to be artificial fill consisting of large bedrock pieces and/or concrete rubble. The second layer, Vs=1,025 m/s, we interpret to be “reef rock” (eolianite). Eolianite, which is Pleistocene to Holocene, consists of well-cemented calcareous fine, to coarse-shell fragments and sand. This reef rock is exposed just offshore as is shown by the dark band of rock in the foreground of the photo above and is mapped throughout the area with a maximum thickness of about 30 m (Pease and Monroe, 1977). The depositional processes forming this unit would cause it to stratigraphically transgress and regress with sea level fluctuations, thus it is plausible that the imaged unit overlies older lagoonal deposits. There is a possible P-wave reflection (from the base of the low-velocity zone?) that indicates that the base of the low-velocity zone could be at about 50- to 55-m depth. At site 7 (Estadio P. Cepeda, see fig. 1), located on the south west side of the Bahia de San Juan, Cretaceous bedrock, believed to be Aymamon Limestone (Tay), was interpreted at 52-m depth (Odum and others, in press). Because the depth of imaging is less than 30 m, neither a V_s30 or NEHRP classification is determined for this site.

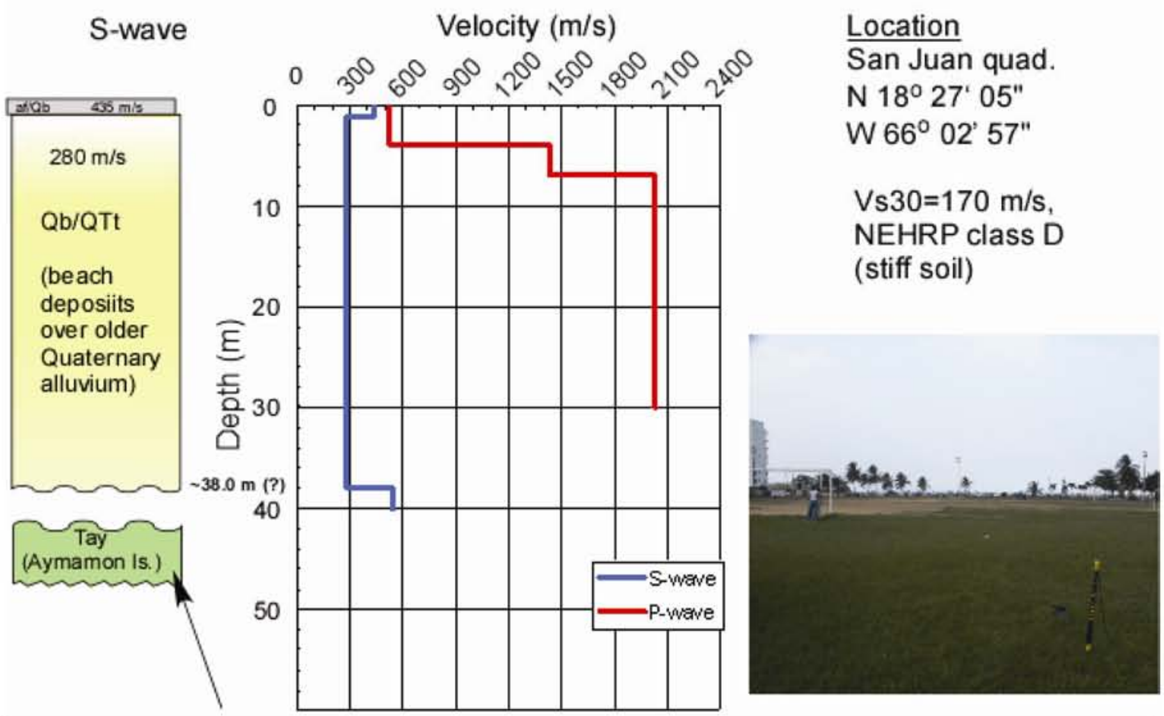
(2) Carolina Beach, Coastal San Juan, PR Area



The Carolina Beach site lies directly on beach sand (Qb) approximately 0.3 km north of the eastern portion of San Juan International Airport and 7 km east of downtown San Juan (visible in background center of photo above). Surficial geologic units at this site are Holocene to Pleistocene beach and abandoned beach-ridge deposits, which consist of fine-to-medium-grain quartz sand and shell fragments generally less than 10 m thick (Monroe, 1977). The modern units locally overlie older Pleistocene to Miocene (QTt) units consisting of beach, high terrace, and alluvial fan deposits, and these unconsolidated units unconformably overlie Miocene Aymamon and Aguada Limestones.

Although two Vs layers were identified (uppermost unit is 1 m thick and not shown), we believe that only one geologic unit is present. We interpret this unit (Qb/QTt) to be composed of modern and older beach deposits possibly interfingered with alluvial fan material at depth. Due to the coarse and unconsolidated nature of this deposit, shear-wave energy from the timber placed directly on the beach sand attenuates quickly. Although a strong reflection boundary was not observed in the data, the actual thickness of the Qb/QTt unit is probably less than the 30 m indicated on the figure above. Geologic mapping indicates that this material has a wide distribution in the San Juan coastal area (Pease and Monroe, 1977). The V_s30 for this site is 285 m/s, which is NEHRP soil type “D” (stiff soil).

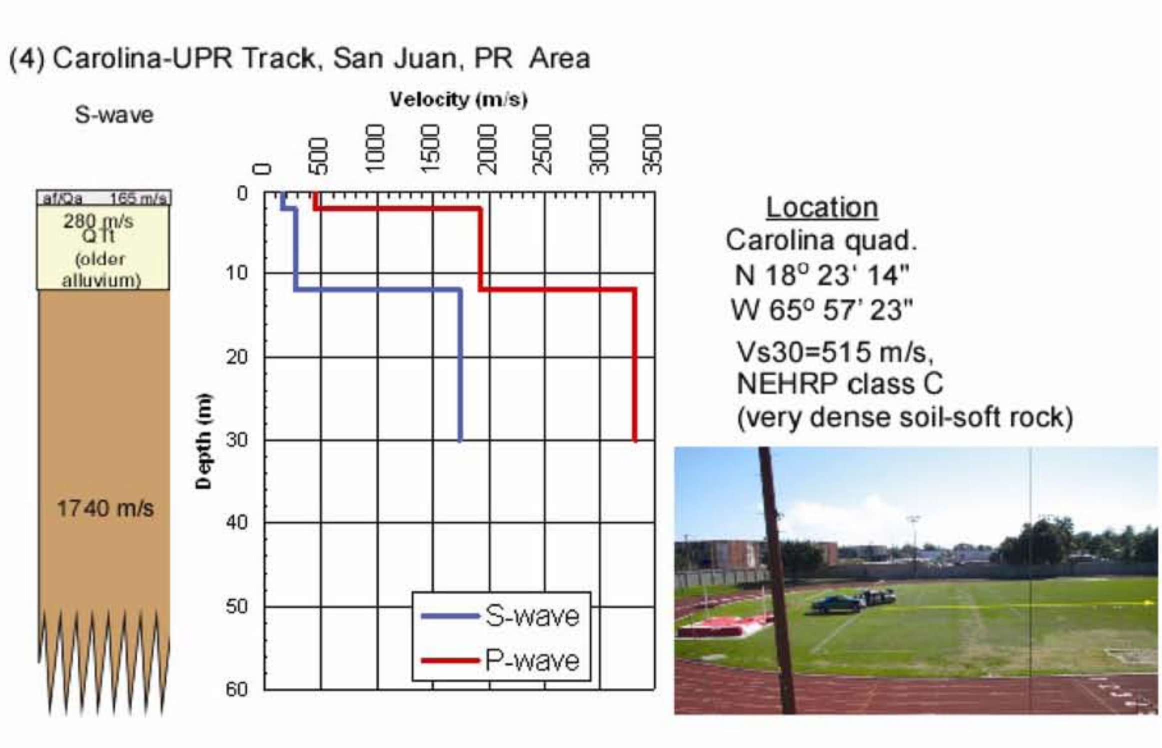
(3) Barbosa Park, Coastal San Juan, PR Area



Reflector between units exists; however, interpreted depth is poorly constrained and is believed to be shallower.

The Barbosa Park site is located in a similar geologic setting as the Carolina Beach site (site 2) with the primary difference being that Barbosa Park is approximately 100 m inland of the currently active beach and lies in an area of urban development (fig. 1).

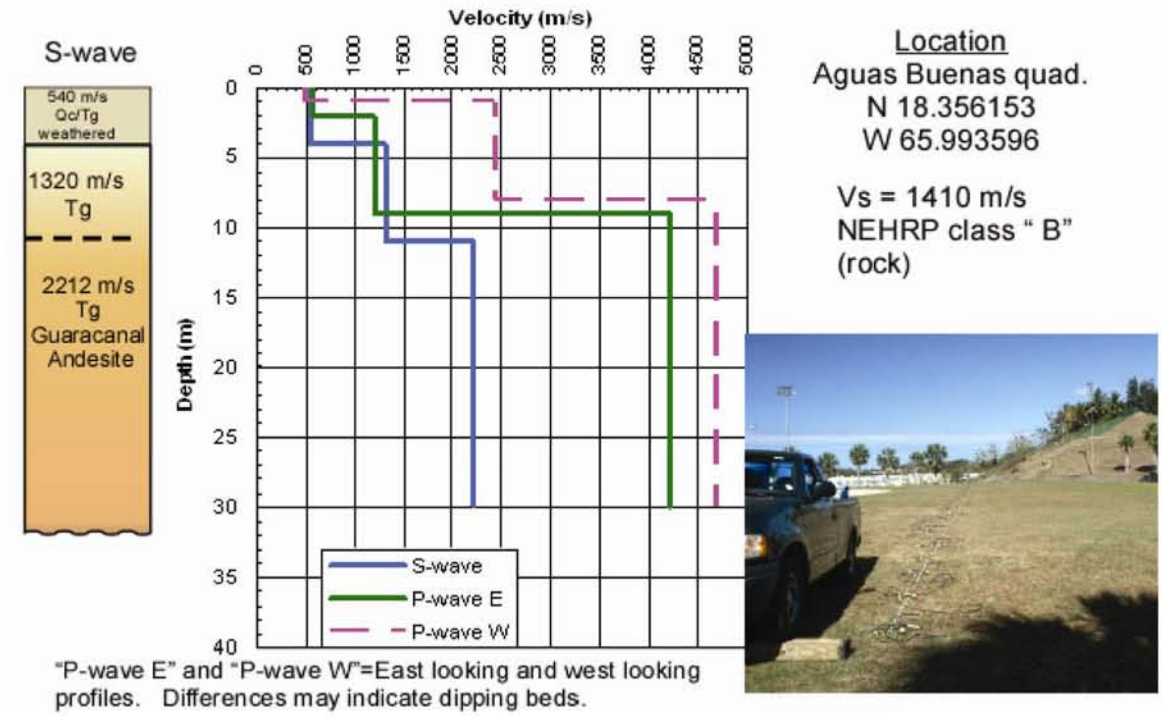
The Vs depth versus velocity profile for this site shows two layers; the uppermost layer with a Vs=280 m/s and the lower layer with a Vs=545 m/s. Based on similarity in the geologic setting and layer velocities (Vs=280 m/s at this site and Vs=290 m/s at the Carolina Beach site), we interpret the upper layer to be Qb/QTt. Based on geologic position and similarity of velocity, we interpret the deeper layer, Vs=545 m/s, to be Aymamon Limestone (Tay). The thickness of the Qb/QTt layer is poorly constrained and is probably less than the calculated depth of about 38.0 m. The V_s30 for this site is 285 m/s, which corresponds to a NEHRP type classification of “D” (stiff soil).



The track and field complex located within the city of Carolina is located approximately four km inland from the coast and at an elevation of approximately 10 m (figs. 1 and 2). Near-surface geology is mapped as Pleistocene. Lithologic units are believed to be older terrace and alluvial-fan materials (QTt) with a thin veneer of Holocene alluvium (Monroe, 1977). These units unconformably overlie the Upper Cretaceous Frailes Formation, which is composed of calcareous mudstone, medium- to thick-bedded volcanic sandstone, and volcanic breccia (Monroe, 1977).

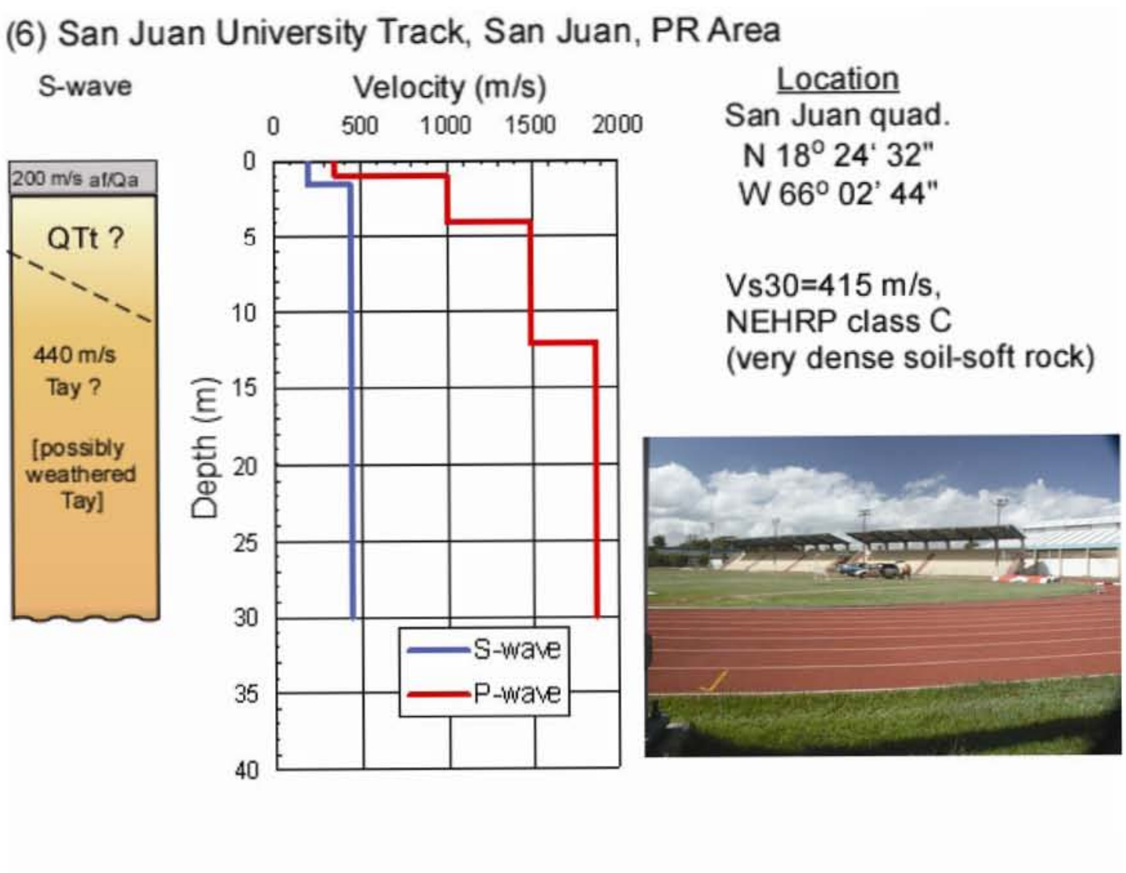
Two primary geologic units beneath a thin surficial layer are identified from the seismic velocity structure at this location. The unit from 2- to 12-m depth (Vs=280 m/s) is interpreted to be the geologic unit QTt; however, the interpreted 10-m thickness of this unit possibly includes a weathered zone of the underlying Upper Cretaceous Frailes Formation. The Vs and Vp of this unit is similar to that of other interpreted QTt units. We interpret the higher velocity (Vs=1,740 m/s) unit to be the Frailes Formation (Kf). The V_s30 for this site is 515 m/s, which is NEHRP type "C".

(5) Encantada, Foothills San Juan,PR Area



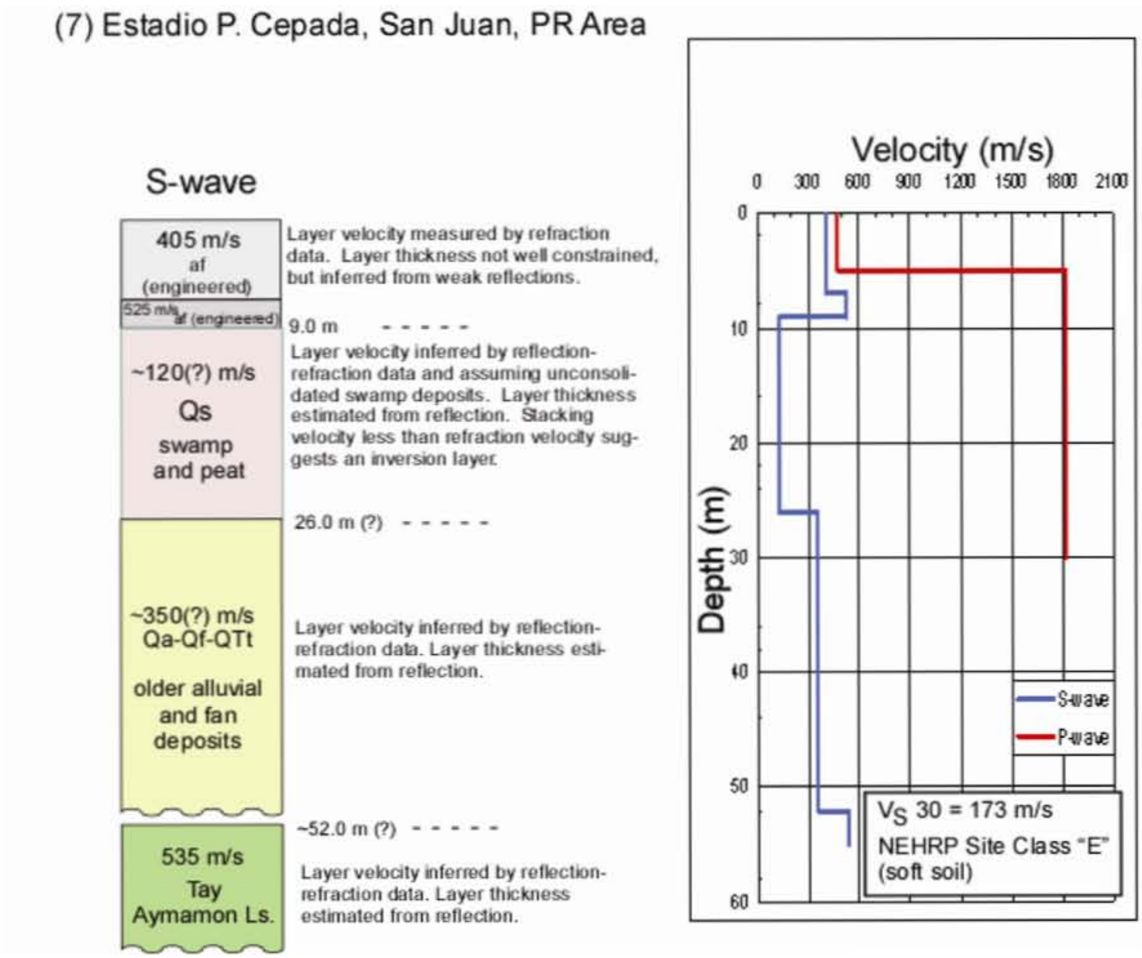
This site is located approximately 10 km inland from the ocean front, at an elevation of approximately 30 m, and lies within the southern foothills of the San Juan area. Portions of the athletic field where the survey was conducted have been excavated to flatten the area, and weathered volcanic bedrock is exposed in the surrounding hills (see photo above). To calculate the V_s30 for this site, we used an average of the shear-wave data from the two profiles to generate the depth versus velocity profile (blue line). These profiles should be considered to be an average for this site because, as was true with the P-wave profiles, the east and west profiles look different.

Depth versus velocity curves and geologic interpretation of Vs layers are shown above. Geologic mapping indicates that the hills are composed of Tertiary volcanic and volcaniclastic rock units (Pease, 1968). The layer from 0 to 4 m, Vs=540 m/s, is interpreted to be soil, slope colluvium (Qc), and probably includes some weathered bedrock material. The layers from 4 to 11 m, 1,320 m/s, and below 11 m, 2,212 m/s, are interpreted to be units in the Guaracanal Andesite with the upper layer representing weathered material and/or an interbedded unit (example given, breccia and tuff). The V_s30 for this site is 1,410 m/s, the highest value measured in this study, and corresponds with NEHRP class "B" (rock).

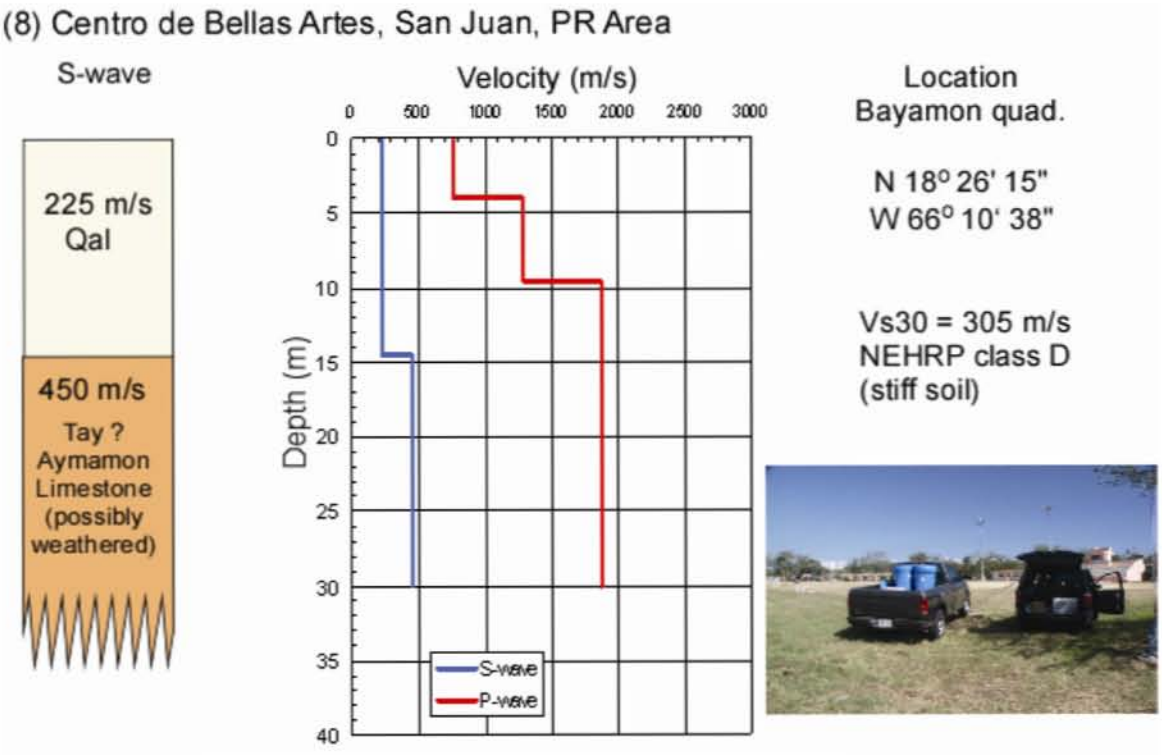


This site is located at an elevation of 25 m and approximately 5.5 km from the coast line (figs. 1 and 2). The geologic setting is similar to the Carolina-UPR track site in that it is several kilometers inland from the ocean front and is in the vicinity of hills composed of Tertiary and older bedrock. Geologic mapping indicates the surficial unit at this site is QTt (Monroe, 1977).

Beneath a thin layer of artificial fill (af) and soil, only one velocity layer was identified from the seismic refraction-reflection data. Although the surficial map unit is QTt, the calculated unit thickness at this site is uncertain and may be less than 30 m as plotted. Approximately 200 m to the north of the site is an outcrop of Aymamon Limestone (Tay). The Vs of 440 m/s is higher than what has been determined for the QTt unit at other sites and lower than the typical values of 525-630 m/s that have been calculated for the Aymamon Limestone (Odum and others, in press). We speculate that the material imaged at this site may consist of unconsolidated QTt material and that the QTt may be partially cemented by calcareous enriched ground water from the underlying partially weathered Aymamon Limestone (Tay). Information from geotechnical borings are needed to better constrain the thickness of the QTt at this site. The V_s30 for this site is 415 m/s, which makes it a NEHRP class “C” site (very dense soil-soft rock).

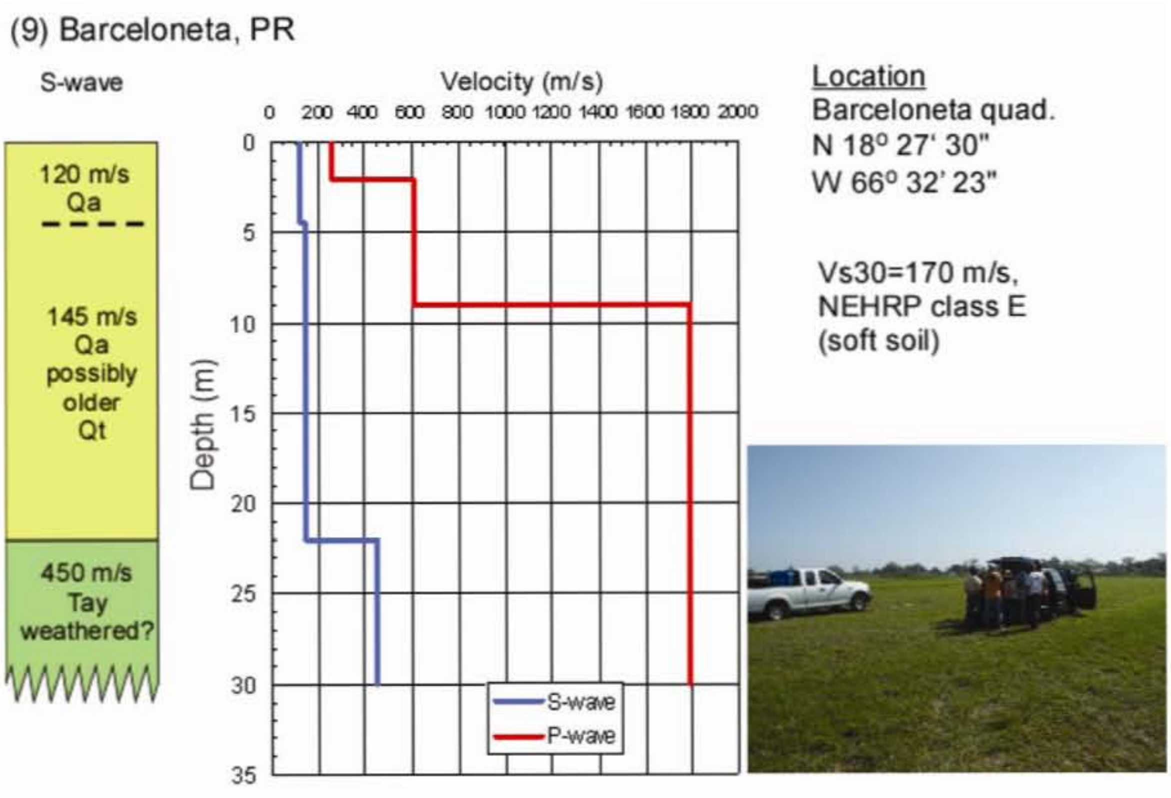


The Estadio Pedro Cepeda stadium is built on an artificial fill surface, which overlies bay mud and swamp deposits associated with Bahía de San Juan (Kaye, 1959). This site has a complex stratigraphic sequence as is indicated by the presence of five interpreted velocity layers that include a low velocity unit bounded on either side by higher velocity layers. We interpret the layers from 0- to 7-m (Vs = 405 m/s) and 7- to 9-m (Vs =525 m/s) depth to be engineered artificial layers associated with construction site stabilization over the bay and swamp deposits. From approximately 9- to 26-m depth (Vs = ~120 m/s) there is a low-velocity layer which we interpret to be bay mud, swamp, and peat (Qs). At this location a thickness of 17 m or more is very reasonable for this unit, as Kaye (1959) reported that a logged water well at the U.S. Naval Reservation (3.5 km away on the northeast side of Bahía de San Juan) penetrated 25 m of bay mud and swamp material (Qs). The Vs determined for this Qs unit is similar to those determined for similar lithologic deposits at other locations (in example 55-100 m/s San Francisco bay mud (Fumal, 1978)). The layer from ~26- to ~52-m depth (Vs=~350 m/s) is interpreted to be older alluvium and alluvial fan and terrace deposits (QTt), which are expected to be found in this stratigraphic position. The deepest layer, below ~52 m (Vs = ~535 m/s), is interpreted to be the Aymamon Limestone (Tay). The V_s30 for this site is 173 m/s, the lowest value measured in this study, and corresponds with a NEHRP category "E" (soft soil).



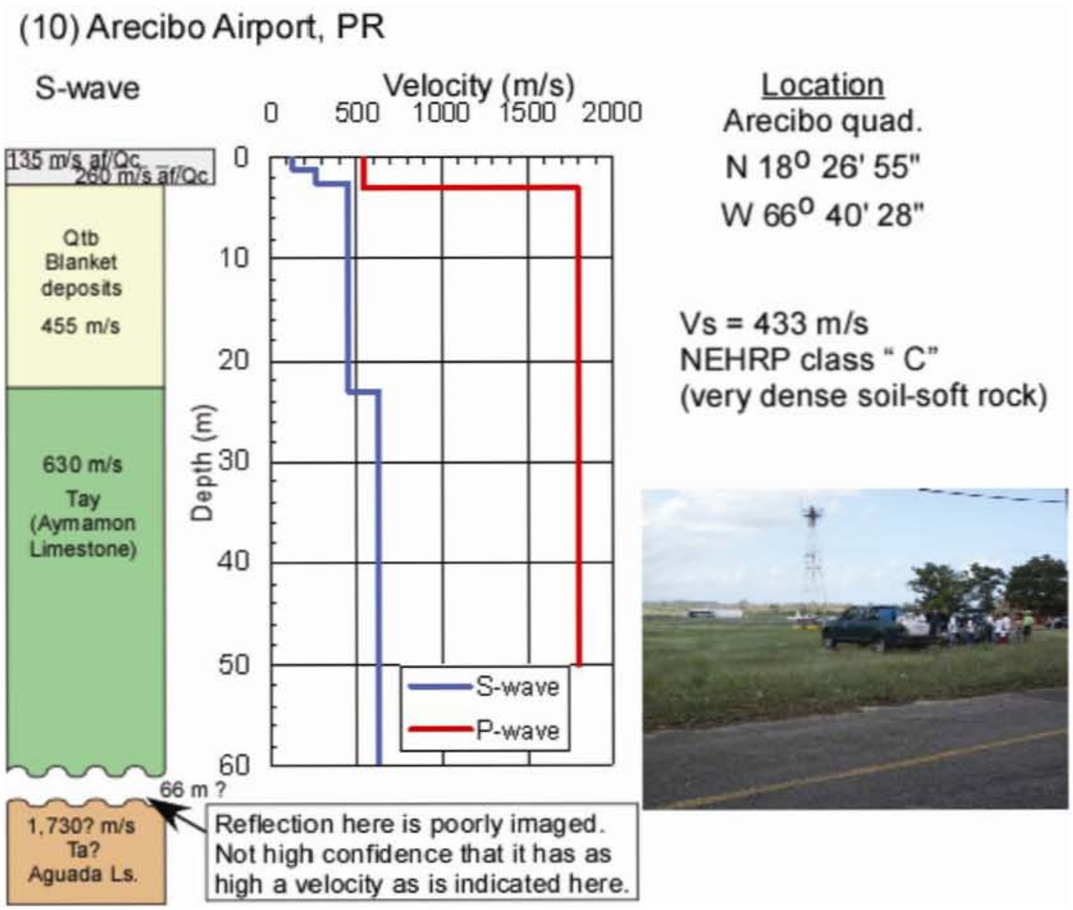
This profile was acquired on the flood plain of the Río de Bayamon, at an elevation of 3 m, and approximately 4 km west of site 7 (Estadio P. Cepeda) (fig. 1). This location, approximately 2 km from the coast, has a stratigraphy of bedrock units of middle Tertiary marine sedimentary rocks, predominantly limestone with interbedded sandstone, which have been incised by river drainage and modified by karst processes (fig. 2). Overlying this eroded surface are river alluvium, swamp, and lagoonal deposits of Pleistocene and Holocene age (Briggs, 1965, 1966; Briggs and Akers, 1965; Zapp and others, 1948).

Vs and Vp depth versus velocity curves along with a lithologic interpretation of the Vs profile are presented above. The velocity unit (Vs=225 m/s) from 0 to 14.5 m is interpreted to be predominantly recent river alluvium (Qa) with possibly some sections that include older alluvial and terrace units, as well as, buried swamp and organic material. We interpret the velocity layer below 14.5-m depth (Vs=450 m/s) to be weathered Aymamon Limestone (Tay), which is exposed in river bluffs and isolated hills near the survey site. The Aymamon Limestone is very fine- to fine-grained pure limestone that is commonly thick bedded, chalky, and locally coarsely fragmental (Briggs, 1968). A velocity of 440 m/s was interpreted for weathered Aymamon Limestone in the San Juan area and 450 m/s at Barceloneta (site 9). It is possible that the Aguada Limestone (Ta), which underlies the Aymamon, is partially sampled at this site. The V_s30 for this site is 350 m/s, which corresponds to a NEHRP class "D" site.



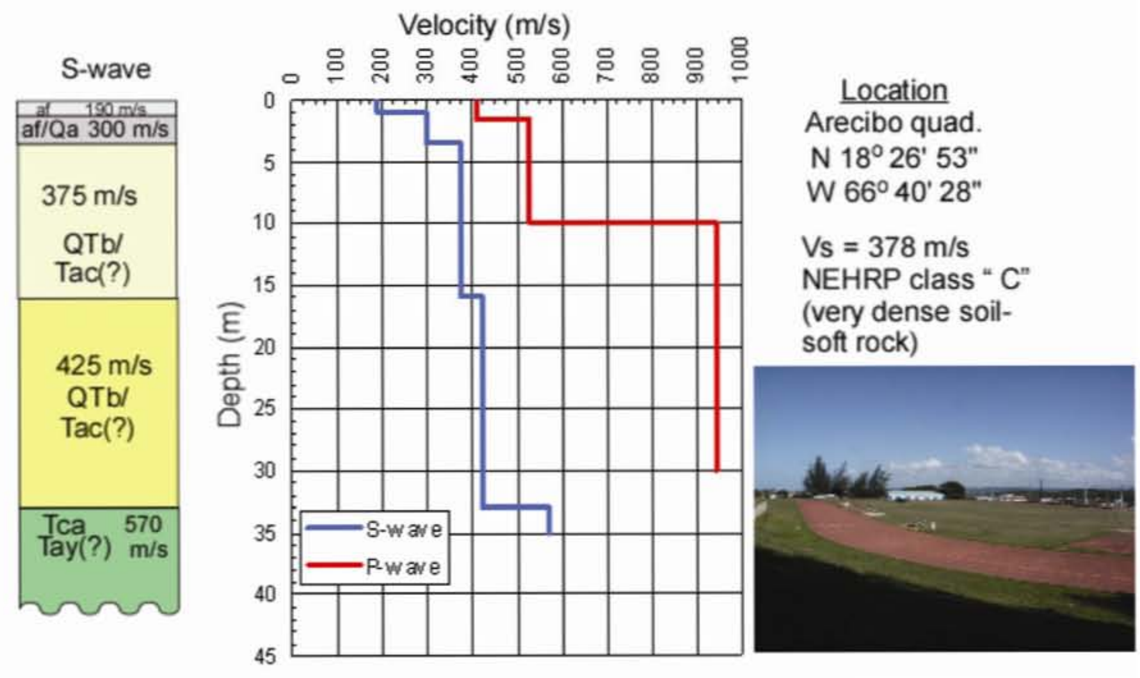
This profile was acquired on the flood plain of the Río Grande de Manati, at an elevation of 5 m, near the town of Barceloneta (fig. 1). This location is 3 km from the coast and 22 km west of San Juan. Bedrock units in this area are middle Tertiary marine sedimentary rocks, predominantly limestone with interbedded sandstone, which have been incised by river drainage and modified by karst processes (fig. 2). Overlying this eroded surface are upland plateau eolian Blanket deposits, river alluvium, swamp, and lagoonal deposits of Pleistocene and Holocene age (Briggs, 1965; Briggs and Akers, 1965; Zapp and others, 1948).

The velocity unit (Vs=120 m/s) from 0- to 4.5-m is interpreted to be recent river alluvium (Qal), and it is possible that this section includes buried swamp and organic material. The unit from 4.5- to 23-m depth, Vs=145 m/s, is interpreted to be older alluvial (Qal) deposits. We interpret the velocity layer below 23-m depth, Vs=450 m/s, to be weathered Aymamon Limestone (Tay), which is exposed in river bluffs less than half a kilometer from the survey site. A Vs of 450 m/s was interpreted for weathered Aymamon Limestone at site 8 in the San Juan area. The V_s30 for this site is 170 m/s, which makes it a NEHRP class “E” site.

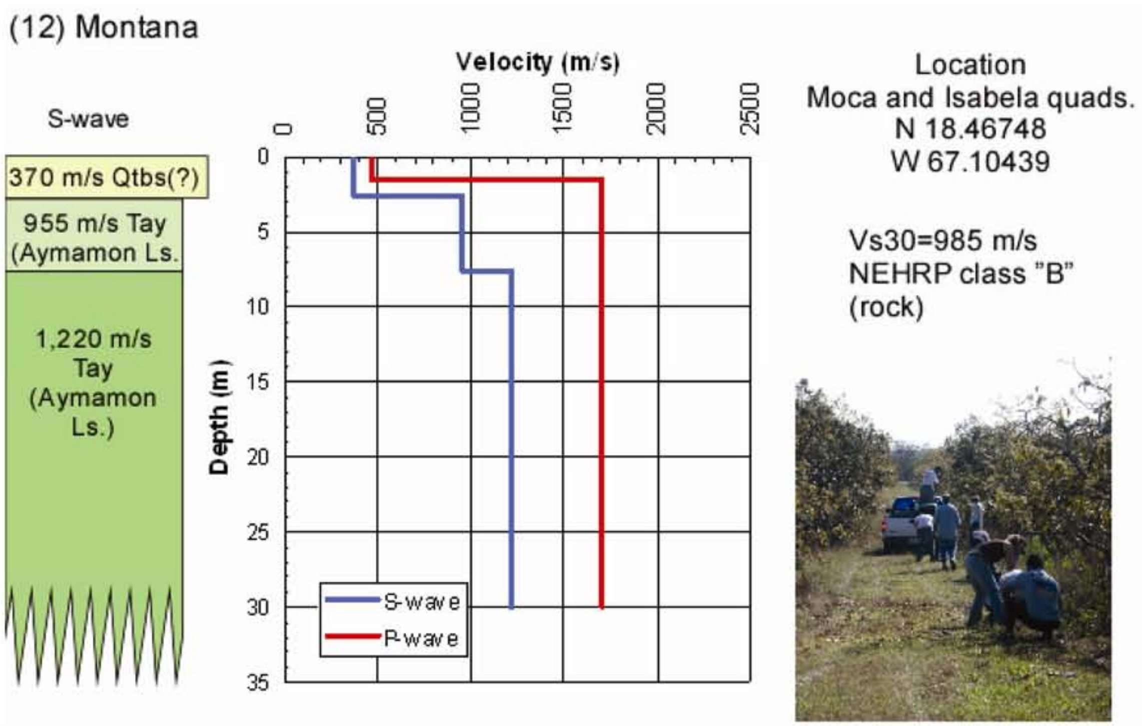


This site is located approximately 3 km inland, is partially on the flood plain of the Río Grande Arecibo, and occupies a similar geographical position as the Barceloneta site (site 9). The shear-wave velocity versus depth curve shows two shallow units (Vs=135 and 260 m/s), which are interpreted to be artificial fill, colluvium, and alluvium. The unit from 2.5- to 23-m depth, Vs=455 m/s, is interpreted to be Blanket deposits (Qtb). Blanket deposits, Miocene-to-recent in age, are stranded sands that have been laterized concurrently with solution of the underlying limestone (Briggs, 1966). Blanket deposits, friable to well cemented in exposure and as much as 30 m thick, are found in discontinuous patches overlying the Aymamon Limestone (Tay) and the Aguada Limestone (Ta) in this area. Although it is possible that some of the material in the lower part of this velocity layer might be weathered Aymamon Limestone, we believe that a difference of 180 m/s indicates two different lithologies. Therefore, we interpret the velocity layer below 23-m depth, Vs=630 m/s, to be the Aymamon Limestone (Tay). A poorly constrained reflection observed in the seismic data suggests that there may be a velocity layer boundary at approximately 66-m depth. The Vs for this unit is 1,730 m/s. It is speculative but this reflection may be from the top of the Aguada Limestone, which underlies the Aymamon Limestone. The V_s30 for this site is 433 m/s, which corresponds to NEHRP type classification “C” (very dense soil-soft rock).

(11) Arecibo College Track

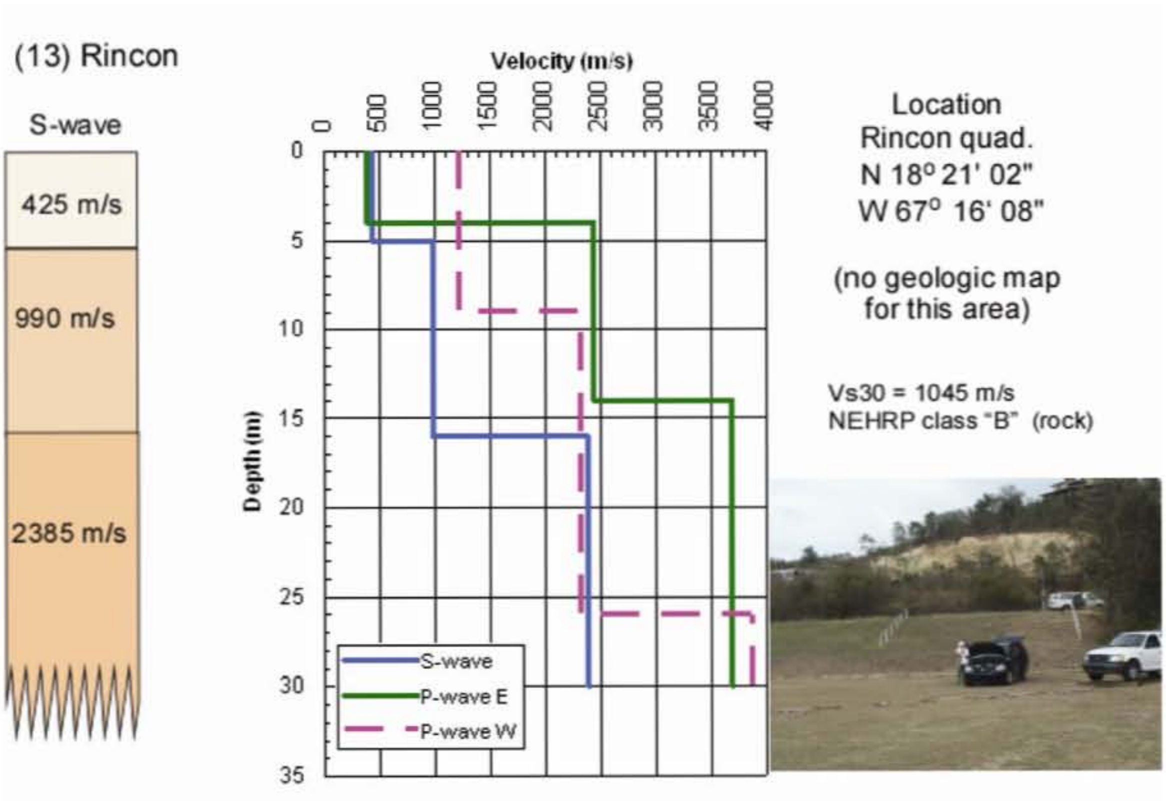


The Arecibo College track site is located approximately 9 km west of the airport site (site 10) and sits on a bluff 17 m above the river flood plain. The primary surficial unit at this site is Quaternary to Tertiary Blanket deposits (QTb) (Briggs, 1966). The depth versus velocity interpretation shows that beneath 1 m of artificial fill (af) there are four Vs layers. The shallowest of these layers from 1.0- to 3.5-m depth, Vs=300 m/s is, probably Holocene unconsolidated soil composed of colluvium, alluvium, possibly wind blown dune material, and probably includes some of the underlying QTb unit. Layers from about 3.5 to 16.0 m and 16.0 to 33.0 m (Vs=375 and 425 m/s, respectively) are interpreted to be Blanket deposit sands (QTb). Blanket deposits, Miocene to recent in age, are stranded sands that have been laterized concurrently with solution of the underlying limestone (Briggs, 1966). The deepest velocity unit imaged (below 33.0 m), Vs=570 m/s, is interpreted to be Cumay Limestone (Tca), which has been mapped in outcrop near the site. However, it is possible that erosion removed the Cumay Limestone and the unit imaged is the Aymamon Limestone (Tay). The layer 4 velocity at this site (Vs=570 m/s) is similar to that determined for the interpreted Aymamon Limestone at Arecibo Airport (Vs=630 m/s). The V_s30 for this site is 376 m/s, which is at the low-velocity end of NEHRP soil type C (very dense soil-soft rock).



This site is located approximately 3 km south of the northern coast and at an elevation of 140 m (fig. 1). There was a field error while acquiring data at this site that involved P-wave geophones being used in part of the S-wave array. As a result, there is no reversed S-wave data and the S-wave profile was pieced together from portions of the intended S-wave record. Due to this error, the S-wave interpretation must be considered as a rough approximation.

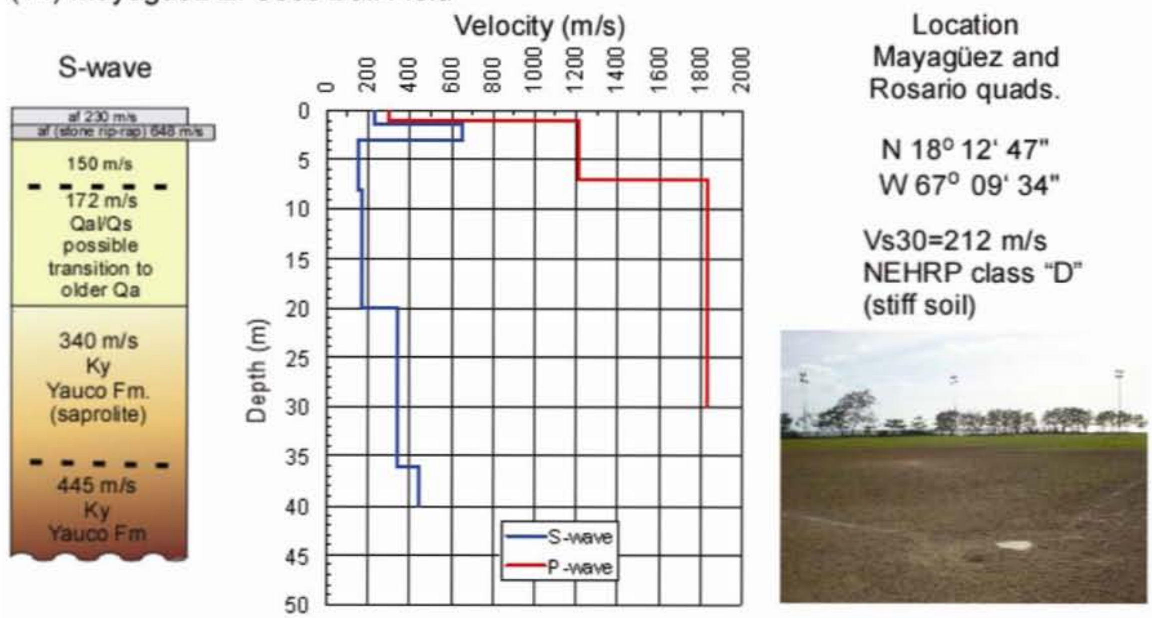
The depth versus velocity profiles for this site show three velocity layers. We interpret the layer from 0 to 2.5 m (Vs=370 m/s) to be Qc (colluvium) along with Qtb (Blanket deposit). Geologic mapping (Monroe, 1969) identifies QTb material near this site and the Vs=370 m/s is similar to that interpreted for some of the Blanket deposits at the Arecibo College track (site 11). The layer from 2.5- to 7.5-m depth, Vs=995 m/s, is interpreted to be Tay (Aymamon Limestone) based on geologic mapping (Monroe, 1969). The Aymamon Limestone, described as a massive, thick-bedded fossiliferous unit, is generally indurated into finely crystalline dense limestone (Monroe, 1969). The Vs for Tay, at this location, is higher than that interpreted at other areas. This may be the result of a higher degree of weathering of this unit at other sites and/or it is possible that at the other sites an upper formational unit with different physical properties is sampled. The velocity layer below 7.5-m depth, Vs=1,220 m/s, may be Tay, or it may be Aguada Limestone (Tau), which is described as a hard limestone. A poorly constrained layer, Vs=1730 m/s, was interpreted from a deep reflector at the Arecibo Airport (site 10) and was interpreted to be Aguada Limestone. V_s30 for this site is 985 m/s, making it a NEHRP class “B” site.



This site lies in the hills directly above the city of Rincon, which lies along the western coast of Puerto Rico (fig. 1). The P-wave data show very different results comparing profiles from either end of the survey. This area has been cut and filled to form the athletic field, and thus bedrock is nearer the surface on the east end of the profile (see photo above). To calculate the V_s30 for this site, we used an average of the shear-wave data from the two profiles to generate the depth versus velocity profile (blue line). These profiles should be considered to be an average for this site because, as was true with the P-wave profiles, the east and west profiles look different.

No detailed geologic map exists for this area. The generalized geologic map (fig. 2) and geologic quadrangle mapping to the southeast of the Rincon quadrangle (Curet, 1986) indicate that the hilly area where this site is located is probably composed of Tertiary and Cretaceous volcanic, volcaniclastic, and sedimentary rocks. Bedrock is exposed in the excavated cliff face directly behind the site (see photo above). We believe that the entire profile samples weathered and more competent bedrock similar in composition to those mapped to the southeast. We note that the velocity layer below 16-m depth, Vs=2385 m/s, has essentially the same velocity (Vs=2400 m/s) as that determined for the Yauco Formation (Ky) at University of Puerto Rico-Mayagüez track (site 15). Of additional interest is the large velocity contrast at this site (at approximately 16-m depth) which is similar to the depth (16.5 m) of the large velocity impedance at site 15. V_s30 for this site is 1,045 m/s, which makes this a NEHRP class "B" site.

(14) Mayagüez-El Seco Ball Field

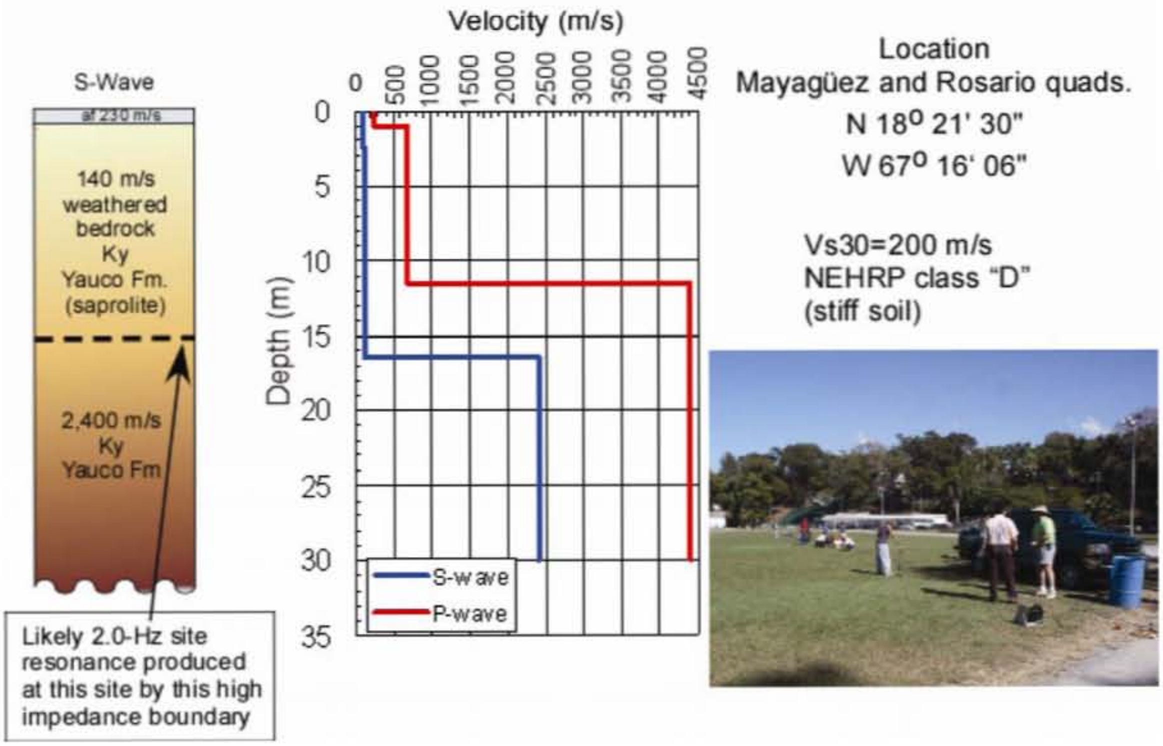


The Mayagüez El Seco baseball field site is located on an artificial-fill platform a few meters above sea level. The simplified near-surface stratigraphy of this area consists of unconsolidated to weakly consolidated alluvium (Qal) overlying Cretaceous interbedded volcaniclastic and sedimentary rock (Curet, 1986). These Cretaceous rocks have been altered by the tropical to subtropical environment to produce near-surface variably-thick sections, depending upon rock type, of highly weathered bedrock (saprolite).

Although six Vs layers were identified at this site we believe that only three primary geologic units are represented over the interpreted 40-m depth. We interpret the first two layers (0 to 1.5 m, Vs=230 m/s and 1.5 to 3.0 m, Vs =648 m/s) as artificial fill (af) layers. The uppermost layer is composed of compacted soil, and the lower unit is likely composed of large boulder-sized and smaller rock pieces. Beneath the fill layers is a section of unconsolidated alluvial and near-shore marine material (Qal) (3.0 to 8.0 m, Vs=150 m/s and 8.0 to 20.0 m, Vs=172 m/s). It is expected that this section is composed of typical interbedded fluvial, coastal plain, and near-shore marine interbedded sediments that consist of gravel, coarse- to fine-grained sand, silt and clay. It is also possible that within the Qal unit are zones of organic swamp and lagoonal sediments that have been identified at other nearby locations and have similar low shear-wave velocities. The slight velocity increase at 8.0 m may represent an older, more consolidated unit and/or a change in lithology character.

Geologic mapping indicates that the unconsolidated Qal unit overlies bedrock that is probably the Yauco Formation (Ky). This Upper Cretaceous unit is composed of interbedded, calcareous, volcaniclastic sandstone, siltstone, mudstone, claystone, limestone, and subordinate breccia and conglomerate (Curet, 1986). As stated earlier, this unit exhibits varying degrees of weathering, resulting in variable thicknesses of saprolite. We interpret the lower two layers (20.0- to 36-m depth, Vs=340 m/s and greater than 36.0 m, Vs=445 m/s) to be weathered Ky bedrock. The V_s30 for this site is 212 m/s, which is NEHRP class "D" (stiff soil).

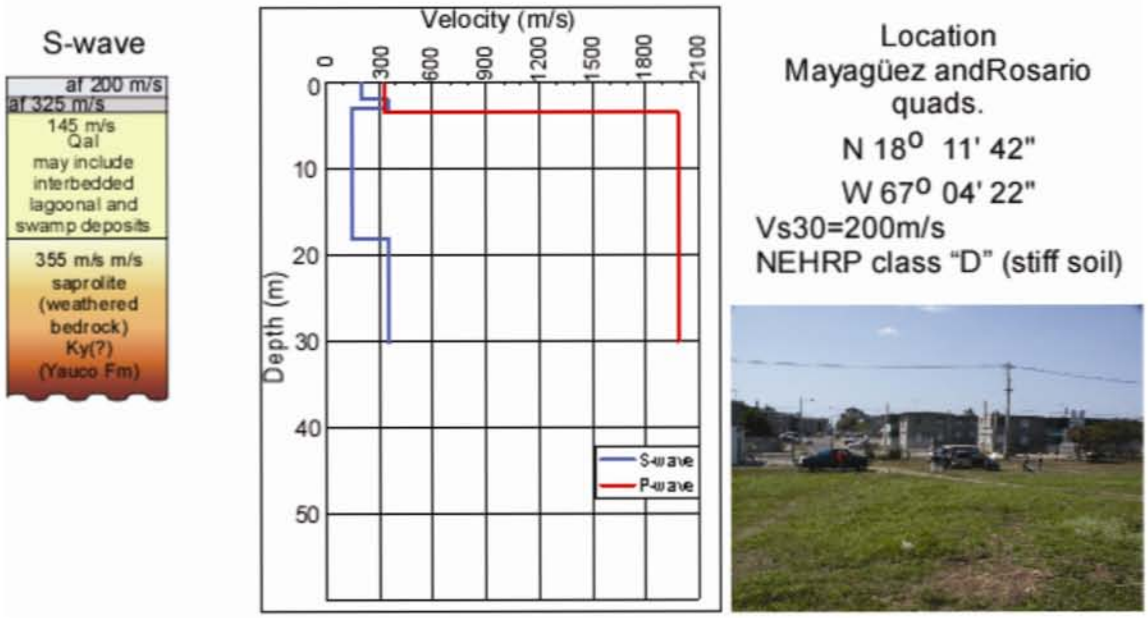
(15) Mayagüez-UPR Track



This site is located within the main track facility at the University of Puerto Rico-Mayagüez, see figure 1. The geographic position of this site places it near surface exposures of the Yauco Formation (Ky), which outcrop less than 50 m from the profile site near the white building in the photograph above.

The Vs versus depth profile identifies three distinct velocity layers. The layer from the surface to 2.5-m depth, Vs=230 m/s, we interpret to consist of modified soil and artificial fill (af) along with possibly a thin veneer of unconsolidated material (Qal). The velocity from 2.5- to 16.5-m depth, Vs=140 m/s, is interpreted as saprolite derived from the weathering of the Yauco Formation (Ky). Located on the UPRM campus, and a few hundred meters from our profile, is a 30-m-deep borehole drilled by Jaca and Sierra Testing Laboratories (2002) that indicates that beneath one meter of artificial fill is 29 m of saprolite. Results of their Standard Penetration Test (SPT) at this drill hole site were as follows: average of 9 blows per ft (bpf) from 0- to 5-m depth, 15 bpf from 5- to 12-m depth, 53 bpf from 12- to 16-m depth, and >100 bpf below 16 m (Jaca and Sierra Testing Laboratories, 2002). The SPT data indicate a distinct physical property change in the bedrock at approximately 16.0-m depth, which correlates with the dramatic increase in shear-wave velocity (Vs=140 m/s to Vs=2,400 m/s) that we interpret at approximately the same depth. The V_S30 velocity for this site is 200 m/s, which is NEHRP class "D" (stiff soil). It is likely that a 2.0-Hz site resonance will be generated at this site during an earthquake based upon the high impedance boundary at 16.5-m depth. Potential earthquake resonance frequency, *f*, is calculated from the zero-offset reflection traveltime *f*=1/2T, where T is the two-way traveltime of the reflection.

(16) Mayagüez-Candelaria

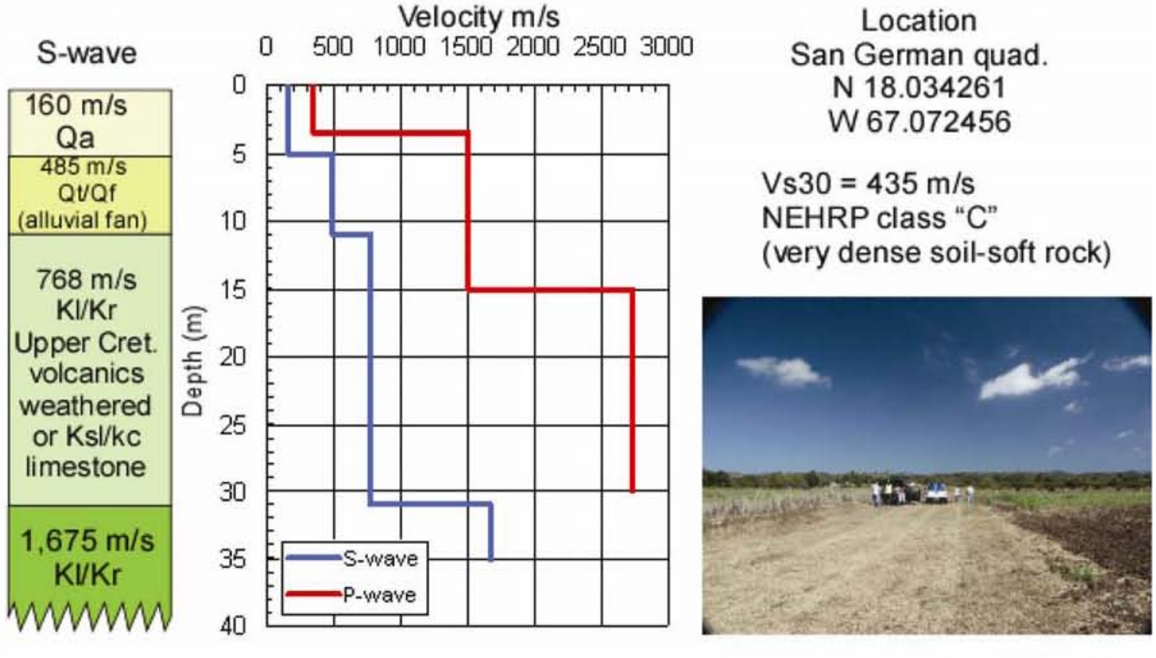


This site is approximately 0.5 km from the Bahía de Mayagüez and just west of Highway 2. This traffic noise is responsible for the data degradation that limited the imaging depth at this site. Geographic position and geologic mapping indicate that the primary surficial units in this area are Qal (interbedded fluvial, coastal plain, and near-shore marine sediments), which consist of coarse- to fine-grained sand and gravel and silt and clay. Also present in the area, and immediately east and south of the investigation site, are swamp deposits (Qs) and extensive areas of mangroves.

Two velocity layers are identified in the upper three meters of this site (see velocity versus depth graph above). We interpret the velocity from 0 to 2 m, Vs=200 m/s, to be artificial fill (af). This layer overlies a 1-m- thick layer, Vs=325 m/s, which we speculate is another fill placed into what was probably a swamp area. Beneath the fill is a 15-m-thick, Vs=145 m/s, layer interpreted to be Qal. From 18- to ~30-m depth is a layer (Vs=355 m/s), which we interpret to be saprolite (weathered Upper Cretaceous bedrock (Ky)). The V_s30 velocity for this site is 200 m/s, which is at the low end of a NEHRP class "D" (stiff soil).

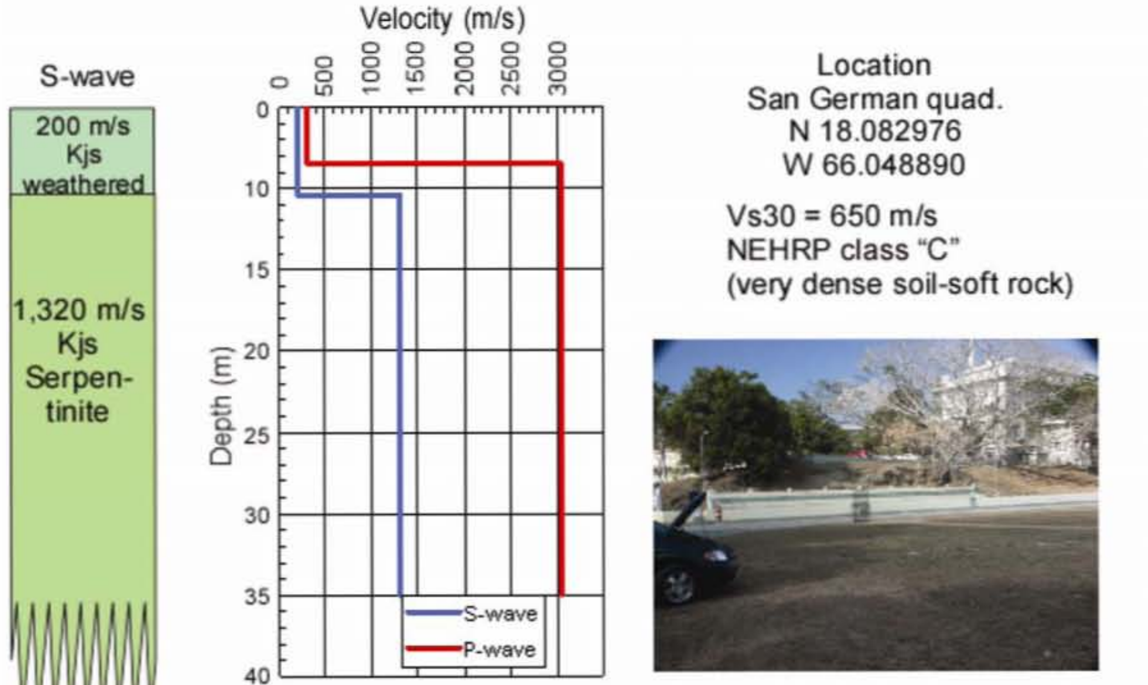
The stratigraphic section and seismic velocity columns for the Candelaria and El Seco (site 14) sites are very similar. Not only is the upper section of weathered bedrock similar (Vs=340 and 355 m/s), but the depth from the surface to the boundary between saprolite and less weathered bedrock is essentially the same at 20 and 18 m, respectively.

(17) Lajas UPR Agriculture Station



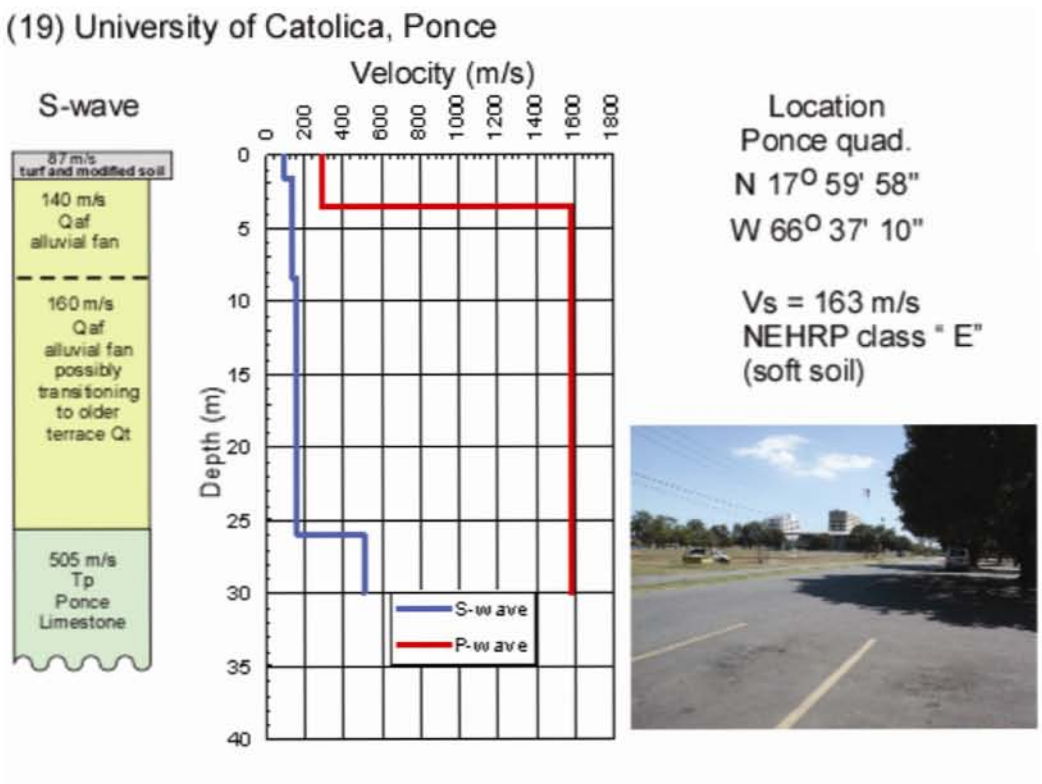
This survey site lies on the relatively flat surface of Valle de Lajas south of a small mountain range composed of Upper Cretaceous volcanic rocks (fig. 1). We interpret the shear-wave velocity layer from 0- to 5-m depth, Vs=160 m/s, to be modern alluvial (Qal) material. The unit from 5- to 11-m depth, Vs=485 m/s, is interpreted to be older Quaternary terrace (Qt) and alluvial fan (Qaf) sequences composed of coarse-grained materials. It may also include some underlying weathered bedrock. Based upon geologic mapping, the unit from 1- to 31-m depth may represent Upper Cretaceous basaltic volcanic rock (Kl- Lajas Formation) that is partly weathered (Volckmann, 1984). The Vs velocity of 768 m/s is similar (800 m/s) to that determined for formation Ka (andesite flows) at Cayey Observatory (site 24). Alternatively, the unit may be composed of Upper Cretaceous limestone (Kc-Cotui Formation or Ksl-Sabana Grande Formation), which are exposed in low hills 1.5 km to the north (Volckmann, 1984). The unit below 31 m depth, Vs=1675 m/s, is interpreted to be volcanic rock (Kl/Kr). The V_s30 for this site is 435 m/s making this a NEHRP class "C" site.

(18) Inter-American Univ., San German, PR



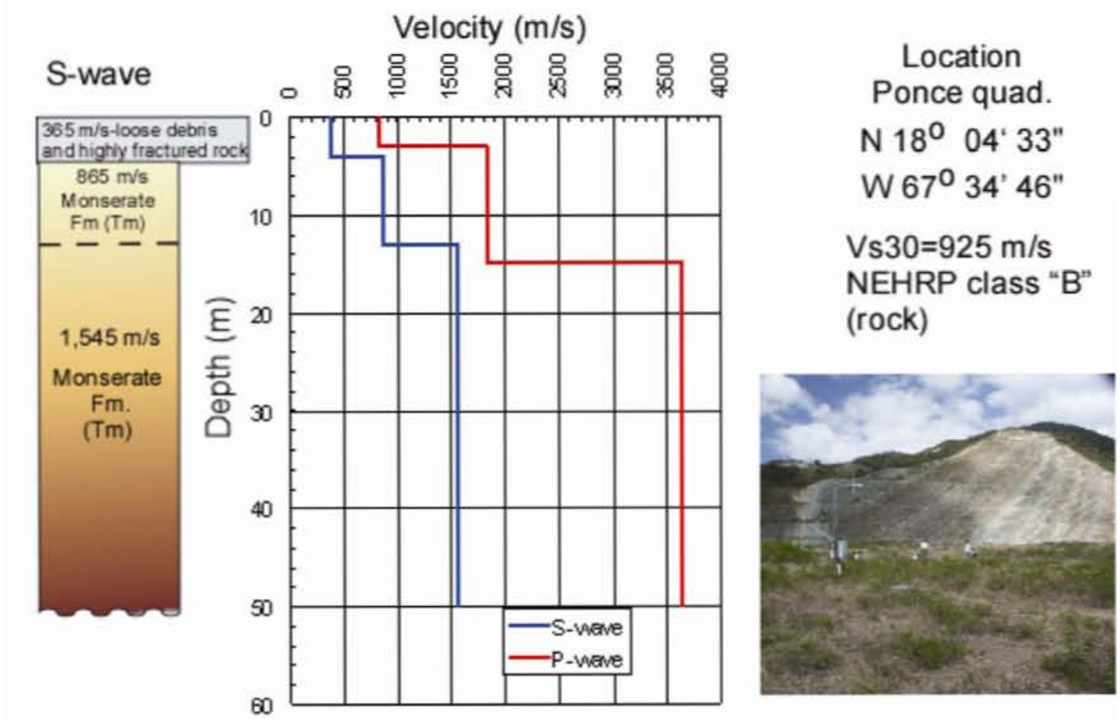
Serpentinite bedrock exposed above white wall in center of photo.

This site is located in southwest Puerto Rico and lies within a low mountainous area between two large alluvial valleys (figs. 1 and 2). The survey was conducted on an athletic field constructed on exposed Lower Cretaceous bedrock, serpentinite (Kjs); see photo above (Volckmann, 1984). The graph above shows two distinct velocity layers that we interpret to be weathered (saprolite) Kjs (Vs=200 m/s, from 0- to 11-m depth) and unweathered bedrock (Vs=1,320 m/s below 11-m depth). The V_s30 for this site is 650 m/s, which makes this a NEHRP class "C" site. The NEHRP description of a class "C" site defines it as very dense soil-soft rock, which is somewhat misleading in this case as geologic maps and the exposure would indicate that this site is located on bedrock. In locations where weathering depths are less, this material would be NEHRP class "B".

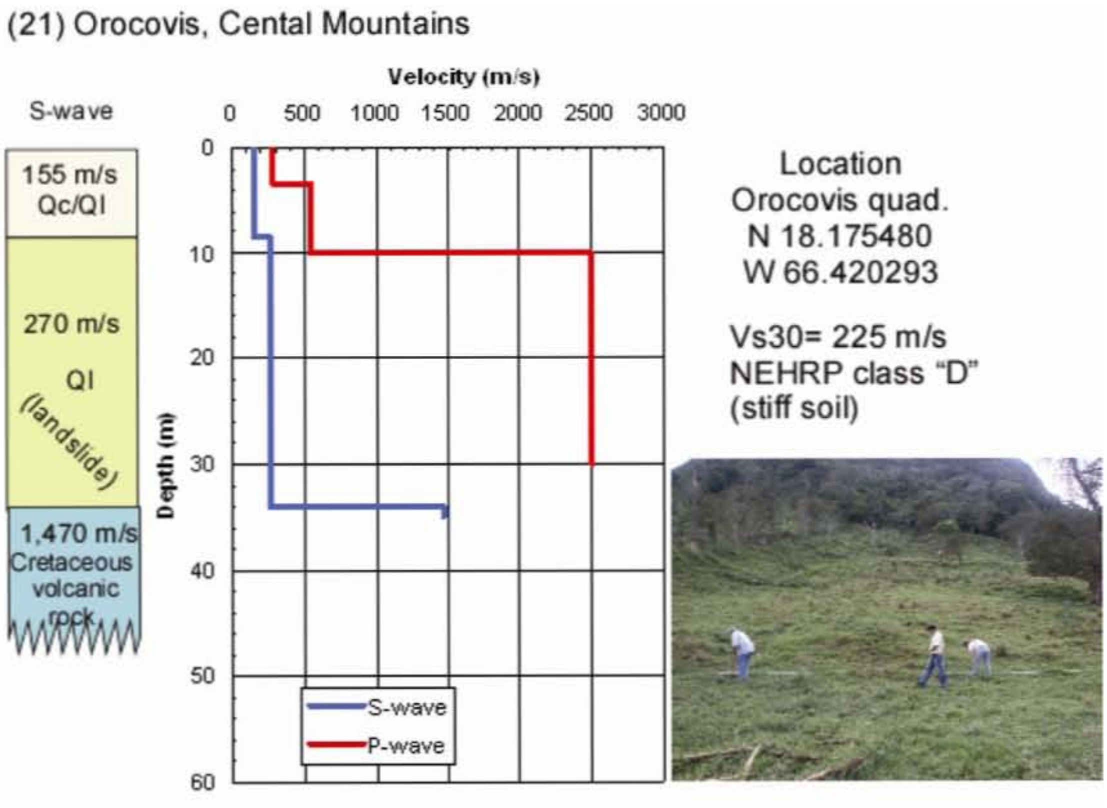


Although four Vs layers are determined from the data at this site (figs. 1 and 2), we believe that only two primary geologic units are sampled. The uppermost layer (0 to 1.5 m) probably represents a combination of turf, soil, and artificial fill. The velocity of 87 m/s is very low for naturally occurring geologic materials. Due to the thinness of the unit, it has little effect on the calculated V_S30 or NEHRP site-classification value. Two layers with similar velocity were determined for the intervals 1.5 to 8.5 m (Vs=140 m/s) and 8.5 to 26.0 m (Vs=160 m/s). We believe that both of these units are associated with river alluvium and alluvial fan deposits. The change in Vs at 8.5 m probably represents a change in overall physical property (grain size) characteristics and/or a transgression into an older alluvial fan or Pleistocene terrace(?) unit. Velocities determined at this site are consistent with those interpreted for other Qaf and Qal deposits. An alluvial fan unit thickness of approximately 25 m is not unreasonable for the depositional environment at this site. At the town of Salinas, 35 km to the east, a similar geologic environment is present, and geologic contouring of the base of the permeable alluvium beneath the alluvial fan varies from 15- to 38-m depth (McClymonds and Ward, 1966). A single unit interpretation for this site is supported by the constant V_P velocity of 1,580 m/s, which is typical of water-saturated, unconsolidated to weakly consolidated coarse-grained lithologies that dominate alluvial fan deposits. We believe that the highest velocity unit (Vs=505 m/s), below 26.0-m depth, represents the Ponce Limestone (Tp-Miocene). An alternative interpretation is that erosion has removed all, or most, of the Ponce Limestone unit, and the lower velocity layer is sampling all, or part of, the Juana Diaz Formation (Oligocene to Miocene). This unit, described as calcareous sandstone overlain by chalky limestone, may be seismically similar to the overlying Ponce Limestone (Krushensky and Monroe, 1975). The V_S30 for this site is 163 m/s and classifies as a NEHRP class "E" (soft soil).

(20) Cerrilos Dam, Central Mountains

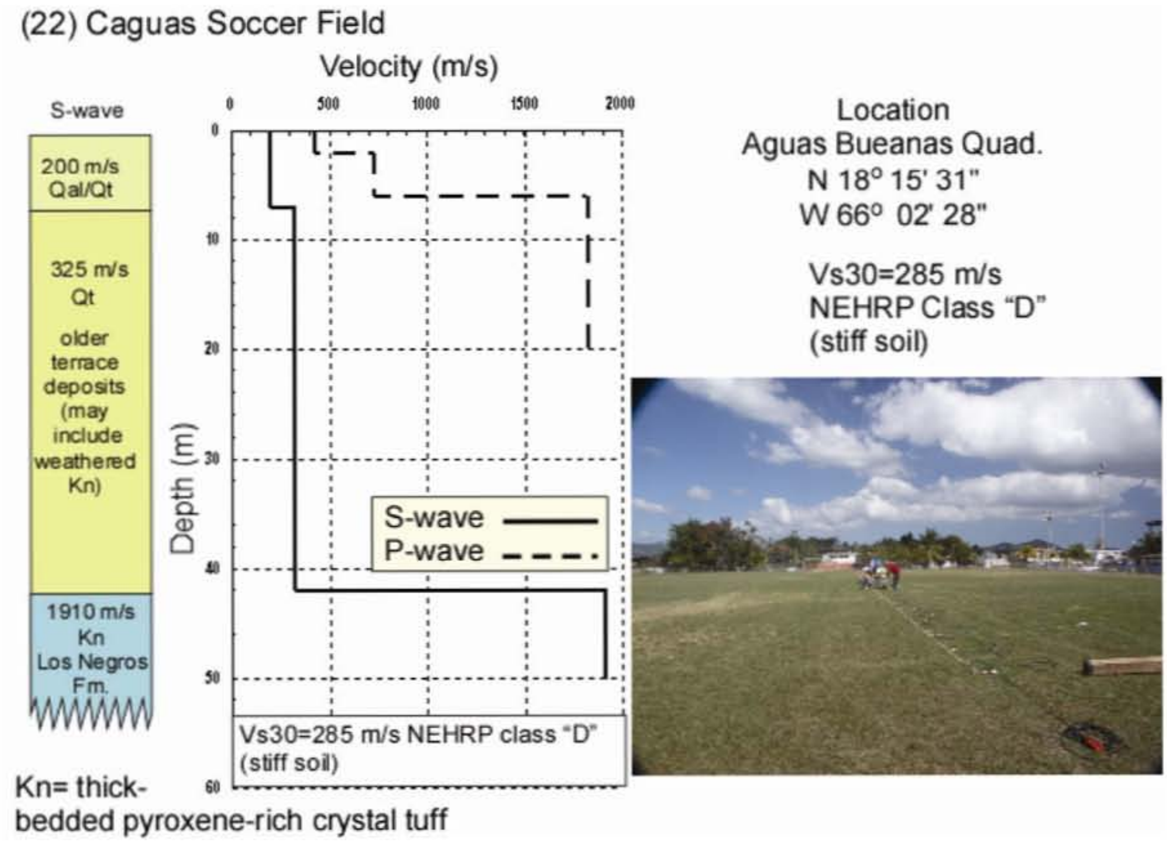


This survey was conducted on an excavated bedrock bench above, and to the southwest of, the dam at Lake Cerrillos. The 89-m-long profile passed within 5 m of PRSN's broadband seismic station, CELP. Surface conditions at this site consisted of a thin (10 to 15 cm) veneer of soil containing loose cobbles and coarse material. Exposures in areas excavated for the dam show dipping bedrock units and fractured rock in the near surface (see dipping strata and seismograph station in photo). Although only the Monserate Formation (Tm) was imaged at this site, three distinct Vs layers were calculated (Krushensky and Monroe, 1975). The shallowest layer from 0 to 4 m, Vs=365 m/s, is interpreted to be loose surface debris accumulated during dam construction and probably includes some highly fractured bedrock. The intermediate velocity layer from 4 to 13 m, Vs=865 m/s, likely correlates with weathered and fractured rock related to construction blasting to form the bench area and to inherent natural fractures. We interpret the higher velocity layer from 13 to 50 m, Vs=1,545 m/s, to represent a transition to more competent bedrock. The V_s30 of this site (925 m/s, NEHRP "B") strongly reflects the influence of the shallowest and intermediate velocity layers that predominantly consist of soil, rock rubble, and transitionally fractured and weathered(?) bedrock.



Data at this site were acquired on a landslide deposit resting on the flank of a bedrock knob in the central mountainous area (figs. 1 and 2). Bedrock in this area consists of Upper Cretaceous volcanic sequences. Knobs of volcanic rock are often surrounded by extensive landslide deposits and in most areas the near-surface bedrock has been weathered.

The Vs and Vp velocity versus depth curves for this site show primarily two distinct velocity units. We interpret the upper two units from the surface to 34-m depth, Vs=155 and 270 m/s, to be colluvium (Qc), landslide (Ql) and weathered bedrock material. Below 34 m, we interpret the Vs=1,470 m/s unit to be relatively unweathered volcanic bedrock of the Malo Breccia (Kma/Kmaf). The Malo Breccia is composed of very thick bedded andesite and basaltic pryoclastic and tuff material (Briggs, 1971). The V_s30 for this site is 225 m/s making it a NEHRP class "D" site (stiff soil). The Vs value of 270 m/s may be a good representative estimate for the widespread, thick landslide and colluvial sections found throughout the upper mountainous central core area of Puerto Rico.

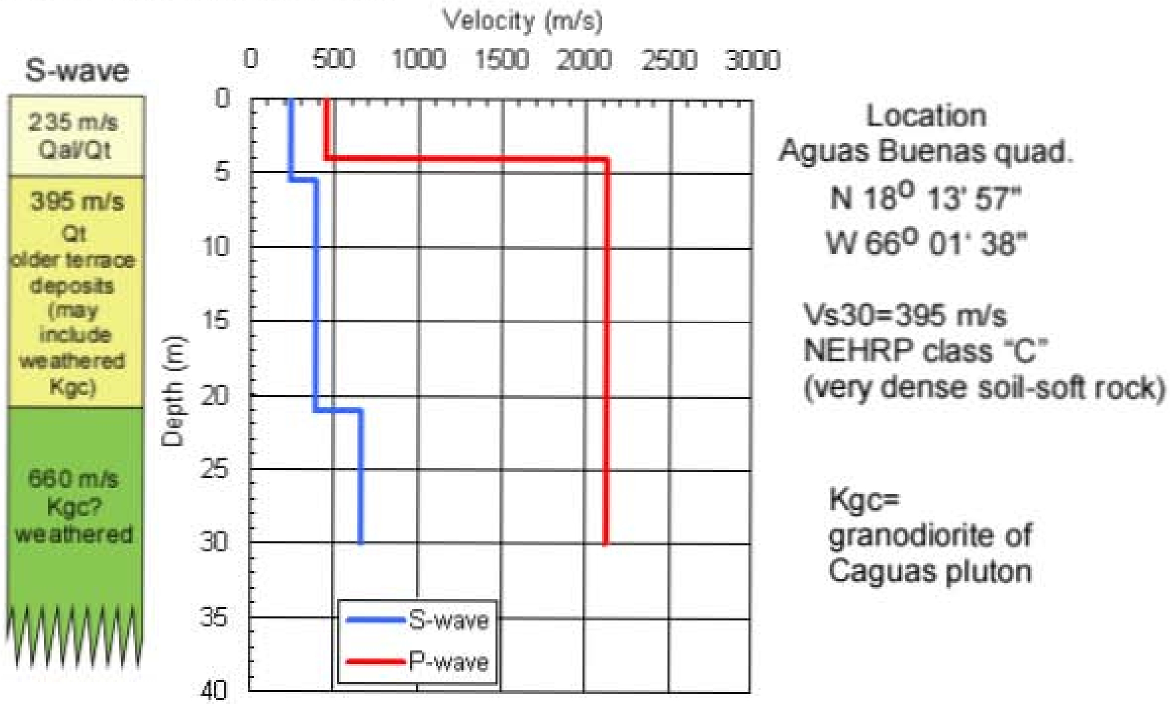


This profile was acquired in an intermountain valley approximately 20 km south of the coast (figs. 1 and 2). The area is rapidly developing as a suburb of San Juan. The simplified near-surface stratigraphy consists of unconsolidated to weakly consolidated alluvium (Qal), older alluvial terrace (Qt), and alluvial fan (Qaf) deposits overlying Cretaceous interbedded volcanic and volcaniclastic bedrock. In places these Cretaceous rocks have been altered by the tropical to subtropical environment to produce variably thick sections, depending upon rock type, of highly weathered bedrock (saprolite) in the near surface.

We interpret the layer from 0- to 7-m depth, within 200 m/s, to be alluvial and terrace material (Qt). The layer from 7- to- 42 m depth, Vs=325 m/s, is believed to be older terrace and/or alluvial fan and probably weathered bedrock. The Vs of 325 m/s is within the range of older terrace deposits (Qt), as well as saprolite soil identified during the 2004 surveys in Puerto Rico (Odum and others, in press). We interpret the layer below 42-m depth with a Vs=1,910 m/s, to be Upper Cretaceous Los Negros Formation (Kn). The Los Negros Formation is composed of thick-bedded to massive basalt tuff, which may show some degree of alteration in proximity to the Caguas pluton (Rogers, 1979).

V_s30 for this site is 285 m/s making it a NEHRP class "D" site. There is a possibility of a strong site resonance at about 1.7 Hz based on the reflection time from the high velocity contrast boundary between the older terrace deposits and Kn at 42-m depth.

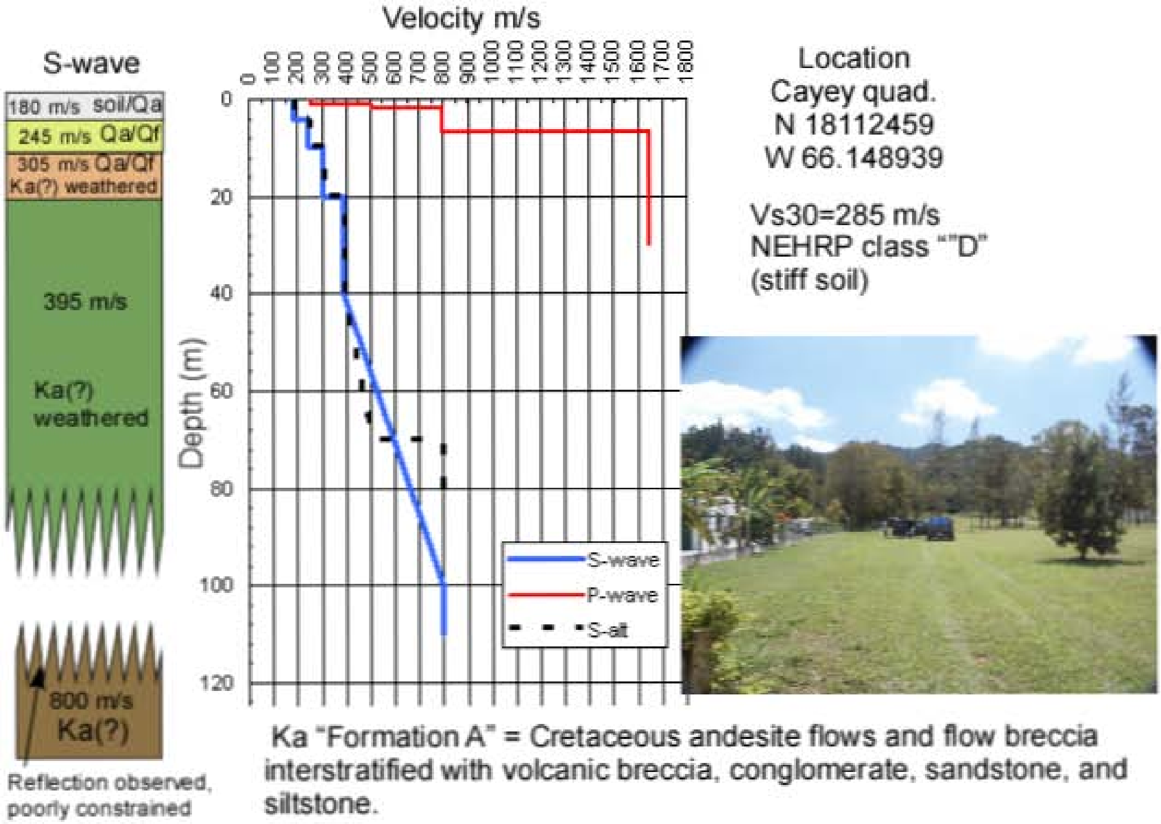
(23) Caguas, Notre Dame



This profile was acquired in an intermountain valley approximately 20 km south of the coast (figs. 1 and 2). The site is 5.5 km southeast of the Caguas soccer field area (site 22) and is geographically similar to that site. The simplified near-surface stratigraphy of this area consists of unconsolidated to weakly consolidated alluvium (Qal), older alluvial terrace (Qt), and alluvial fan (Qaf) deposits overlying Late Cretaceous intrusive rock (Rogers, 1979). In places, these Cretaceous rocks have been altered by the tropical to subtropical environment into variably thick sections, depending upon rock type, of highly weathered bedrock (saprolite) in the near surface.

The Vs and Vp depth versus velocity curves for this site are presented above along with a lithologic interpretation of the Vs profile. The shallowest layer with a Vs= 235 m/s, from 0- to 6- m depth, is interpreted to be modern soil and alluvial material (Qal?-Qt). The layer from 6 to 21 m, Vs=395 m/s, is interpreted to be predominantly older alluvial terrace and alluvial fan material and may include some weathered bedrock. The unit below 21 m, Vs=660 m/s, is interpreted to be weathered Late Cretaceous Caguas pluton, which is composed primarily of granodiorite. The velocity for this plutonic rock is similar to that determined for the Late Cretaceous San Lorenzo granodiorite (775 m/s) profiled near Humacao (Odum and others, in press). The V_s30 for this site is 395 m/s making it a NEHRP class “C” (very dense soil-soft rock) site.

(24) Cayey Observatory

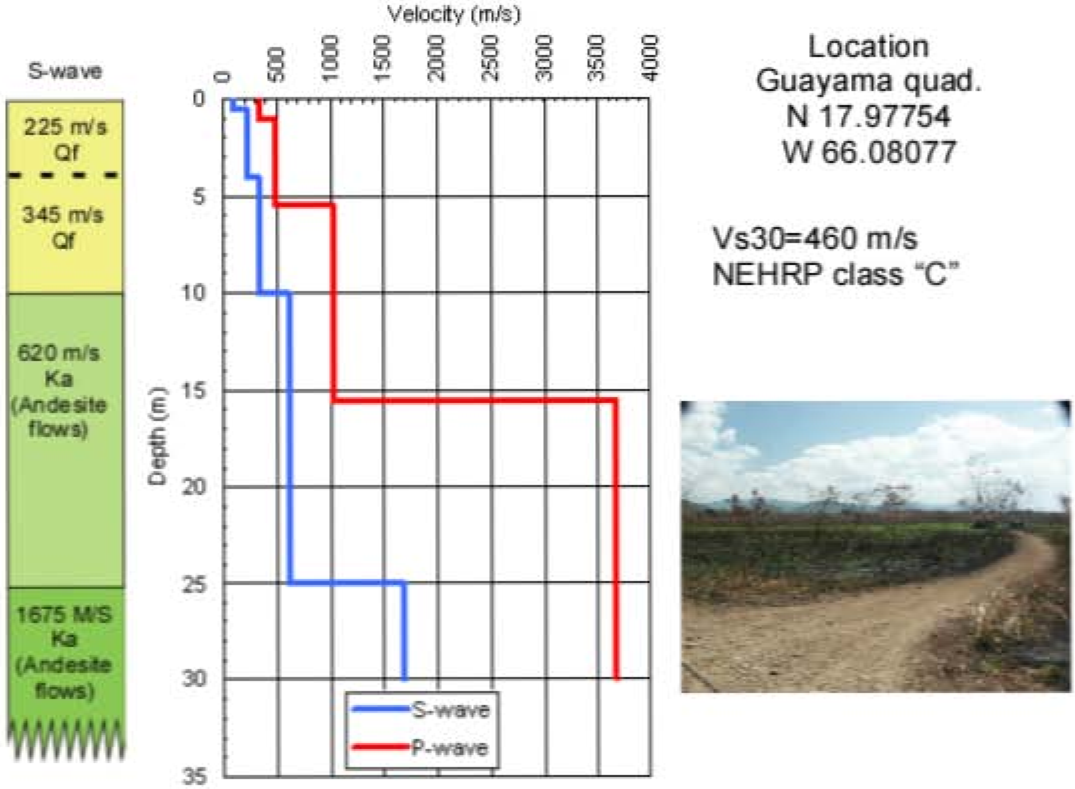


Ka "Formation A" = Cretaceous andesite flows and flow breccia interstratified with volcanic breccia, conglomerate, sandstone, and siltstone.

This profile was acquired on the grounds of the Caguas Observatory, which is the site of a USGS geomagnetic instrument and a PRSN seismograph station. The city of Cayey is approximately 20 km north of the ocean and is constructed within a mountain valley (figs. 1 and 2). The observatory grounds lie on a gently sloping alluvial fan and alluvial terrace surface, which is covered by various thicknesses of colluvium. Underlying bedrock consists of Cretaceous volcanic and volcaniclastic rocks that show various depths of weathering depending on rock type.

The Vs- and Vp-depth versus velocity curves for this site are presented above along with a lithologic interpretation of the Vs profile. The uppermost three velocity layers, 180 m/s, 245 m/s and 305 m/s, from 0- to 20-m depth, are interpreted to be modern soil and colluvium (Qc), and alluvial fan and terrace (Qaf and Qt) sections. The unit below 20- depth is geologically mapped as Formation A, which consists of interstratified volcanic breccia, conglomerate, and volcaniclastic sandstone and siltstone (Berryhill and Glover, 1960). Depth of weathering of these units is unknown. Poorly constrained reflection data hints at a velocity layer, Vs=800 m/s, below 100-m depth. The V_s30 for this site is 285 m/s making it a NEHRP class "D" (stiff soil) site.

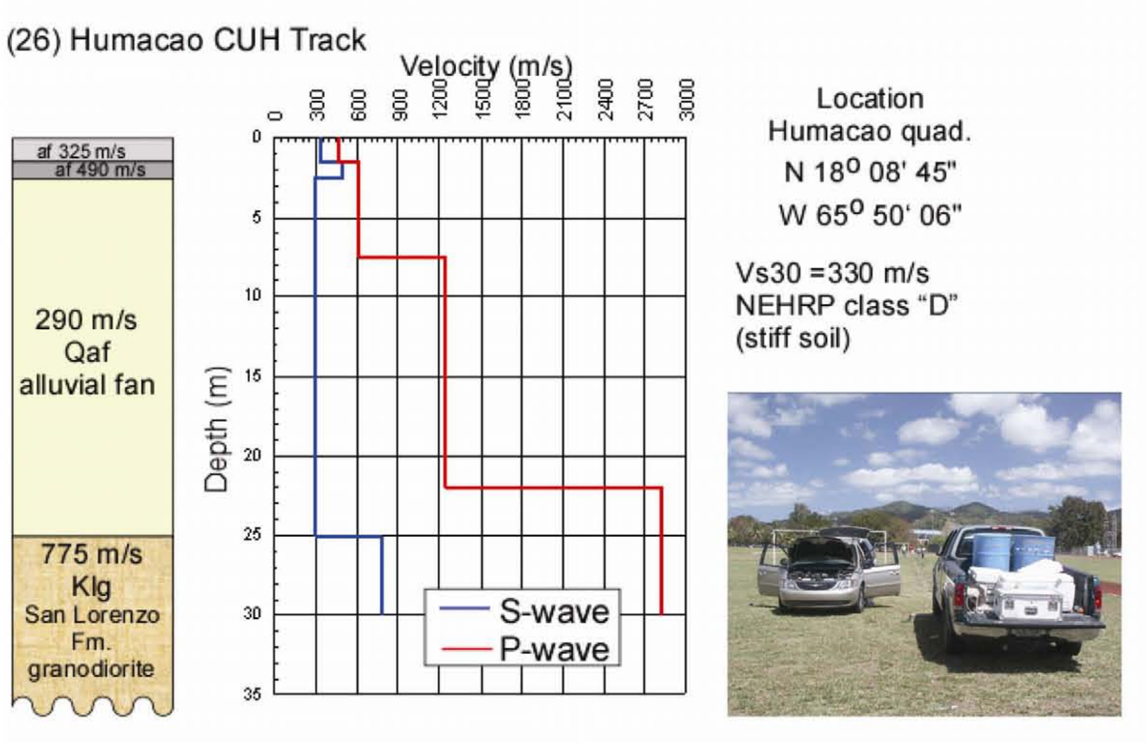
(25) Guayama



Ka "Formation A" = Cretaceous) andesite flows and flow breccia interstratified with volcanic breccia, conglomerate, sandstone, and siltstone.

This site lies a few kilometers inland from the southern Puerto Rico coast on the gently sloping surface of an alluvial fan (figs. 1 and 2). No geologic map exists for this area, but it is believed that the near-surface geology is similar to mapped geology a few kilometers to the west and consists primarily of alluvial fan material over Cretaceous volcanic sequences.

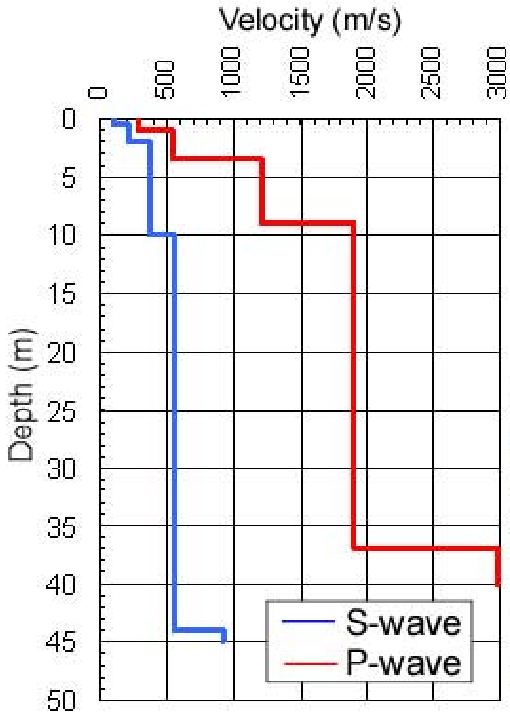
The depth versus velocity curve for this site shows four velocity layers. We believe, however, that only two geologic units are imaged. We interpret the uppermost layers, 0- to 4.5-m (Vs=225 m/s) and 4.5- to 10- m depth (Vs=345 m/s) to be alluvial fan material (Qaf). Water wells drilled to the base of the alluvium in the neighboring quadrangle show the thickness of fan material ranging from thin (couple of meters) near the mountains to greater than 40 m near the coast (Berryhill, 1960). The velocities of these upper two units are consistent with those interpreted for other alluvial fan deposits on the island. The unit from 10- to 2-m depth, Vs=620 m/s, is interpreted to be Ka Formation, which consists of volcanic andesite flow and interstratified volcaniclastic material. This is the same volcanic material that is found at the Cayey Observatory (site 24). The velocity for this layer may include some Qaf material, as well as weathered Ka and/or volcaniclastic material. The velocity layer beneath 25-m depth, Vs=1,675 m/s, is also interpreted to be more competent Ka material. The V_s30 for this site is 460 m/s, which makes it a NEHRP class "C" (very dense soil-soft rock) site.



This survey was conducted on the Community University-Humacao track in the city of Humacao, which is located approximately 6 km inland from the east-central coast (fig. 1). The majority of the urban area, which includes the track complex, is built upon alluvial fan (Qaf) material deposited by the Río Humacao as it exits the mountainous area a few kilometers to the west. The Qaf unit (Holocene to Pleistocene) consists of unconsolidated to weakly consolidated, poorly to well sorted, clay- to boulder-sized material in fans and stratified valley-fill deposits as much as 25m thick (M'Gonigle, 1978). The Qaf material unconformably overlies a complex of bedrock units including granodiorite of the San Lorenzo Formation (Upper Cretaceous) and lava and volcaniclastic rocks of the Pitahaya Formation (Lower Cretaceous).

Two near-surface Vs layers were identified (0 to 1.5 m, Vs=325 m/s and 1.5 to 2.5m, Vs= 490 m/s). We interpret these upper two Vs layers to be compacted artificial fill (af) and engineered soil associated with the construction of the campus track complex. We interpret the unit from 2.5- to 25.0-m depth, Vs=290 m/s, to be alluvial fan (Qaf) material. Geologic mapping indicates a typical thickness of 25 m for the Qaf unit in this area, which correlates well with the 21-m thickness determined from the seismic refraction-reflection data. We interpret the unit below 25.0 m, Vs=775 m/s, to be weathered San Lorenzo Formation granodiorite (Klg). Jaca and Sierra Testing Laboratoreis (2002) drilled a 30 m deep borehole at a site located on a hill 3 km from our profile. They reported that only weathered San Lorenzo granodiorite was encountered in the borehole. Their downhole velocity calculations showed a range of Vs from 450 to 760 m/s, similar to our measurements, with a 1,220 m/s measurement at the very bottom of the hole. The calculated V_s30 for this site is 330 m/s and classifies it as NEHRP "D" (stiff soil).

(27) Fajardo Airport



Location
Fajando Quadrangle
N 18° 18' 54"
W 65° 38' 49"

Vs30 =426 m /s
NEHRP class "C"
(very dense soil-soft rock)

This site lies southwest of the city of Fajardo at an elevation of approximately 20 m (fig. 1). The ball field, across from the airport, is constructed on an alluvial fan or terrace surface of a small tributary to the Río Fajardo, which has a large alluvial plain to the southeast of the site. Nearby hills contain outcrops of the upper unit of the Fajardo Formation (Kfsu). We believe that this Kfsu unit is the bedrock sampled by the seismic data. The upper unit of the Fajardo Formation is composed of thin-bedded, locally cherty, tuffaceous siltstone and sandstone that may contain some calcareous layers near its top (Briggs and Aguilar-Cortes, 1980).

Although five shear-wave (Vs) layers were identified, we believe that only three primary geologic units are represented over the imaged 50-m depth. The upper two layers (0 to 0.5 m, Vs=100 m/s, and 0.5 to 2.0 m, Vs=210 m/s) represent a thin layer of turf and modified soil and a thicker layer of unconsolidated colluvium and alluvium, respectively. Based on the geomorphic position of this site, the layer from 2.0 to 10.0 m, Vs=365 m/s, is interpreted to represent weakly consolidated and possibly weakly laterized clay, as well as fine- to coarse-grained colluvium, alluvium and alluvial fan material (Qaf-Qal). Because of the higher Vs, we speculate that some of these materials may be older, and more consolidated, than the recent Qal material in the Río Fajardo flood plain. It is also possible that this layer may contain weathered bedrock. The velocity layers from 10-to 44-m depth, Vs=550 m/s, and 44- to 50-m depth, Vs=920 m/s, are both believed to represent the upper unit of the Fajardo Formation with the 67 percent difference in velocity being either the result of weathering or a change in formation lithology. The V_s30 for this site is 426 m/s and corresponds to NEHRP soil type "C" (very dense soil-soft rock).

Summary of Site NEHRP Classifications

Site characterization data were acquired at 27 sites located within and around urban areas, intermountain valleys, and at two PRSN broadband seismograph stations throughout Puerto Rico. Geologic maps indicate that near-surface units range in age from Holocene (bay mud, beach, and alluvial deposits) to Cretaceous (volcaniclastic sediments and plutonic rock). Overall data quality is considered to be good and velocity columns to a depth of at least 30 m were estimated for all but the Escambron site (site 1, see text for an explanation). In this study, all interpreted layer thicknesses and velocities, to a depth of 30 m, were used in the calculation of V_s30 for a specific location. This means that calculations include the velocities and calculated thicknesses of the one or two near-surface thin layers of artificial fill even though these layer thicknesses are often poorly constrained. From the calculated velocity data, V_s30 and NEHRP site classifications were determined, based on the table 2 categories, and are shown in table 3 along with the depth and value of the highest Vs and Vp determined for each site. Figure 3 groups sites by NEHRP classification and shows the following distribution: three class "E" (V_s30 below180 m/s), ten class "D" (V_s30 between 180 and 360 m/s), nine class "C" (V_s30 between 360 and 760 m/s), and four class "B" (V_s30 greater than 760 m/s).

At all three NEHRP class "E" sites, data imaged thick sections (15 to 25 m) of modern alluvial and/or lagoonal material. Site 7 (Estado P. Cepeda), in the San Juan area, is located on a high velocity artificial-fill pad that overlies a thick section (17 m) of low velocity bay mud and swamp deposits. All three of these sites have V_s30 values that are close to the lower class "D" boundary indicating that in these areas the thickness of the low velocity unit is the major factor in determining the site NEHRP class. However, the thick (9 m) artificial fill layers at site 7 elevates the V_s30 value toward the class "D" boundary.

For the 10 class "D" sites, the lowest three V_s30 values were found in the Mayagüez area where geologically mapped "bedrock" (Cretaceous) has been deeply weathered by the tropical environment to produce a saprolite soil. Saprolites are transitional by nature and show an increase in both strength and velocity with depth. Velocities for a formation are variable with depth depending on site location as seen at site 15 (that is, as low as V_s=140 m/s in the upper 17 m with a sharp jump to 2,400 m/s below 17 m). Such sharp changes in velocities can produce local site resonance in the event of an earthquake. If the saprolite zone at these sites were a few meters thicker, then the site classification would be "E" rather than "D". Other class "D" sites have thick sections of unconsolidated beach, alluvial deposits, weathered bedrock, or landslide material. In the case of site 26, Humacao-CUH track, the V_s30 value of 330 m/s is close to the lower NEHRP class "C" boundary. It is the thicknesses of the alluvial and alluvial fan units at this location that are the primary factors for the class "D" rating, as the underlying Cretaceous intrusive granodiorite has a V_s of 775 m/s.

All sites that were interpreted to be NEHRP class "C" typically have a thick section of Pleistocene to Tertiary, weakly indurated blanket, alluvial fan and older terrace deposits, which in all cases except one, have Vs between 360 and 760 m/s. The one exception is site 4 (Carolina track) where the unconsolidated unit is thin, and the V_s30 is highly influenced by the underlying Tertiary bedrock. Additionally, all class "C" sites imaged either a Tertiary formation (limestone and/or clastic sedimentary rock) at depth or more competent intrusive or volcaniclastic bedrock beneath an upper weathered zone.

All of the “C” sites had V_s30 velocities in the lower to middle range of this category and therefore were not close to being considered borderline “B” sites. All four class “B” sites imaged Tertiary or older intrusive or volcaniclastic bedrock near the surface.

In general, while there may be a wide range of individual velocities within a column, it is often the thickness of the layer overlying Tertiary or older bedrock that is the major factor in determining whether a site is classified as “C” or “D” (for example, site 15). At “B” class sites, the classification is clear at the sites sampled; however, the weathering depth is variable and needs to be considered when extrapolating this classification category to the surrounding areas.

When analyzing and comparing individual and grouped V_s30 values, two factors involved in the data calculation need to be remembered: (1) in this study all units at a survey site, including artificial fill (af), are used in the calculation of V_s30 and the subsequent NEHRP class category and (2) near-surface and thin velocity layers, often consisting of one or two layers of artificial fill, are sometimes poorly constrained with respect to thickness; however, the calculated thickness values are used in calculating V_s30. Neither factor played a significant role in the calculated site classifications during this study. They, however, do have an effect, and under certain circumstances could change a site’s NEHRP classification. Figure 4 examines the effect of site specific presence and thickness of artificial fill units on V_s30 calculations at a class “D” site (El Seco, site 14). The first column shows the results as determined in this report. The next two hypothetical calculations show the changes in calculated V_s30 value by first removing the second unit af layer and then by removing both layers. The resulting change in the V_s30 value is a reduction of approximately 3 percent and 0 percent respectively, at this site. In this case there was only a minor shifting of the Vs30 value toward the next lower site classification. It is recommended that when V_s30 values and/or class designations are being projected beyond the limits of where they were obtained that factors such as surface layer thickness and velocity be examined for relevancy and modified as appropriate.

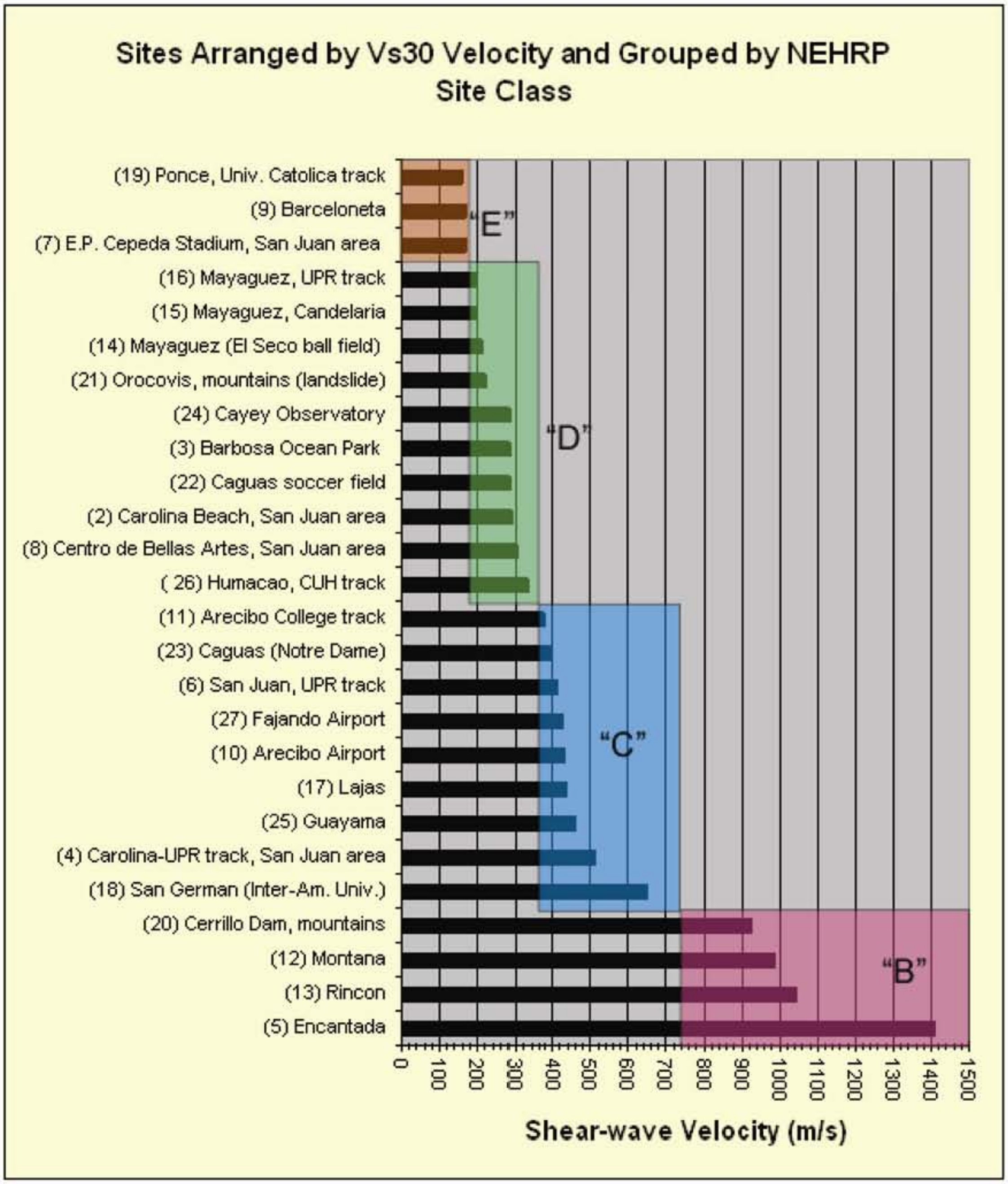


Figure 3. Sites arranged by NEHRP site classification code in order of increasing V_s30.

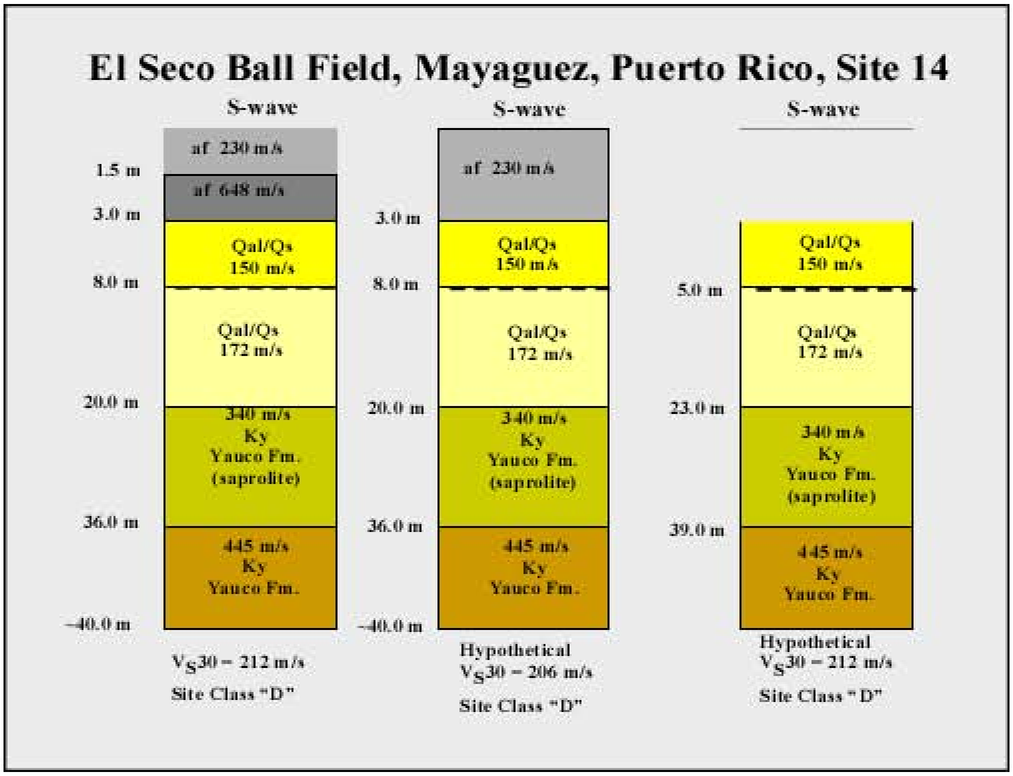


Figure 4. Influence of calculated Vs30 values at a site where one or more artificial surface high velocity layers (in example, artificial fill) exists. First column shows results from this report; second column shows results if both artificial layers have Vs of lowest fill; third column shows results of natural setting with no artificial fill.

Acknowledgments

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