FINAL TECHNICAL REPORT

Ground Motions Evaluation and Geotechnical Database for the City of Mayagüez, Puerto Rico

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January 9, 2006

Technical Abstract

This project had two main components: 1) Development of a geotechnical database for the city of Mayagüez, Puerto Rico; and 2) Evaluation of ground motions considering the local site effects based on data from the first component.

The geotechnical database summarizes available geological, geotechnical, and other relevant information available from different sources for the city of Mayagüez. The database was created using an ArcView platform. The database was developed to help with earthquake hazard mitigation efforts in Western Puerto Rico which require adequate geotechnical knowledge of the region. As part of this component of the project, additional information was generated by means of geophysical tests carried out in several sites within Mayagüez. The geophysical testing included seismic refraction and SASW tests. As part of these efforts, preliminary maps of liquefaction susceptibility and NHERP soil types were generated. This database is an initial step needed to develop seismic hazard maps for the area. However, several knowledge and information gaps were identified after completion of the database: 1) In general more geotechnical information, particularly of good quality, is needed to better characterize the region; 2) Characterization of the bedrock/soil interface including general bedrock depth and interface characteristics (e.g., residual soils with diffuse interface); 3) soil predominant period maps; 4) quantification of dynamic properties of unique soils of this area (e.g., residual soils, calcareous sand, etc); among others.

The second component of the project involved evaluation of ground motions for Mayagüez considering local site effects. This evaluation was carried out by means of one dimensional ground response analyses performed at fifteen representative sites within the city of Mayagüez. The response spectra at the surface for each site was evaluated and compared with current code design provisions. In general, computed response spectra were found to be higher than recommended by the UBC-97 code. The highest amplifications were computed for sites located on thick deposits of alluvial soils. More research is recommended to better quantify local site effects expected for Mayagüez.

Keywords: Regional Seismic Hazards, Amplification, Geotechnical Database, Liquefaction, Local Site Effects

Non-Technical Summary

This project had two main components: 1) Development of a geotechnical database for the city of Mayagüez, Puerto Rico; and 2) Evaluation of ground motions considering the local site effects based on information found during the first component.

The geotechnical database developed summarizes available information from public and private sources. This database is the first step needed to develop seismic hazard maps for the region. Data enetered in this database is available to the public for planning and mapping purposes.

The second component involved evaluation of seismic ground motions for Mayagüez. This evaluation was carried out to assess influence of local soil effects. Computed response spectra at the surface of fifteen representative sites within Mayagüez were evaluated and compared with current code design provisions. In general computed response spectra were found to be higher than recommended by the UBC-97 code. Further research is strongly recommended in this area.

Acknowledgements

We would like to acknowledge the collaboration provided by many undergraduate and graduate students that helped with the efforts of geotechnical data collection and organization. Special thanks go to Arturo Llavona who did the first large effort of organizing the geotechnical data available for the city of Mayagüez.

Special thanks to Prof. Jim Bay, University of Utah, for his assistance, valuable comments and discussions on the SASW tests carried out as part of this project. We would also like to thanks Jack Odum, Robert Williams, and William Stephenson, from the USGS Geologic Hazard Team, for providing assistance during seismic refraction geophysical testing as well as for sharing their own geophysical test results which were carried out in Mayagüez through a collaboration effort with the Puerto Rico Seismic Network and Puerto Rico Strong Motion Program.

Finally we would also like to thank the Department of Recreation and Sports of Mayagüez, for permitting us access to several park facilities for carrying out geophysical testing.

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CHAPTER 1 Introduction

1.1 *General Introduction*

This research project had two main goals. The first goal was to generate a comprehensive geological and geotechnical database for the city of Mayagüez, Puerto Rico. This project goal attempts to address the important information gap related to the lack of adequate and sufficient information regarding the subsurface soils of the city of Mayagüez. For this component, the project also entailed carrying out geophysical testing within the city of Mayagüez to further populate the geotechnical database generated as part of this project. The second goal of the project was to evaluate seismic ground motions that could be expected in Mayagüez considering local site conditions based on the soil zonation maps generated as part of the geotechnical database component.

This chapter presents the justification of the developed research project, the objectives, a brief description of the methodology adopted to carryout the research, and a description of the organization of this report.

1.2 *Justification*

The United States (US) commonwealth of Puerto Rico has a population of about 3.8 million (2000 Census), for a territorial extension of the island of approximately 160 km from east to west by 50 km from north to south. This results in a population density higher than any US state. The island of Puerto Rico is situated in a highly seismic setting as shown in Figure 1.1. The main sources of seismic activity in the Puerto Rico region are: 1) the Puerto Rico Trench a subduction zone to the north; 2) the Muertos Trough, a subduction zone to the south; 3) the Anegada Trough, an extension zone to the east; 4) the Mona Canyon, and the extension zone to the west. All these regions have been deemed capable of producing seismic events greater than M7.0, and historical records show evidence that all these seismic sources have generated such magnitude events (e.g., Asencio, 1980; Moya and McCann, 1992, Clinton et al., In press). Furthermore, the USGS seismic hazard maps (Mueller et al., 2004) indicate a seismic hazard similar to high seismic areas of western USA. The current standard building code in Puerto Rico, the 1997 UBC code, assigned Puerto Rico as seismic Zone 3.

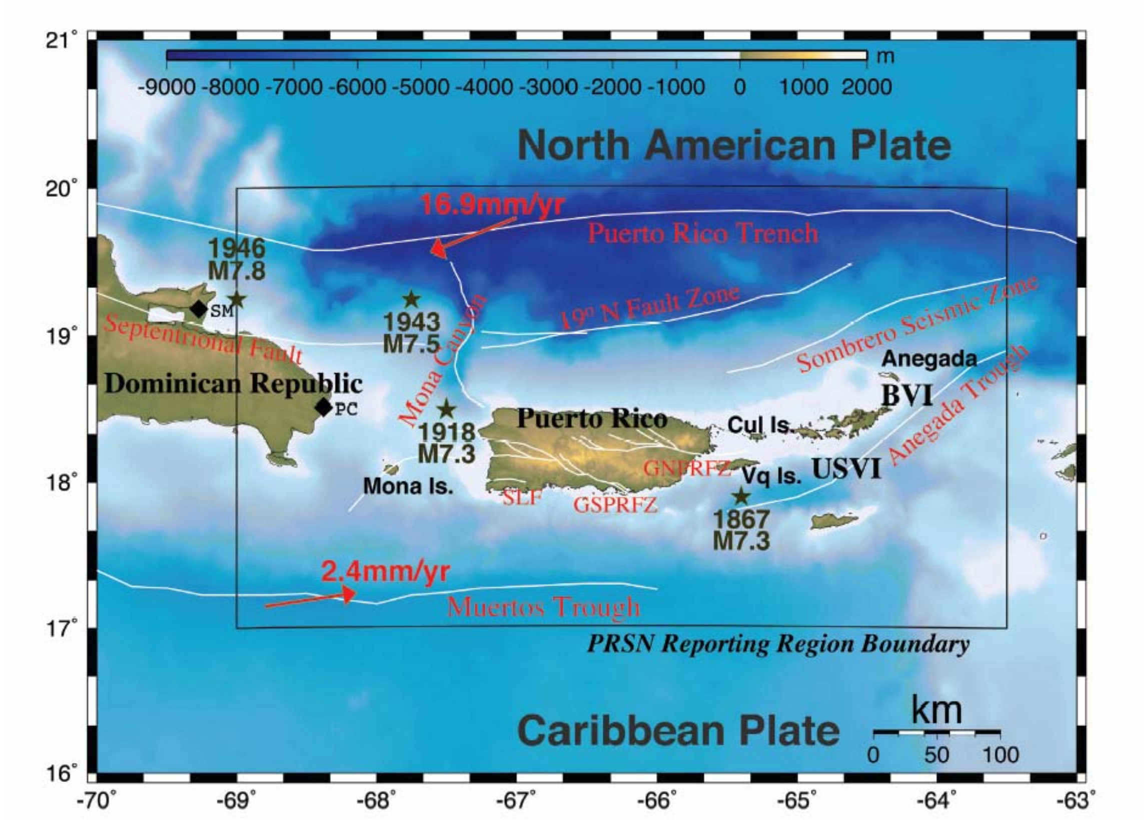


Figure 1.1 Puerto Rico Seismic Settings and Major Faults (From Clinton et al., In press)

For the specific area of this research, Mayagüez has been subjected to the 1918 earthquake (Reid and Taber, 1919). This event was generated by the Mona Canyon source with a M7.3 (Pacheco and Sykes, 1992). This event caused substantial structural damage, induced liquefaction near Mayagüez, generated a tsunami, caused about $4 million dollars in damage and killed 116 people (Reid and Taber, 1919; Moya and McCann, 1992; Mercado and McCann, 1998). With the Mayagüez area having a far greater density of population and infrastructure (with most of its infrastructure which has not been tested by strong seismic events since the 1918 earthquake) a similar large seismic event would likely lead to far more severe loss of life and infrastructure (Clinton et al., In press).

Despite the high seismicity of Mayagüez and its high population density, research to adequately assess and mitigate earthquake hazard lags behind other seismically active region of the United States. Important needs include proper characterization of geotechnical/geological data of the region as well as quantification of expected ground motions. This research project attempts to address the gap of geotechnical/geological data for Mayagüez and estimation of surface ground motions considering local site effects.

1.3 *Objectives*

This research project had two main objectives: 1) to develop a geotechnical/geological database for the city of Mayagüez, Puerto Rico; and 2) to assess potential ground motions for the area considering local site conditions.

Specific objectives of this project were:

- Gather and organize existing geotechnical, geological, geophysical, and hydrological data for the city of Mayagüez.
- Perform geophysical tests (SASW and seismic refraction) to extend the geotechnical information available for Mayagüez, P.R.
- Design and develop a comprehensive geotechnical database using a Geographic Information System (GIS) platform such as ArcView/GIS.
- Perform ground response analyses for representative sites of Mayagüez that consider the different types of local site effects.

The project objectives were achieved through three subprojects completed by graduate students and supervised by the PIs of this project. The theses titles are as follows:

- Llavona, A. (2004), "Classification of NEHRP soils for the City Mayagüez" (In Spanish), Master of Engineering Thesis, Civil Engineering Department, University of Puerto Rico at Mayagüez. Supervised by Dr. Jose A. Martínez.
- Perez, E. (2005), "Ground Response Spectra at Surface for Mayagüez considering in-situ Soil Properties", Master of Science thesis, Civil Engineering Department, University of Puerto Rico at Mayagüez. Supervised by Dr. Luis E. Suárez.
- Lugo, C. Y. (In preparation), "Geotechnical Database and Geophysical Testing for the City of Mayagüez", Master of Engineering Thesis, Civil Engineering Department, University of Puerto Rico at Mayagüez. Supervised by Dr. Miguel A. Pando.

1.4 *Report Organization*

This report consists of six chapters: Chapter 1 gives a general context of the study, including the general seismicity of Puerto Rico, and research objectives. Chapter 2 presents a general description of the Mayagüez area, e.g. seismic settings, geology, topography and ground water conditions. This chapter also includes a literature review of the most relevant seismic studies previously done in Mayagüez related to geotechnical/geological mapping, liquefaction susceptibility mapping, and pertaining to seismic evaluations. Chapter 3 presents results of the geophysical testing performed in the Mayagüez area for this study and compares them with applicable results from previous geophysical studies also performed in the area. Chapter 4 presents details about the geotechnical database developed for Mayagüez using ArcView/GIS 9.0. This chapter also provides basic guidelines on how to use the basic tools of the program and a brief description of the layers included in the database. Chapter 5 presents the results of the ground motion evaluation. Conclusions and recommendations for future work are given in Chapter 6. The geotechnical database is stored in the enclosed DVD. Additional copies are available from the USGS NEHRP program or by contacting the PI of this project.

CHAPTER 2 Background and Literature Review

2.1 *Introduction*

This chapter presents a general description of Mayagüez city and vicinity related to: seismic settings, general geology, topography, and ground water conditions. This chapter also presents a literature review of previous studies that involved seismic hazard evaluations or geotechnical/geological mapping efforts for the Mayagüez area.

2.2 *General Description of the Mayagüez Area*

2.2.1 *General location*

The island of Puerto Rico is located in the Caribbean Sea between Latitudes 18º and 18.5ºN and Longitudes 65.25º and 67.25ºW. The area of study for this project concentrated on the city of Mayagüez which is located in the western end of the island as shown in Figure 2.1.

Figure 2.1 Location of study area

2.2.2 *Seismic Settings*

The island of Puerto Rico is located in a very active and complex tectonic region in the northeastern Caribbean Sea. Most of the seismic activity of the area is produced by the convergence and lateral translation of the North American and Caribbean Plates beneath the Puerto Rico Platelet (Tuttle et al., 2003) as shown in Figure 2.2.

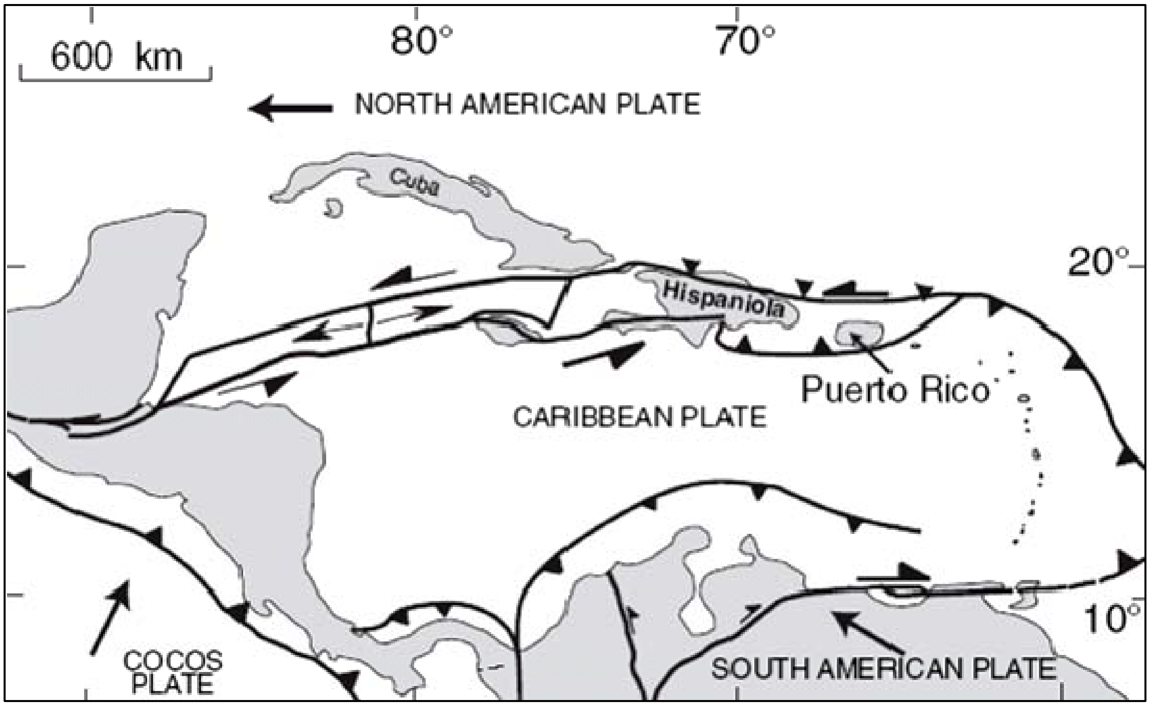


Figure 2.2 Tectonic Plates Settings for the Caribbean Region (From Tuttle et al., 2003)

Figure 2.3 shows how Puerto Rico is surrounded by offshore active faults which are considered the major sources of seismic activity on the island. The Mona Canyon and the Anegada Passage are extension zones located to the west and east side of the island, respectively. There are two subduction zones to the north and south side of Puerto Rico called the Puerto Rico Trench and Muertos Trough respectively. Also there are segments of the Great Southern Puerto Rico Fault Zone (GSPRFZ) and Great Northern Puerto Rico Fault Zone (GNPRFZ) that cross the island from northwest to southeast. Additional to the offshore seismic sources mentioned above, an inland source has recently been identified as capable of generating M7.0 events (Prentice et al., 2000; Prentice and Mann, 2005). This inland fault is identified in Figure 2.3 as SLF for the abbreviation of South Lajas Fault which is located in the south west corner of Puerto Rico.

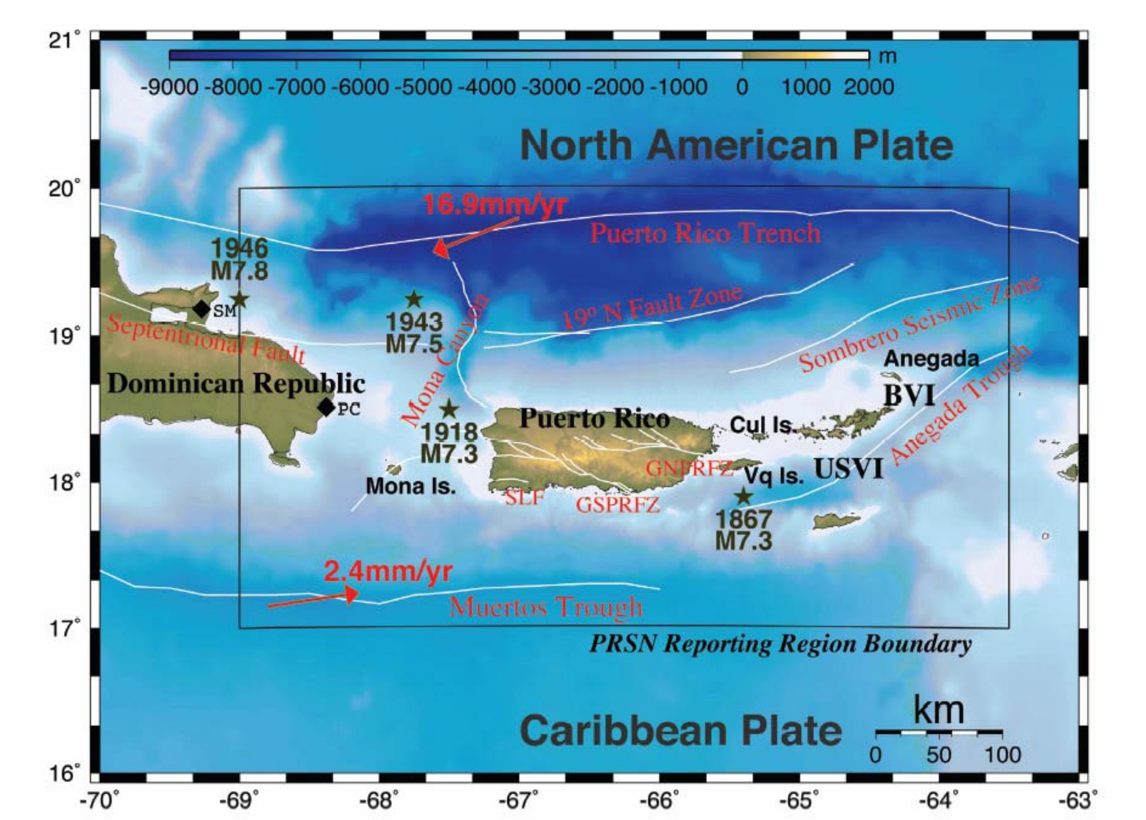


Figure 2.3 Seismic Settings and Major Faults (From Clinton et. al., In press)

The most important seismic potential sources for the Mayagüez area are the Puerto Rico Trench, the Muertos Trough and the Mona Passage (McCann, 1987). Historic records demonstrate that strong earthquakes have occurred in the Puerto Rico Trench in the past (Sykes et al., 1982). It is believed that the Puerto Rico Trench is capable of generating maximum events of M ~ 8.0 as there is evidence that in 1943 it produced an event of M ~7.75 (McCann, 1987). Also, according to McCann (1987) the Muertos Trough is considered to be capable of producing events of M ~7.5 to 8.0. However, the seismicity produced by the Mona Passage is considered the most threatening for the west coast due to the proximity to the area. This zone is capable of generating shocks of M ~ 7.5 to 8.0 (McCann, 1987). In 1918, this zone generated the most damaging event for the Mayagüez area with an estimated magnitude of 7.5. Approximately 116 people died due to this event and $4 million in property damage was estimated (Reid and Taber, 1919).

2.2.3 *Geology*

The general geology for the Mayagüez area has been mapped by and Mattson (1960) and Curet (1986). Figure 2.4 shows the different geologic units identified by Curet (1986). Table 2.1 provides a brief description of these units. In general, the Mayagüez area lies between the contact of two different geologic units: the Sierra Bermeja Complex and a volcanic complex (Gelabert, 1968; Moya and McCann, 1992). The Sierra Bermeja Complex is composed mainly by volcanic and metamorphic rocks of pre-Cretaceous to Early Cretaceous age and is considered to be the oldest rock formation in the island. The volcanic complex is a folded sequence of sedimentary and volcanic rocks of the Late Cretaceous to Early Tertiary age that overlays the Sierra Bermeja Complex (Moya and McCann, 1992).

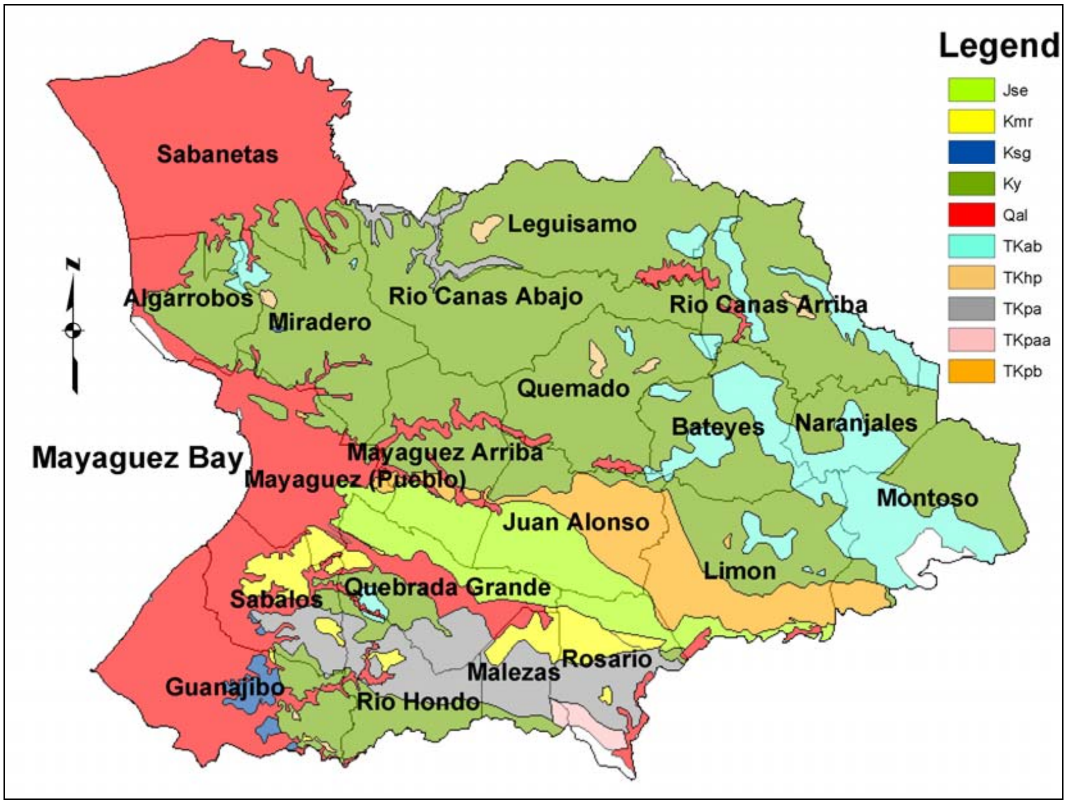


Figure 2.4 Generalized Geology Map of Mayagüez (Adapted from Curet, 1986)

The areas near the shoreline are to a large extent sand beach deposits characteristic of coastal environments. These sands are composed mainly by quartz sands formed in the Holocene and are described as mainly rounded, moderately to well sort sands with minor gravel sizes (Moya and McCann, 1992). Near the rivers (e.g., Guanajibo River) the soils are alluvial deposits from the Late Pleistocene and Holocene. They are described as poorly to moderately sorted, moderately to well-bedded sand, silt, and cobble or boulder gravel (Moya and McCann, 1992). At the Guanajibo River, the thickness of the alluvium deposits range from 50 to 100 ft (Colón-Dieppa and Quiñonez-Martínez, 1985). In the Añasco river flood plain the deposits are typically more than 100 ft thick (Colón-Dieppa and Quiñonez-Martínez, 1985). In the vicinity of the Yagüez River alluvial soils were found to extend to the final depth investigated of 120 ft (Capacete and Herrera, 1972) and are believed to extend from 170 ft to up to 300 ft in some

Mayagüez alluvial plains (McGuinness, 1946; Rodríguez and Capacete, 1988). The Sabanetas and Downtown districts of Mayagüez are mostly comprised of alluvial soils. The Algarrobos, Miradero, Sábalos, and Guanajibo neighborhoods of Mayagüez also have alluvial deposits but to smaller extents since they are predominantly residual soils. The residual soils in the Mayagüez area are typically located in the mountainous terrain away from rivers and creeks.

Table 2.1 Geologic Units for the Mayagüez Area (After Curet, 1986)

Age	Formation/Unit	Description
Holocene	Qal alluvium	Sand, silt and gravels, includes rock falls and landslide deposits
Early Tertiary Maestrictian (Maest.)	TKpb Basalts	Basalts and basalts weathered
	TKpa Andesite-diorite	Porphyritic andesite- diorite
	TKpaa Andesite-diorite	Altered porphyritic andesite-diorite
	TKhp Diorite	Porphyritic hornblende diorite (massive)
	TKab Basalt	Porphyritic augite basalt (massive)
Maestrictian and Campanian	Kmr Maricao Formation	Massive breccia, conglomerate sandstone and limestone
	Ky Yauco Formation	Calcareous volcanoclastic sandstone, siltstone, claystone, limestone, breccia, conglomerate
Maestrictian and Turonian	Ksg Sábana Grande Formation	Massive breccia, conglomerate sandstone, siltstone, claystone and limestone
Pre. Late Kimmeridgian	Jse Serpentinite	Massive and weathered serpentinite

A recent USGS study by Rodríguez-Martínez et al. (2004) divided Mayagüez into five hydrogeologic terranes according to the hydrogeologic and topographic characteristics and the ground-water resource development potential. The five hydrogeologic units proposed in this study are shown in Figure 2.5.

The first terrane identified by Rodríguez-Martínez et al. (2004), Mayagüez Hydrologic Terrane 1 (MayHT1), was restricted to lowlands, including the coastal areas and alluvial terraces along rivers and creeks in the mountainous interior. This terrane was subdivided into upper zone and a lower zone (underlying the upper zone). The upper zone is composed mostly of Quaternary alluvium and to a lesser extent, Quaternary mangrove and swamp deposits. According to Rodríguez-Martínez et al. (2004) the alluvium zone of this terrane is predominantly fine grained material, with high contents of silt and clay and small amounts of sand. The authors report presence of some localized deposits of gravel and sand which could have considerable thicknesses found mostly in the vicinity of ancient and present river channels deposits. This study estimated that the thickness of the upper zone generally ranged from 50 to 100 ft. The lower zone, underlying the upper zone, consists of pre-Quaternary fluvial and marine sandstones and Late Cretaceous and Early Tertiary-age volcaniclastics (sandstones, siltstones, claystone, and breccia) and limestones. The lower zone is underlain by Middle and Late Cretaceous-age serpentinite and intrusive igneous rocks (Curet, 1986). The thickness of the lower zone is unknown. The volcaniclastics rocks found on this zone were originated either from the deposition of volcanic eruption materials directly to the sea or from erosion and final deposition of existing volcanic rocks (Curet, 1986).

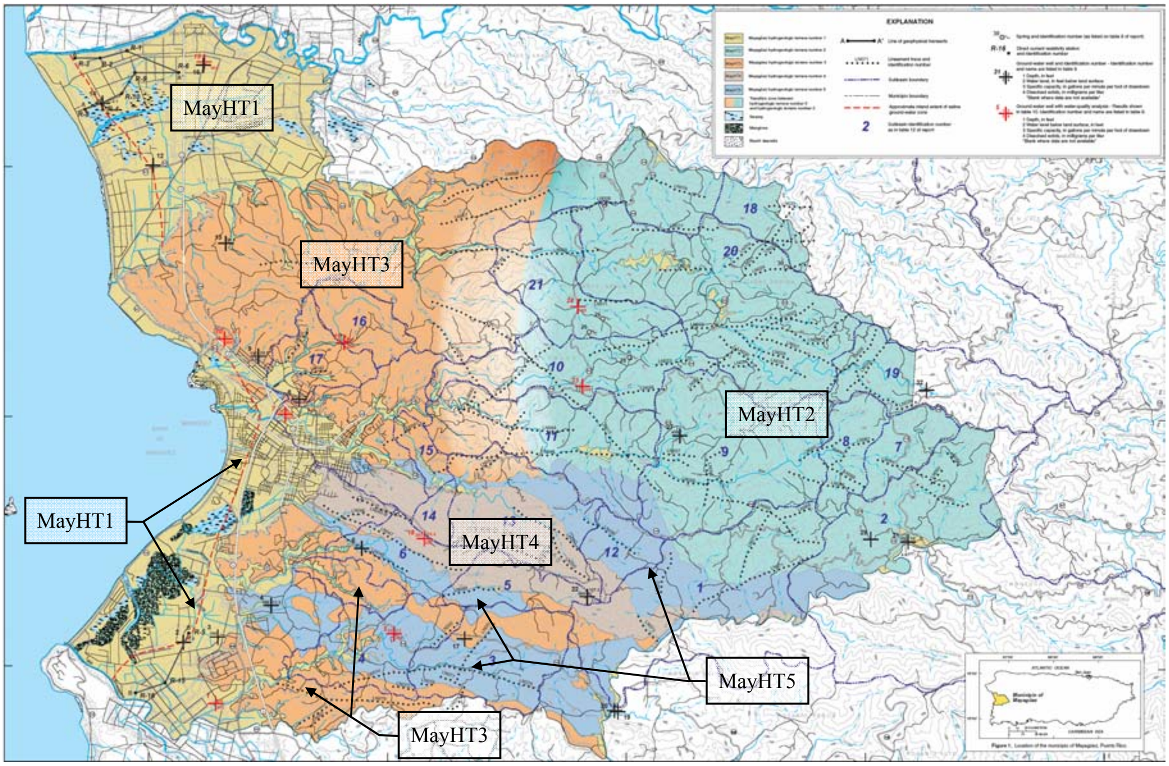


Figure 2.5 Hydrogeologic Terrane Units for Mayagüez from Rodriguez-Martínez et al. (2004)

The second terrane defined by Rodríguez-Martínez et al. (2004) was labeled MayHT2. It consists of volcaniclastic rocks intruded by intrusive igneous rocks. This terrane is located on the barrios (neighborhoods) of Río Cañas Abajo, Montoso, Bateyes, and Naranjales. The volcaniclastic and intrusive rocks are Cretaceous and Tertiary in age (Curet, 1986). The volcaniclastic units found in MayHT2, in order of decreasing aerial extent are the Yauco Formation and the Maricao Formation (Curet, 1986). The Yauco Formation is mainly composed of interbedded and calcareous volcaniclastic sandstone, siltstone, mudstone, claystone, limestone, and subordinate breccia and conglomerate while the Maricao Formation consists mostly of breccia with minor amounts of conglomerate, volcaniclastic sandstone, and limestone.

Rodríguez-Martínez et al. (2004) defined the third hydrogeologic terrane, MayHT3, as consisting primarily of the Yauco Formation, subordinate amounts of the Maricao Formation, and minor intrusive igneous rocks of basaltic and dioritic composition (Curet, 1986). The MayHT2 and MayHT3 hydrogeologic terranes are continuous and separated by a poorly defined transitional zone, mainly in the Barrios of Leguísamo, Río Cañas Abajo, and Quemado (Rodríguez-Martínez et al., 2004).

The hydrogeologic terrane MayHT4, is located in the southern part of Mayagüez and is restricted to the Cerro de Las Mesas upland. It consists mostly of serpentinite, a rock consisting mostly of the mineral serpentine, and other minor intrusive igneous rocks presumed to be of Early to Middle Tertiary age. Rodríguez-Martínez et al. (2004) indicates that in large areas of the MayHT4 hydrogeologic terrane the serpentinite bedrock is directly exposed with no soil cover.

The last hydrogeologic terrane defined by Rodríguez-Martínez et al. (2004), MayHT5, consists of intrusive igneous rocks of Tertiary and Cretaceous age (Curet, 1986). These igneous rocks are of basaltic and dioritic composition, similar to those found in hydrogeologic terranes MayHT2 and MayHT3.

2.2.4 *Topography*

Mayagüez is located on one of the coastal valleys of the west side of Puerto Rico. The topography of the Mayagüez area consists of mild to flat terrain in the coastal deposits and alluvial valleys, and sloping ground and mountainous terrain, in the east and northeast part of the city.

The coastal deposits are found along the Mayagüez Bay coastline. Other low lying areas of the region, are in the alluvial valleys of the principal rivers of the area, e.g., the Yagüez and Guanajibo rivers. A large flatland is located at the mouth of the Guanajibo River, which is located at the south part of the Mayagüez city. The mountainous terrain is related to the central range of mountains located on the east part of the city starting near the coastal area and rapidly rising to 350 meters above mean sea level.

The five Mayagüez hydrogeologic terranes of Rodríguez-Martínez et al. (2004) have different topographic characteristics. MayHT1 is described as flat and lowlands. MayHT2 consists of sloping grounds with variable slopes with most exceeding 15 degree angles. MayHT3 is also sloping ground but gentler slopes compared to MayHT2 with most of the slope inclinations equal to or less than 15 degrees. Units MayHT4 and MayHT5, were reported as having slopes angles ranging from less than 15 to more than 45 degrees.

To illustrate the topography of Mayagüez, an elevation cross section was generated to show the topographic profile in the north to south direction. The location of the cross section is indicated in Figure 2.6. The resulting topographic profile for this cross section is shown in Figure 2.7. This figure shows that the Sabanetas and the Mayagüez downtown (Pueblo) neighborhoods are low lying lands in which the elevation ranges mostly between 2 m and 15 m above mean sea level. As mentioned in the previous section, these two regions are mainly composed of alluvial deposits which potentially makes them susceptible to liquefaction.

According to the U.S. Census Bureau (2000), almost 33 percent of the Mayagüez population lives in the Mayagüez downtown (Pueblo) area and 38 percent of the Mayagüez housing units are located in this area. On the other hand, only 2.7 percent of the population, and 2.5 percent of the total housing units, are located on the Sabanetas area. Population and Housing Units values for the other Mayagüez neighborhoods intersected by the topographic cross section of Figure 2.7 are listed in Table 2.2.

Table 2.2 Population Data for Areas along the N-S Topographic Profile (from US Census Bureau, 2000)

N-S Profile Geographic Area	Estimated Population	Housing Units	% Total Population	% Total Housing Units
Sabanetas	2,645	985	2.7	2.5
Miradero	5,510	2,155	5.6	5.5
Mayagüez (Pueblo)	32,043	14,932	32.6	37.9
Sábalos	10,271	3,773	10.4	9.6
Guanajibo	7,165	2,754	7.3	7.0

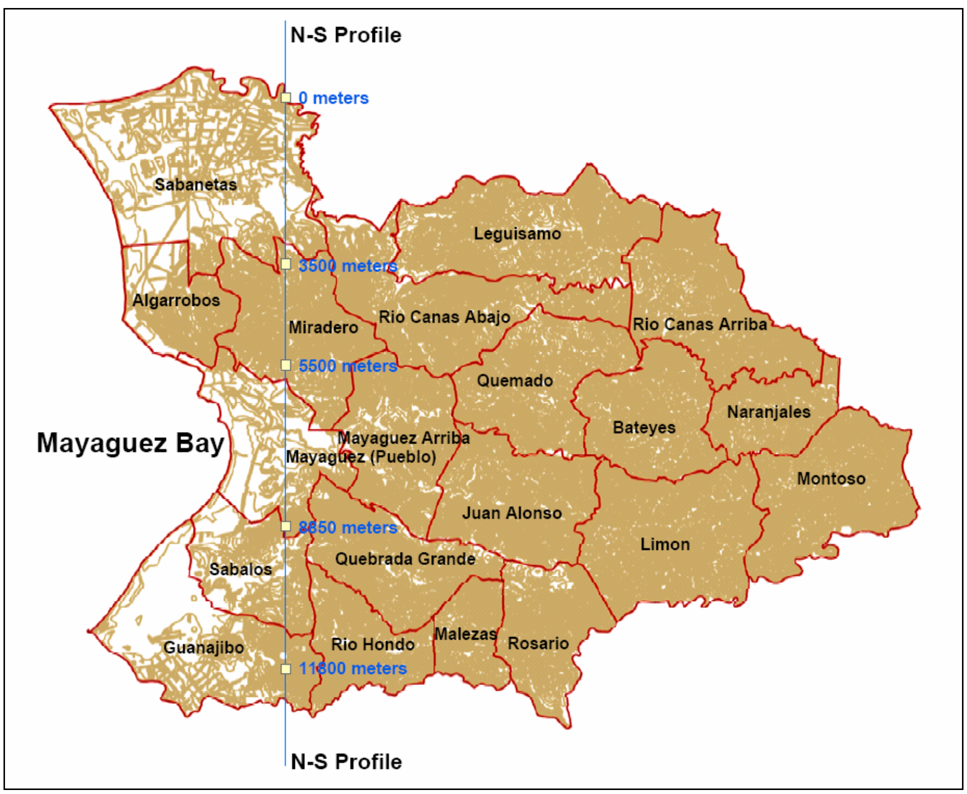


Figure 2.6 Location of N-S Topographic Profile

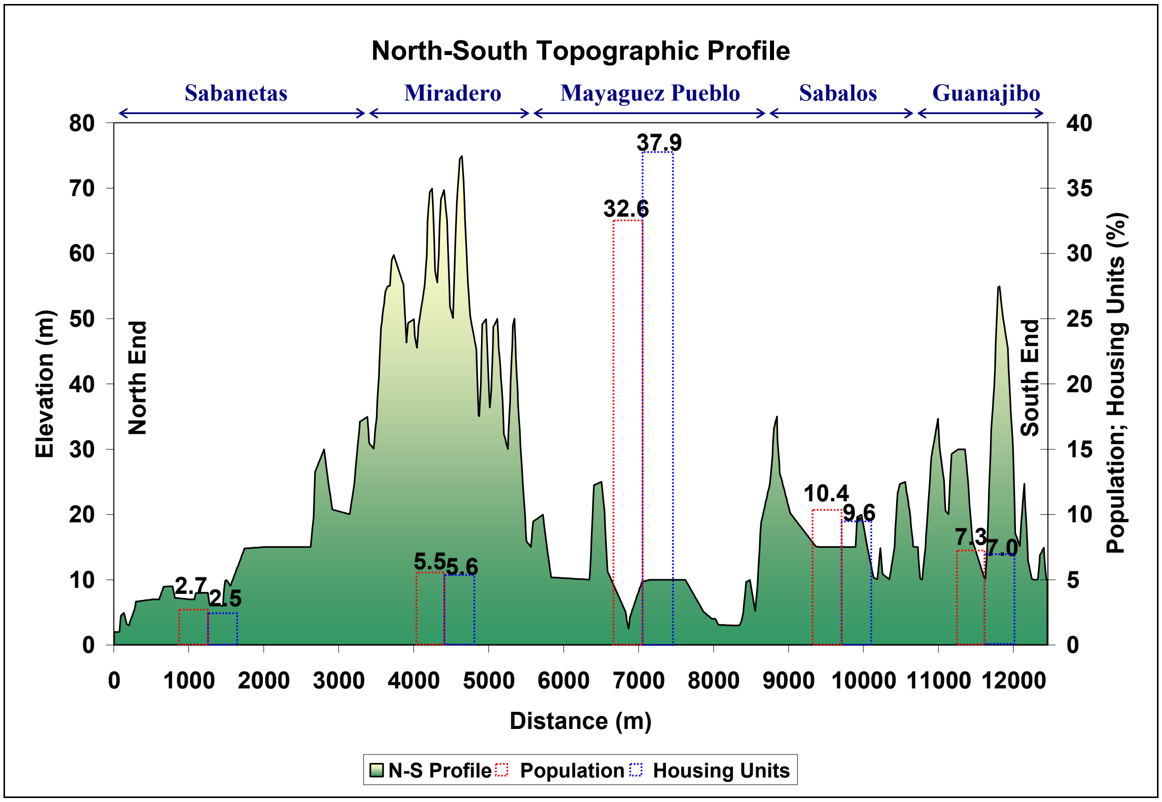


Figure 2.7 Topographic Profile and associated population data for N-S Section of Figure 2.6

Figure 2.7 illustrates the higher population in the Mayagüez (Pueblo) neighborhood compared to the other neighborhoods intersected by the N-S cross section line.

2.2.5 *Ground Water*

Information regarding ground water conditions is presented in this subsection. This information is important for liquefaction potential evaluations. Assessment of the liquefaction potential of a site must consider current and seasonal fluctuations of groundwater level conditions. Unfortunately most of the geotechnical studies available for this project did not have adequate information of the groundwater conditions. The current state of geotechnical practice does not typically involve installation of piezometers for groundwater monitoring. Most of the geotechnical borehole logs typically only present water conditions at the end of borehole drilling. This information is usually not considered representative or reliable due to time lag effects related to the time required for equilibration of ground water conditions inside the borehole with external water boundary conditions. This timelag is higher for fine grained soils. Of the more than 500 geotechnical borings examined for this project less than 1% included information of groundwater beyond the depth inside the boring at the end of drilling. Unfortunately this is representative of the current state of practice of the geotechnical profession in most firms in

Puerto Rico. Therefore, for this project, ground water levels were based on available data from monitoring wells in the study area. The USGS operates and maintains several groundwater wells in Mayagüez and historical data is available in their *Ground Water Levels database* (www.usgs.gov). For the Mayagüez County, a total of 142 groundwater wells were found on the USGS database. Unfortunately, very few of these wells provided enough historical data to determine a ground water level pattern. The most reliable set of data came from the well located at the Mayagüez Ports Authority ("Autoridad de los Puertos" well). This well is located in the North end of Mayagüez within the Sabanetas neighborhood. This well is located in the flatland areas of Mayagüez at an elevation of about 6 meters above mean sea level. Figure 2.8 summarizes ground water level data for this well. The water levels shown monthly average values representing depths in feet below ground surface. The data shown corresponds to 16 years of information ranging from 1967 to 1984.

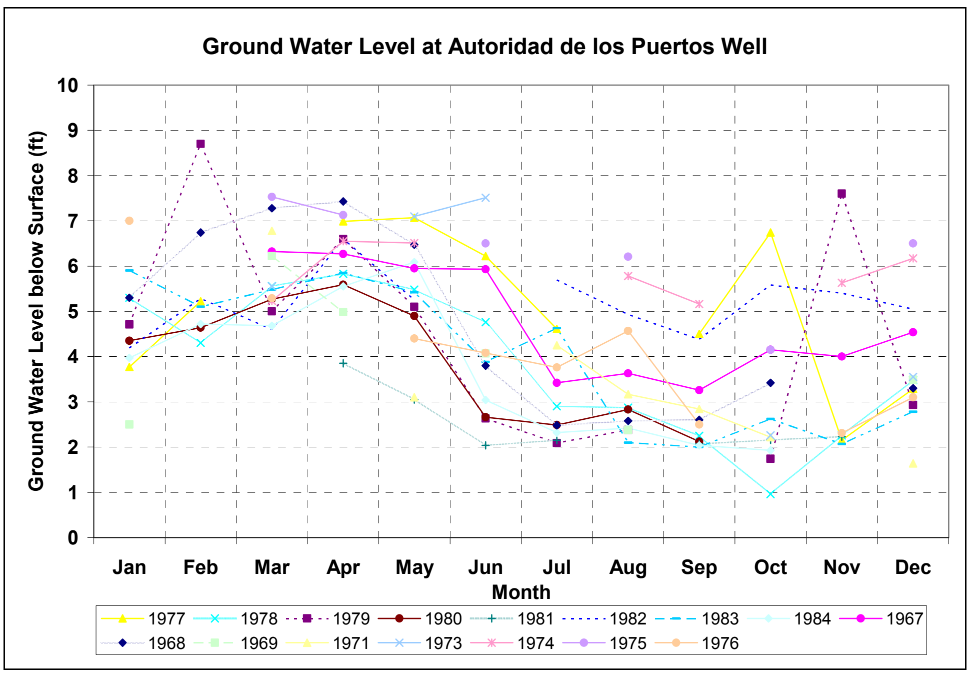


Figure 2.8 Ground Water Level information from the Mayagüez Ports Authority Well

Using the available data from this well, the average trend lines were calculated as shown in Figure 2.9. This figure also shows average monthly rainfall quantities based on data from 1971 to 2000. Figure 2.9 shows how in this area of Mayagüez the ground water level fluctuates from 5 to 9 ft depth in the dry season (from January to July), and from 4 to 6 ft depth in the rainy season (from July to November).

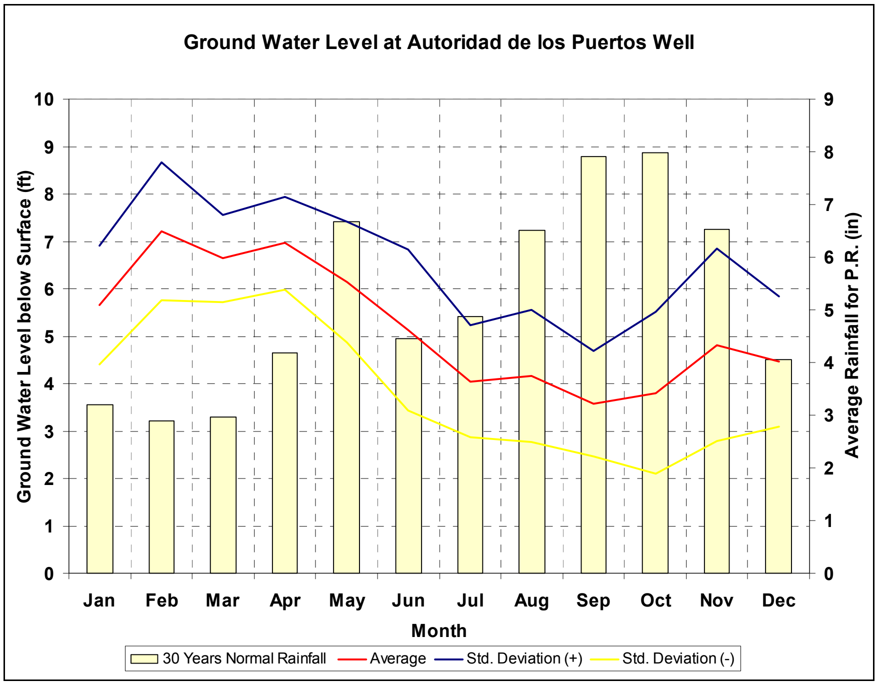


Figure 2.9 Ground Water Level combined with Average Rainfall in PR

The study by Rodríguez-Martínez et al. (2004) defined generalized relations between depth to water and topographic relief for the Mayagüez area based on available historic water-level measurements. The generalized observations regarding water levels made by Rodríguez-Martínez et al. (2004) are as follows:

- The water level in the coastal plain is generally less than 10 ft below ground surface.
- The water level in the valleys of the main rivers of the Mayagüez region are likely between 10 ft and 15 ft below ground surface.
- In sloping terrain with varying degrees of inclination, the water depth generally lies between 15 and 40 ft.
- In hilltops, the water depth is generally greater than 40 ft but but not greater than 110 ft (depending on the elevation of the hilltop).

All groundwater information collected for this NEHRP study was stored in the geotechnical database developed for this project.

2.3 *Previous Seismic Hazard Studies for the Mayagüez Area*

This subsection presents a summary of the most relevant studies previously done for Mayagüez related to seismic hazard evaluations or mapping.

2.3.1 *Reconnaissance Report for the 1918 Earthquake by Reid and Taber (1919)*

Reid and Taber (1919) performed a detailed study of the effects of the 1918 Earthquake to the islands of Puerto Rico, Vieques, and St. Thomas. The epicenter of October 11, 1918 earthquake was estimated to be approximately 15 km west off the coast of the Aguadilla-Mayagüez Region. Reid and Taber (1919) described the earthquake as beginning with a pronounced vertical vibration, which was followed by horizontal oscillations. A tsunami created by the earthquake hit the western portion of Puerto Rico soon after the earthquake. Reid and Taber (1919) estimated the intensity of the shock in Mayagüez, having at that time a population of about 17,000, between VIII and IX in the revised Rossi-Forel scale.

Reid and Taber (1919) described Puerto Rico as extremely mountainous, with no large areas of flat land and with narrow alluvial plains in places along the coasts which extend for several miles up the larger valleys. They indicated that the apparent intensity was always greater on the alluvial soils than compared to corresponding sites located on competent ground such as rock or residual soil. The authors also reported more noticeable damage in areas with alluvial soils, particularly in ground where the water stood close to the surface. An important factor contributing to the large extent of property damage and loss of life in Mayagüez was believed to be associated to the presence of alluvial soils and high water table (Reid and Taber 1919). The authors reported that a large percentage of the infrastructure, including bridges, railroad lines, pipelines, and utility cables, was damaged or affected in the Mayagüez area by the 1918 earthquake. Damage included severe cracking in brick, masonry, and concrete structures.

2.3.2 *Seismic Hazard Study by McCann (1987)*

McCann (1987) identified different seismic sources for western Puerto Rico. Recurrence intervals were estimated for each of these sources to generate earthquakes having Modified Mercalli intensities (MMI) greater than VII. The author found recurrence periods for most of the seismic sources between 29 to 68 years. The author suggested that seismic sources close to the Mayagüez area, particularly those to the west, are the most critical, and not the sources to the north of the island (e.g., Puerto Rico North Trench).

2.3.3 *Seismic Hazard Study by Moya and McCann (1992)*

Moya and McCann (1992) carried out a seismic vulnerability study of the Mayagüez area for the Puerto Rico Seismic Safety Commission. Three major earthquake sources were considered for Mayagüez: the Puerto Rico North Trench, the Mona Canyon, and the Mayagüez or Cordillera Fault. As part of this study the authors estimated seismic vulnerability within Mayagüez based on geologic characteristics. The authors divided the Mayagüez region into zones of seismic susceptibility for three different seismic hazards: soil amplification (i.e., PGA amplification due to local site conditions), liquefaction potential, and soil failure. Table 2.3 presents the criteria used for classification of the different zones. A map showing the different zones is presented in Figure 2.10.

The authors also estimated the tsunami threat for Mayagüez. The study considered tsunami threat to be limited to the coastal area within a distance of 300 to 400 meters from the coast and to terrain with ground elevations from 2 to 6 meters above sea level. In this study the authors identify the coastal region of Mayagüez as the most prone to suffer severe damage during a major earthquake.

Table 2.3 Seismic Susceptibility Zone Classification for the Mayagüez Area (Moya and McCann, 1992).

Zone	Soil Amplification	Liquefaction Potential	Soil Failure Potential
A – 1	Non Significant	Low	Very Low
A – 2	Non Significant	Low - Moderate	Low
A - 3	Non Significant - Low	Moderate - High	High - Where materials are not laterally confined and have moderate slope
A - 3 - S	High	High - On soil deposits covered by sand	High - On soil deposits covered by sand
B - 1	Non Significant	None	Very low
B - 2	Moderate - Very High	High - Where materials are not laterally confined	High – Along rivers Lateral Slide
B - 3	High	High - Especially on loose sand deposits	High - Lateral Slide
C - 1	Non Significant	None	Low
C - 2	Non Significant	None	Moderate – High
C - 3	Non Significant	None	High

The Moya and McCann (1992) study was an important contribution towards helping quantify the seismic hazard for the Mayagüez area. Unfortunately, the report did not provide much details on the evaluation methodology, number of sources (and quality) of geotechnical information, and other important data required for ground motion and liquefaction assessments.

For example values of ground acceleration used for liquefaction susceptibility assessment (and the corresponding recurrence interval) were not provided. Similarly, the methodology or criteria used to assess the potential for soil failures was not provided in the report for the Puerto Rico Seismic Safety Commission.

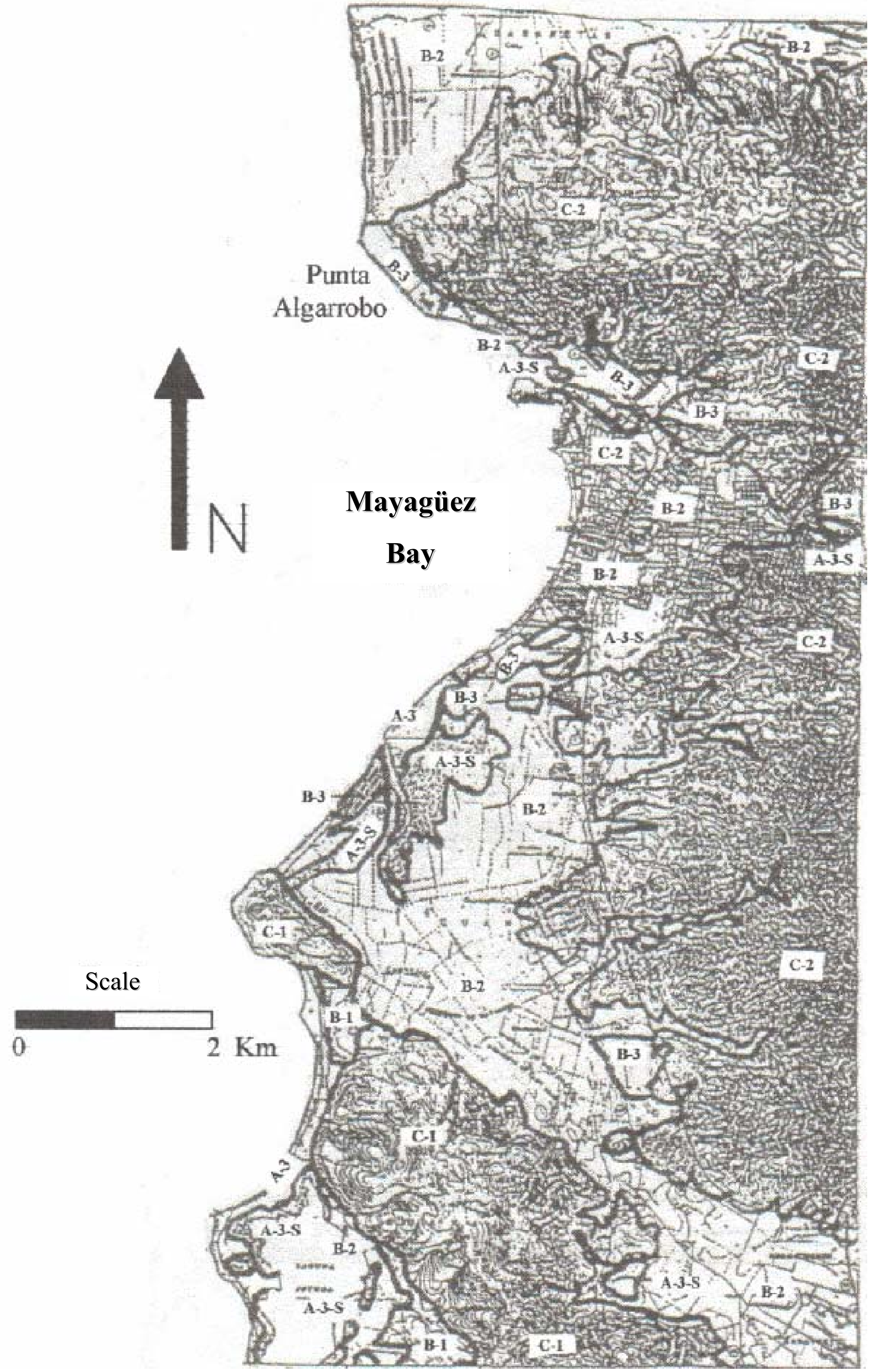


Figure 2.10 Zone Classification Map according to Moya and McCann (1992) [See also Table 2.3]

2.3.4 *Geophysical and Geotechnical Testing by Macari (1994)*

Macari (1994) performed a series of geophysical and geotechnical tests within the Mayagüez area. The geophysical tests were carried using the procedure of Spectral Analysis of Surface Waves (SASW). The geotechnical testing consisted of cone penetration testing (CPT) at several sites within the city of Mayagüez using a CPT device from Georgia Tech. A total of eight sites were studied in western Puerto Rico but only three sites were within the Mayagüez. For each site the author determined profiles of shear wave velocity as well as CPT information that included tip and sleeve resistance as well as pore pressure data. The three sites studied by Macari (1994) within Mayagüez were: the Athletic Field at the UPR-Mayagüez, the India Brewery in front of the UPR-Mayagüez campus, and a site adjacent to the PR-2 highway near the Darlington building. The field tests revealed that the three sites were composed of deep deposits of alluvial soils with relatively low average shear wave velocities (below 200 m/s). The SASW tests nor the CPT soundings were sufficient to help determine the thickness of the soft alluvial sediments, but it was inferred that they extended beyond the depth of CPT exploration of 30 m. In addition to these sites, Macari also studied a site at the Guanajibo valley, located adjacent to the Mayagüez Bay and the Guanajibo River. At the Guanajibo river valley, Macari (1994) found that the shear wave velocity increased quickly with depth reaching values above 600 m/s at 9 m depth. It is possible that this Guanajibo river site had shallow bedrock. The shear wave velocity profiles and CPT soundings performed by Macari (1994) are included in the geotechnical database created for this USGS NEHRP project.

2.3.5 *Seismic Hazard Study by Macari (1997) and Macari and Hoyos (2005)*

Macari (1997) performed a GIS-based seismic hazard analysis for Western Puerto Rico as part of a USGS NEHRP grant. As part of this study the authors carried out a preliminary liquefaction potential assessment using the liquefaction simplified procedure (Youd et al., 2001) and the Liquefaction Potential Index (LPI) concept proposed by Iwasaki et al. (1982). The liquefaction susceptibility assessment was made assuming a maximum credible earthquake with a magnitude ($M_w = 7.5$) and considering several peak ground accelerations (PGA) values varying from 0.05g to 0.15g (based on McCann, 1993). Using this range of PGA values the authors computed LPI values to help develop preliminary liquefaction hazard maps. The authors assigned a low liquefaction potential to regions with LPI values less than 5, a moderate liquefaction potential for LPI values ranging between 5 and 15, and a high liquefaction potential for LPI values greater than 15. The main results from this study are summarized in Macari and

Hoyos (2005). Figure 2.11 shows the liquefaction hazard map developed for a PGA of 0.15g. This figure shows a large area of Mayagüez would be susceptible to liquefaction for a scenario involving a PGA of 0.15 g. As discussed later in this chapter, PGA values between 0.2 and 0.37g are recommended by recent studies for Mayagüez (considering rock conditions hence PGA values could be higher considering amplifications due to local site effects). Furthermore, it is not clear whether this study considered adjustment in the liquefaction potential estimates to account for the fines content of many of the sandy deposits in coastal Mayagüez. This was considered by Llavona (2004) (see Subsection 2.3.10) as an important factor since many geotechnical studies in the Mayagüez area reported sands to be silty and sometimes clayey (i.e. fines contents between 15 and 30% could be considered reasonable). Based on current liquefaction assessment methods (e.g., Youd et al., 2001) soils with large fines contents would have a higher liquefaction resistance than clean sands with similar conditions. Another factor not mentioned explicitly in this study is the influence of sloping ground, which for Mayagüez is also considered an important factor given its topography.

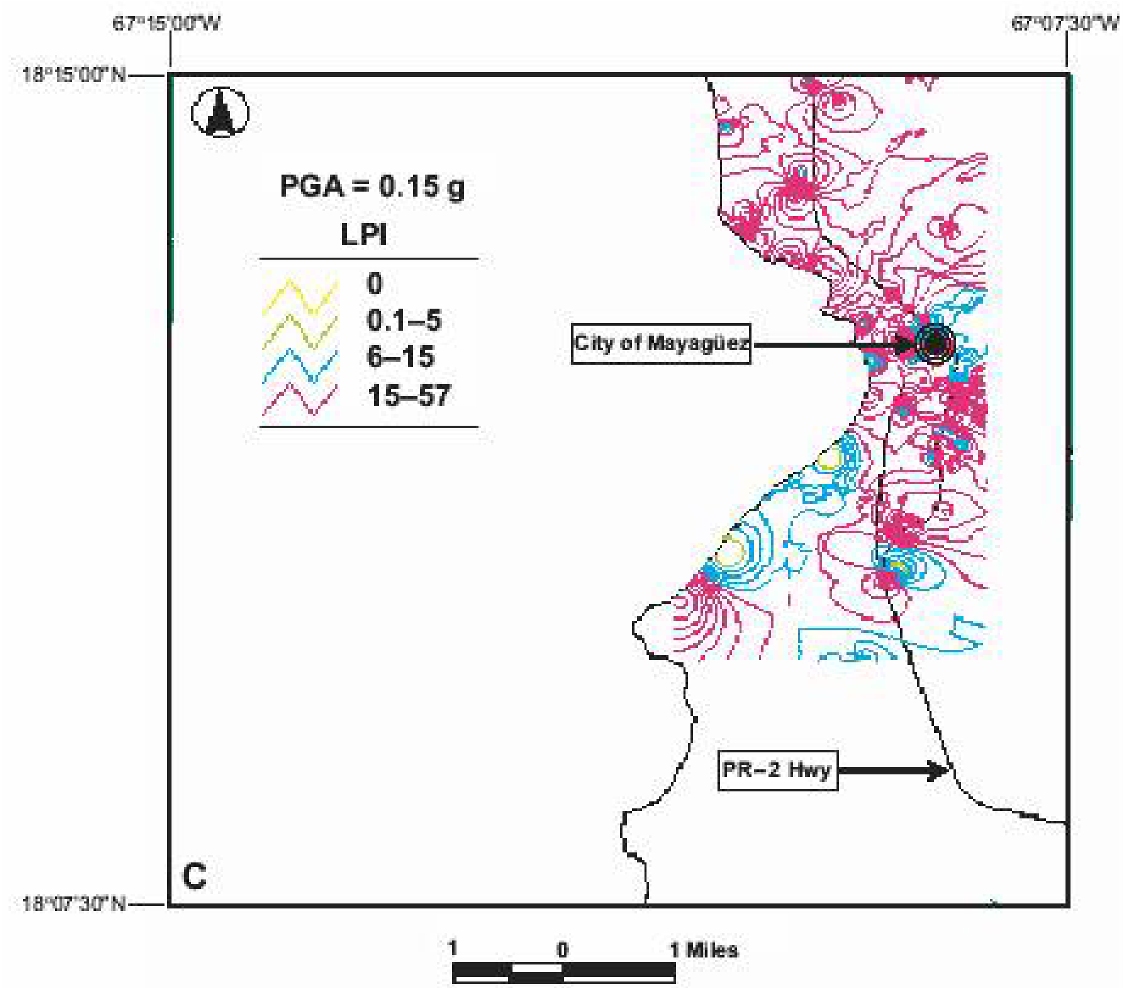


Figure 2.11 Liquefaction Hazard Map by Macari and Hoyos (2005) for PGA = 0.15 g

The authors indicate this was a pilot study so results should be viewed as preliminary in nature and recommend a more detailed and comprehensive study for an accurate assessment of the liquefaction potential assessment for Western Puerto Rico. The authors recommended additional research and use of a larger data set of soil properties. As mentioned before, this study focused on providing details regarding a GIS–based framework for identifying and mapping seismic hazards for Western Puerto Rico.

2.3.6 *Probabilistic Seismic Hazard Analysis for Puerto Rico by Dames and Moore (1999)*

The Puerto Rico Earthquake Commission sponsored a probabilistic seismic hazard analysis for Puerto Rico which was carried out by Dames & Moore (1999). In this study, Dames & Moore recommended elastic design spectra for six cities in Puerto Rico including San Juan, Ponce, and Mayagüez. The study was done using catalogues of historic seismic records for the Puerto Rico region and used the seismic zones and the associated maximum credible magnitudes recommended by McCann (1994). The design spectra recommended for Mayagüez is presented in Figure 2.13 (next subsection).

For the city of Mayagüez the Dames and Moore (1999) study recommended peak ground accelerations of 0.37g and 0.66g for return periods of 475 years and 2,475 years, respectively for rock sites.

2.3.7 *Design Spectra for main cities of Puerto Rico by Martinez et al. (2001)*

In an effort to develop elastic response spectra in rock for the cities of San Juan, Ponce, and Mayagüez, Martinez, Irizarry, and Portela (2001) established ten seismic zones based on the most active seismic faults in Puerto Rico. Figure 2.12 shows the seismic zones used in this study. Table 2.4 displays their most relevant characteristics. The authors then reviewed over 15,000 ground motions recorded worldwide that met a series of conditions so that they would be representative of the seismic setting and zones established for the main cities of Puerto Rico (e.g, records must be within characteristics of each seismic zone including epicentral distance, focal depth, magnitude range, etc). This study was based on a MS thesis carried by Irizarry (1999).

For the Mayagüez area, Martinez et al. (2001) found that the response spectrum from two records from the October 10, 1986 El Salvador earthquake, dominates response for all the range of periods. Using all the elastic response spectra the authors obtained a design spectrum for the city Mayagüez. The design spectrum recommended by Martinez et al. for the city of Mayagüez is shown in Figure 2.13. The design elastic response spectrum developed for Mayagüez compared well with the design spectrum recommended in the UBC-97 code for a seismic zone 4 in rock. This figure also shows good agreement with the elastic spectrum recommended by Dames & Moore (1999) which was discussed in the previous subsection.

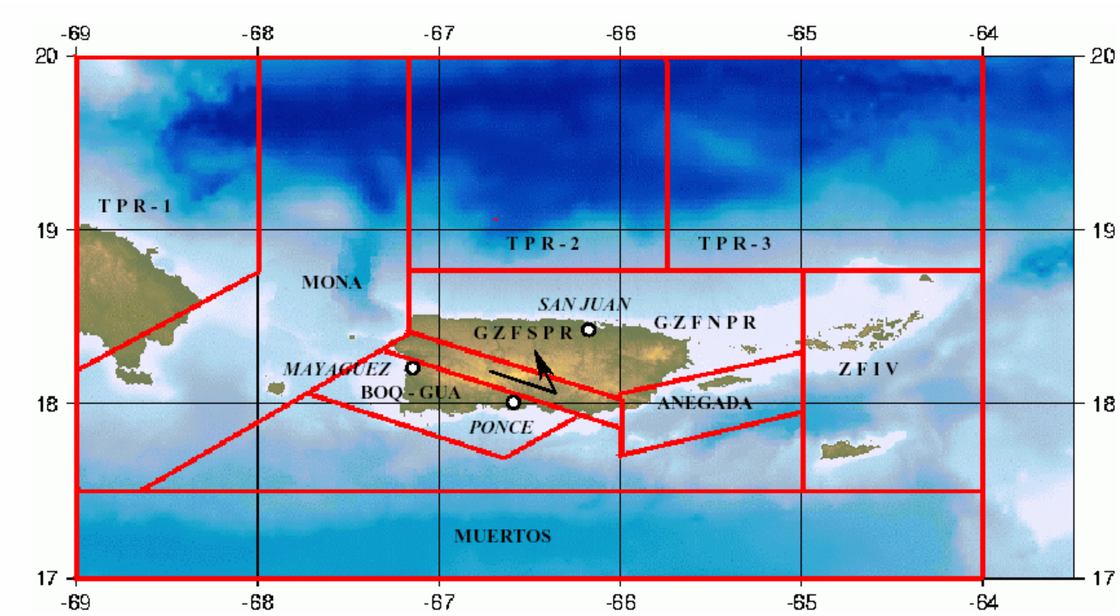


Figure 2.12 Seismic Zones used by Martinez et al. (2001)

Table 2.4 Characteristics of the 10 Seismic Zones used by Martinez et al. (2001)

Seismic Zone	Maximum magnitude	Maximum depth (km)	Epicentral distance from Mayagüez (km)	
			Minimum	Maximum
TPR-1	8.0	150	107	283
TPR-2	8.0	150	59	253
TPR-3	8.0	150	160	392
MONA	7.5	200	20	136
GZFNPR	6.5	40	0	100
GZFSPR	6.5	40	123	232
ANEGADA	7.5	30	19	296
BOQ-GUA	6.5	40	78	363
MUERTOS	7.5	50	21	239
ZFIV	7.5	50	227	345

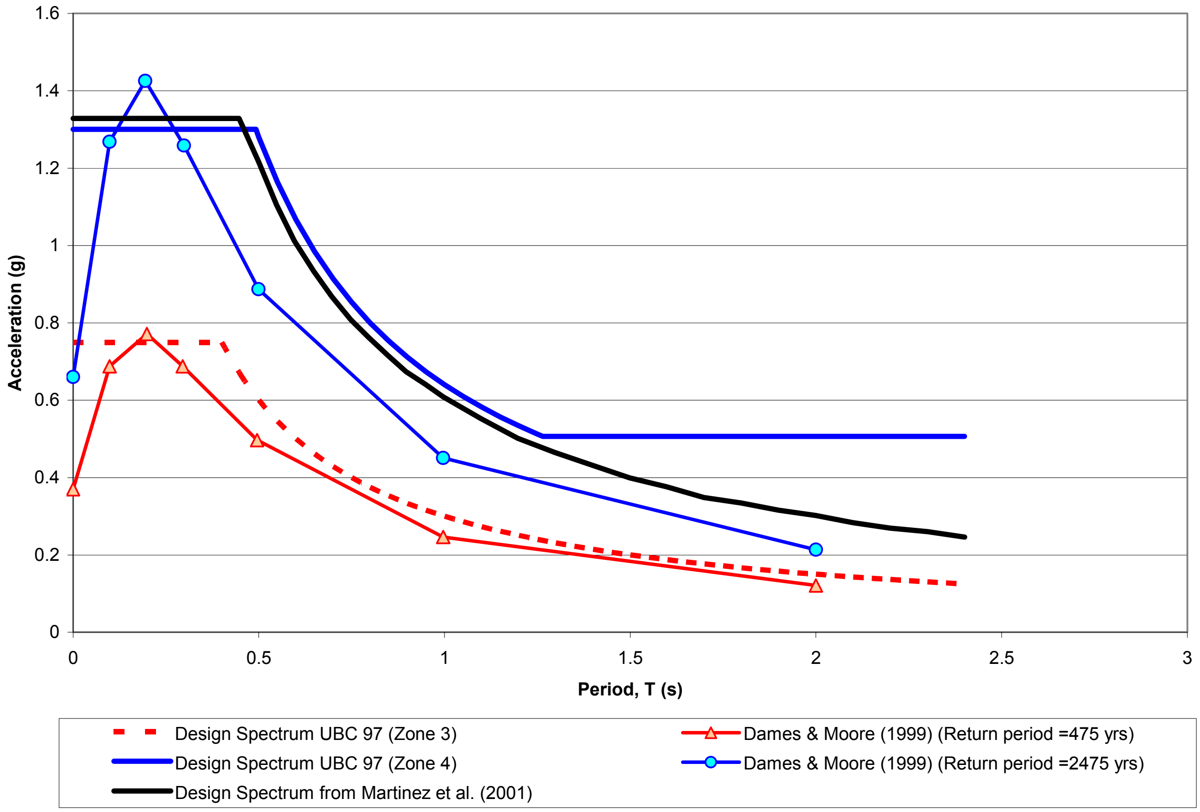


Figure 2.13 Design Spectrum for the City of Mayagüez recommended by Martinez et al. (2001)

2.3.8 *USGS PGA Maps for Puerto Rico by Mueller et al. (2003)*

Recommendations for estimating peak horizontal accelerations for the Mayagüez area considering the different seismic zones affecting the region were provided by Mueller et al. (2003). PGA seismic hazard curves from this study are shown in Figure 2.14. For example, the resulting peak ground acceleration (a_{max}) obtained from this figure for a 250 years recurrence period (Exceedance/Years = 0.004) using the curve titled "all modeled sources" (which represents the probabilistic contribution of each of the modeled sources) is 0.2g. This value would be the estimated peak ground acceleration, for a rock site in Mayagüez, considering all seismic sources and a 250 year return period.

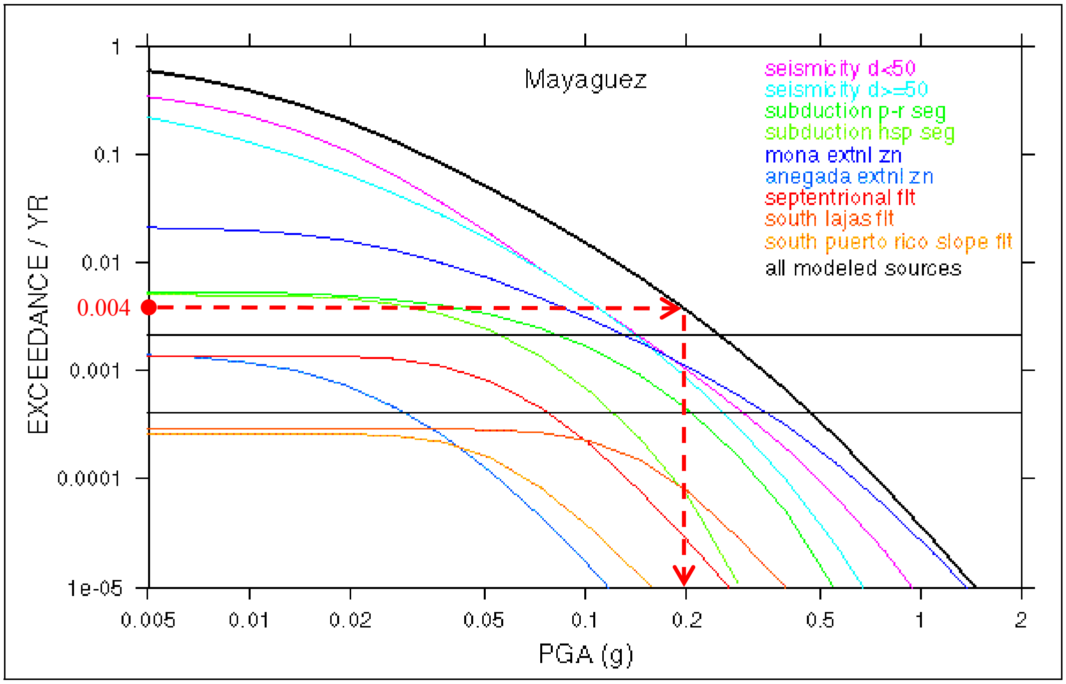


Figure 2.14 PGA Hazard Curves for Mayagüez (from Mueller et al., 2003)

2.3.9 *Paleoseismicity Studies by Tuttle et al. (2003)*

Tuttle et al. (2003) carried out paleoseismicity studies in western Puerto Rico. During river reconnaissance in western Puerto Rico, Tuttle et al. (2003) found 59 liquefaction features along three rivers: Culebrinas, Rio Grande de Añasco, and Guanajibo. The liquefaction features found included a few small sand blows and many small to moderate sand dikes. The authors associate many of these liquefaction features as probably being formed during the 1918 or 1670 earthquakes. Liquefaction potential analyses were used to evaluate several earthquake scenarios for sandy sediments identified from available borehole data near the Culebrinas, Rio Grande de Añasco, and Guanajibo rivers. This study suggested that many of the liquefaction features along the Rio Grande de Añasco and Culebrinas rivers, may have been result of the 1670 earthquake and estimated its magnitude about M ~7 and located it in or near the Añasco River Valley (Tuttle et al. 2003).

This study highlights the significant liquefaction susceptibility of many of the alluvial soils in Western Puerto Rico and draws attention to the importance of better quantifying this susceptibility. Tuttle and co-workers continue work related to reconnaissance of river cutbanks and liquefaction potential analysis in Western Puerto Rico and they have plans to expand work to study rivers in the northern and eastern coasts of Puerto Rico (Tuttle 2004).

2.3.10 *Master in Engineering Thesis at UPRM by Llavona (2004)*

Llavona (2004), as part of a ME thesis in the Civil Engineering Department of UPRM (directed by one of the PI's of this project) gathered geotechnical information from more than 500 geotechnical borings. As part of his thesis, Llavona (2004) developed soil classification maps for Mayagüez based on the provisions of the 1997 Uniform Building Code (UBC 97) which use the NEHRP soil classification system. To a large extent the geotechnical information gathered by Llavona (2004) was the basis for the geotechnical database developed for this USGS-NEHRP project. Figure 2.15 shows the location of the geotechnical studies used by Llavona (2004) for developing the NEHRP soil maps. Each dot represents the location of a geotechnical study which typically had more than one borehole. This figure shows the resulting NEHRP soil classification for each geotechnical study which was used to generate the NEHRP soil maps included in the geotechnical database prepared for this project (please see the enclosed DVD).

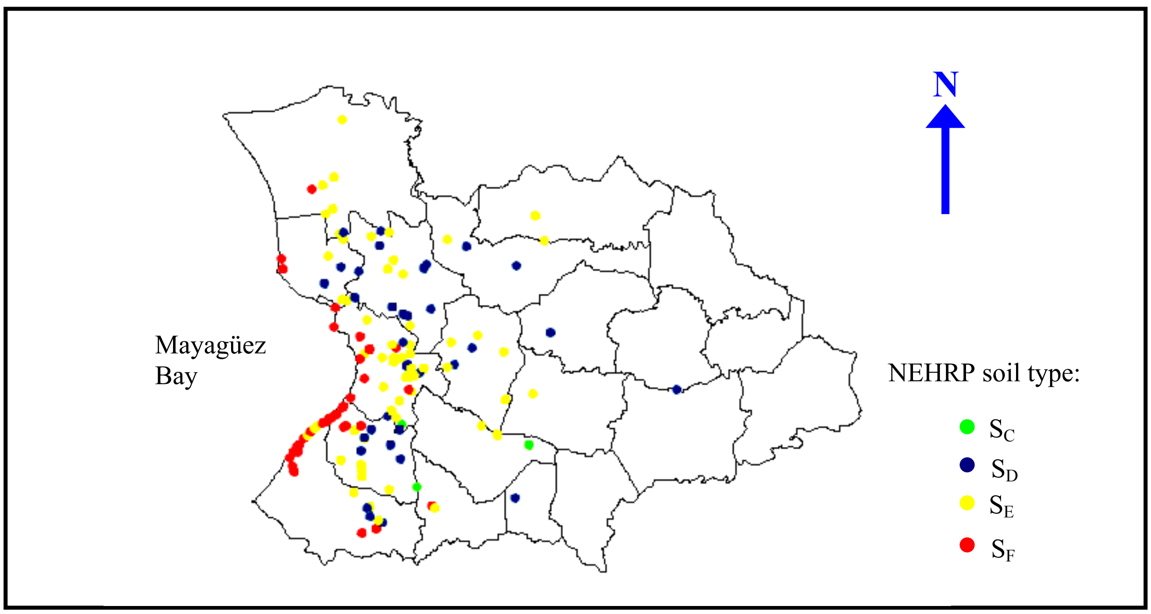


Figure 2.15 Distribution of NEHRP soil types by Llavona (2004).

Llavona (2004) also included in his thesis a liquefaction susceptibility assessment for the city of Mayagüez. The assessment was based on using the simplified liquefaction procedure update by Youd et al. (2001) and the use of the Liquefaction Potential Index (LPI) concept proposed by Iwasaki et al. (1982). The analyses were carried out using the program LicuadoPR developed by Sosa and Pando (2004). For the liquefaction study, Llavona (2004) used the peak ground acceleration (PGA) values recommended by Mueller et al. (2003) for rock sites and a return period of 250 years. Mueller et al. (2003) estimated for rock site conditions in Mayagüez a PGA of 0.2g for a 250 year return period and consideration of all seismic sources. This PGA value was corrected for local site effects using amplification factors estimated as the ratio of the seismic coefficients Ca recommended in the UBC-97 for a seismic zone factor (Z) equivalent to the PGA on a rock site with NEHRP soil type S_B (Ca=0.2). The LPI values estimated by Llavona (2004) for the available geotechnical information are shown in Figure 2.16. The extent of the area identified as being susceptible liquefaction map by Llavona (2004) is presented in Figure 2.17. These maps are included as layers of the geotechnical database of this project (see attached DVD).

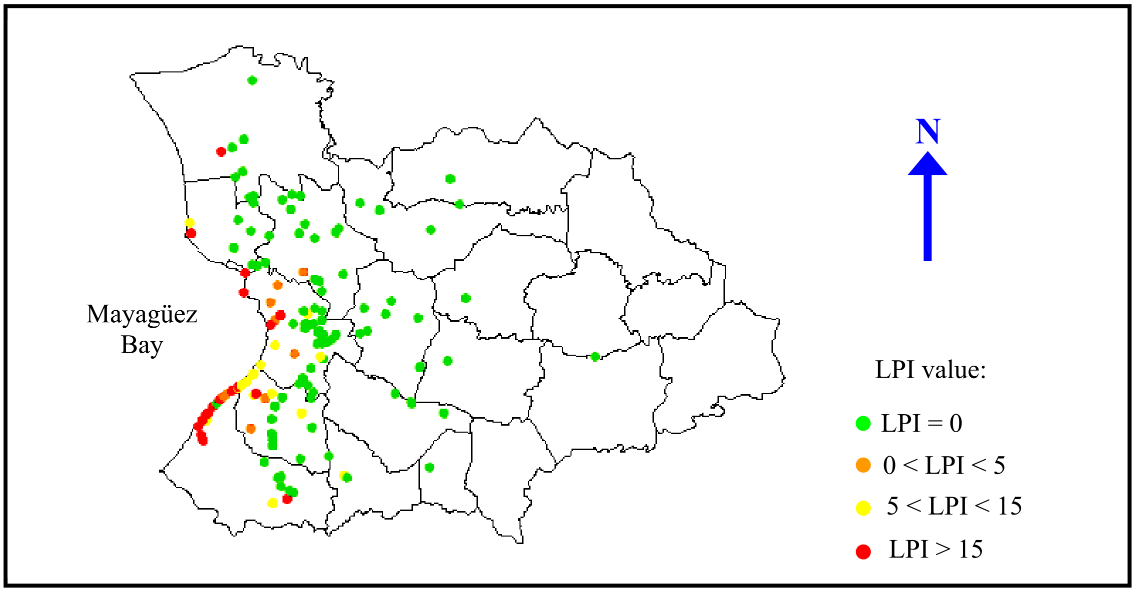


Figure 2.16 Liquefaction Potential Index values for Mayagüez by Llavona (2004)

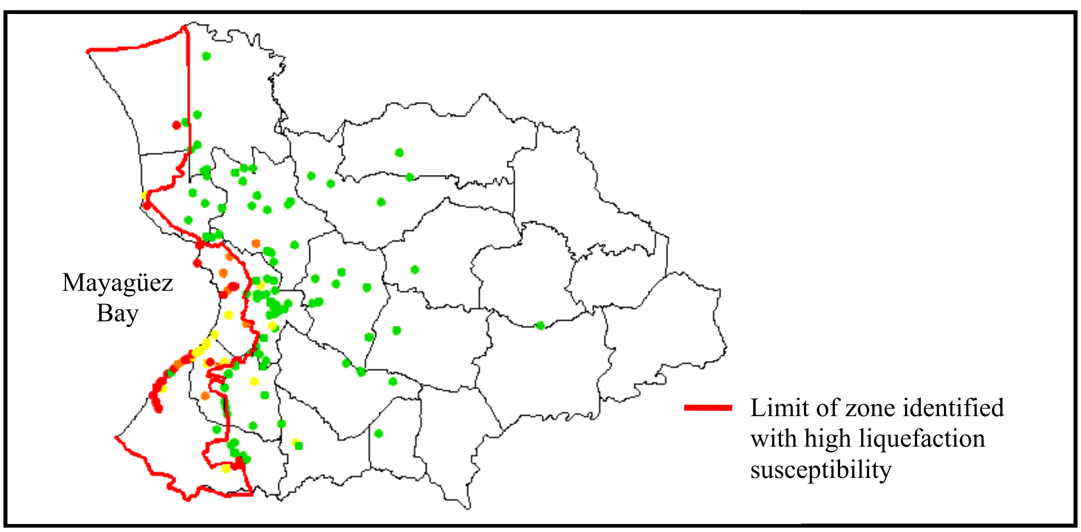


Figure 2.17 High liquefaction susceptibility zone for Mayagüez by Llavona (2004)

2.3.11 *Geophysical testing by Odum et al. (in preparation)*

During the summer of 2003, Odum et al., from the United States Geological Survey carried out geophysical test at several sites in Puerto Rico with partial funding from the Puerto Rico Seismic Network and the Puerto Rico Strong Motion Program. The tests consisted of seismic refraction and refraction microtremor (ReMi) tests. The sites tested in the Mayagüez area, included: El Seco Park, the UPRM track field, and the Candelaria site. From these tests, they obtained shear wave velocity profiles for each site and they classified the sites according to the NEHRP provisions. All sites were classified as NEHRP soil type S_D. More information on these tests results is provided in Chapter 3.

CHAPTER 3 Geophysical Testing in the Mayagüez Area

3.1 *Introduction*

As mentioned earlier, this study included carrying out several geophysical tests in the city of Mayagüez. These geophysical tests consisted of Spectral Analysis of Surface Waves (SASW) and seismic refraction. The tests were carried out to help further populate the geotechnical database developed for this project. This chapter summarizes the geophysical data generated as well as geophysical data from other sources.

3.2 *Geophysical Testing carried out for this Project*

SASW and seismic refraction geophysical testing were carried out as part of this project. The following subsection summarizes the results obtained. All geophysical test results have been included in the enclosed geotechnical database.

3.2.1 *SASW testing*

SASW field tests were carried out at nine locations within the city of Mayagüez boundaries. Site selection criteria were based on sites where geotechnical information was considered limited or insufficient. Figure 3.1 displays the locations of the SASW test sites and Table 3.1 lists their respective geographic coordinates. The Abonos and Highway PR-341 sites are composed primarily of alluvial soils, the Maní Park, Maní, Seco Park, Isidoro García, and Ramírez de Arellano sites are located within coastal deposits, and the Sultanita and Civil sites are located within residual soils. The SASW results for the nine test sites are summarized in the following subsections. The SASW testing carried out for this study was also part of the UPRM MS thesis by Pérez (2005). Assistance with some of the tests and with the data processing was provided by Dr. Jim Bay from Utah State University who many years of experience with SASW testing. Additional details about the SASW testing, including field set up, test procedure, and procedures used for data analysis and reduction can be found in Pérez (2005).

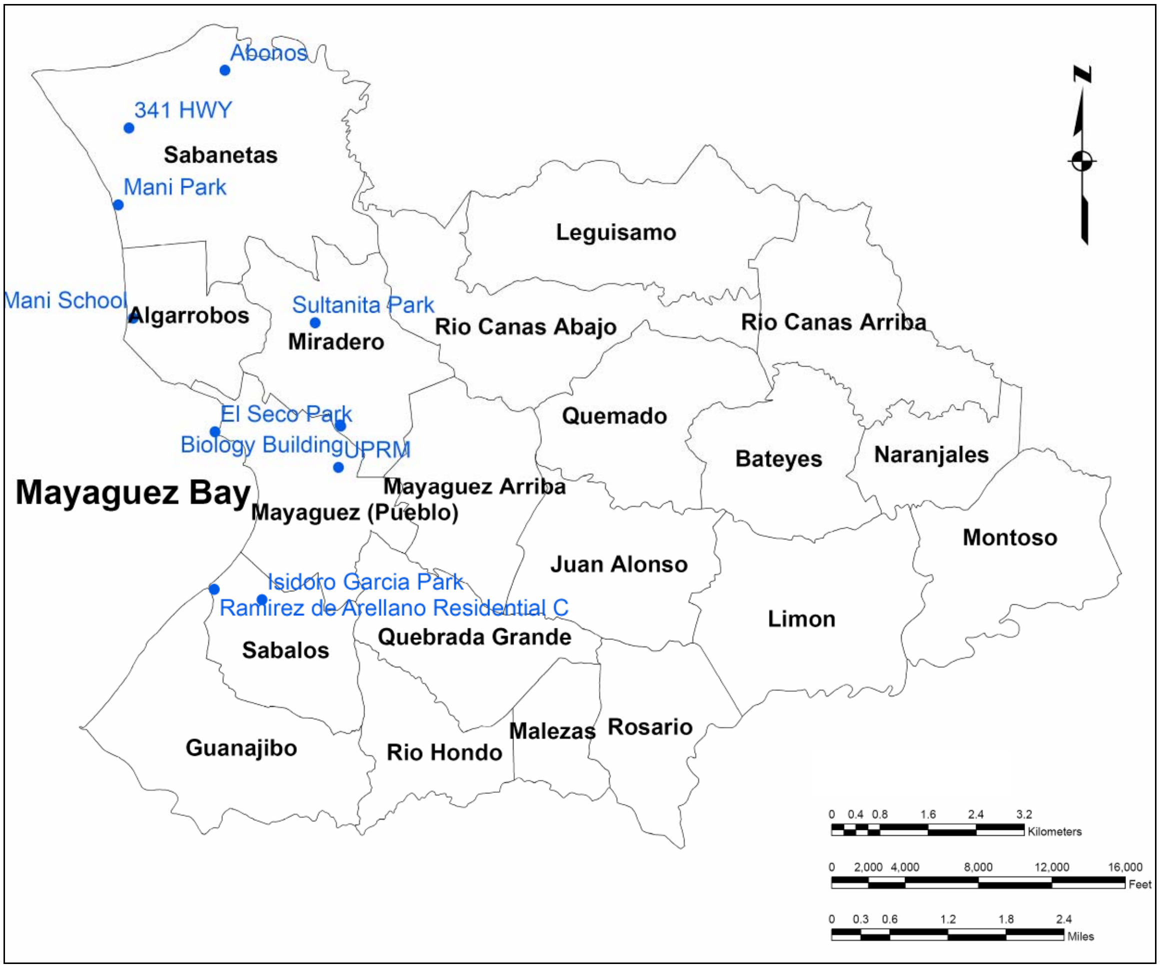


Figure 3.1 Location of SASW tests

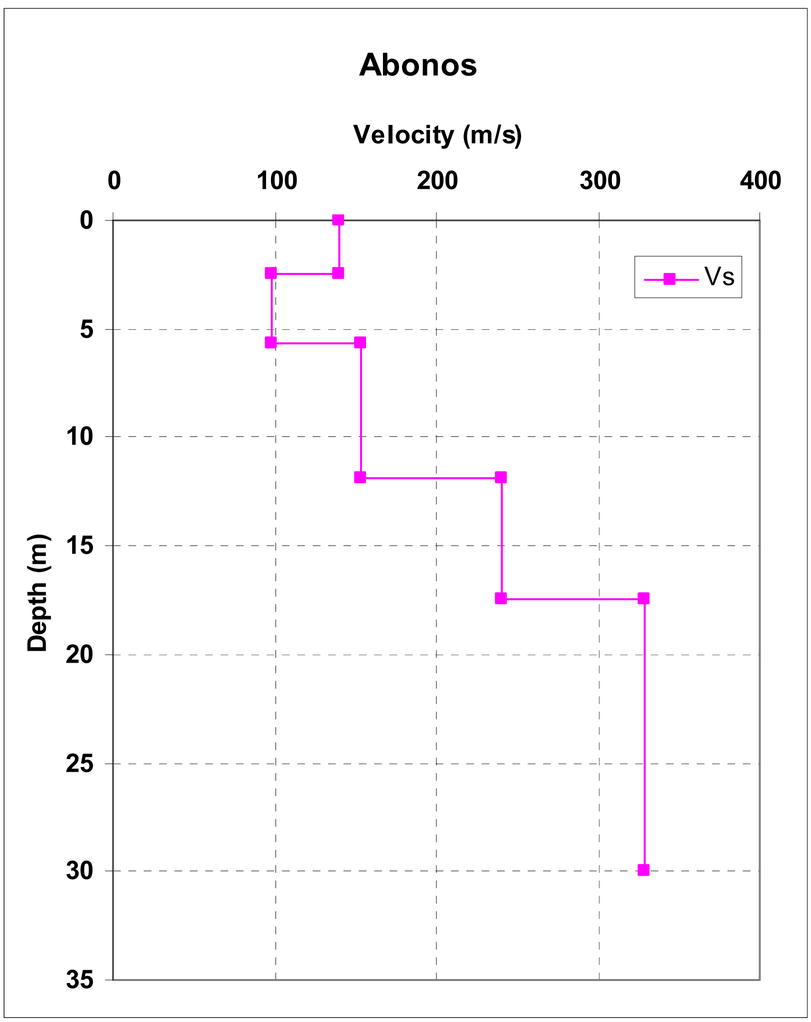
Table 3.1 Geographic Coordinates for SASW Test Sites

Site	Geographic Coordinates
Abonos	18º 16.02N / 67º 09.73W
Highway PR-341	18º 15.83N / 67º 10.58W
Maní	18º 13.79N / 67º 10.33W
Maní Park	18º 14.81N / 67º 10.46W
Seco Park	18º 12.76N / 67º 09.57W
Isidoro García	18º 11' 24N / 67º 09' 14W
Ramírez de Arellano	18º 11.34N / 67º 09.59W
Sultanita	18º 12.81N / 67º 08.65W
Civil Engineering	18º 12.81N / 67º 08.39W

Abonos Site:

The Abonos site is located within the Añasco river valley on the west side of highway PR-2 near the Abonos Super A factory. The site is relatively flat and available geotechnical information suggests the soils at this site are predominantly alluvial deposits extending beyond 100 ft depth (Macari, 1994). The shear wave velocity profile obtained for this site is shown in Figure 3.2. This figure also includes a table with the specific thicknesses and shear wave velocities for each layer found from the SASW inversion for this site. As expected, relatively low shear wave velocities were measured for this site. The generalized site profile is interpreted as consisting of a surficial compacted fill layer to a depth of about 2.5 meters. Below this fill, soft alluvial soils were found with shear wave velocities increasing with depth from 150 m/s to 328 m/s. The average shear wave velocity in the upper 30 meters depth was 196.9 m/s which corresponds to a NEHRP site classification type S_D.

Velocity Profile



Profile Values

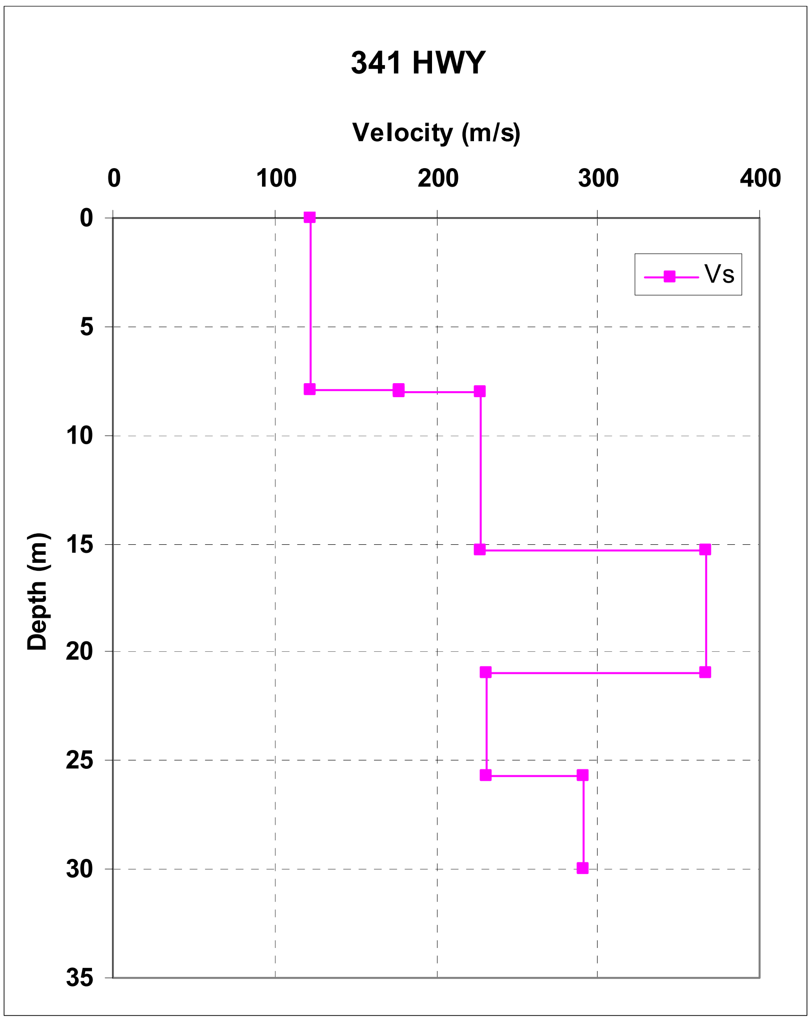
Abonos	
Velocity Profile	
H	Vs
(m)	(m/s)
2.5	140.3
3.2	97.6
6.2	153.3
5.6	240.4
12.5	328.8
Vs30 (NEHRP) =	196.9
Soil Type =	D

Figure 3.2 SASW Velocity Profile for Abonos Site

Highway PR-341 Site:

The Highway PR-341 site is located to the west of the Abonos site and is also within the Añasco river valley next to highway PR-341. The geological/geotechnical conditions of this site are similar to those at the Abonos site. Figure 3.3 presents the velocity profile obtained from the SASW test. This figure also includes a table with the interpreted thicknesses and shear wave velocities for each layer found at this site. A relatively stiff layer was found at a depth of 15 meters. The average shear wave velocity in the upper 30 meters depth was estimated to be about 203 m/s and thus its NEHRP site classification is S_D.

Velocity Profile



Profile Values

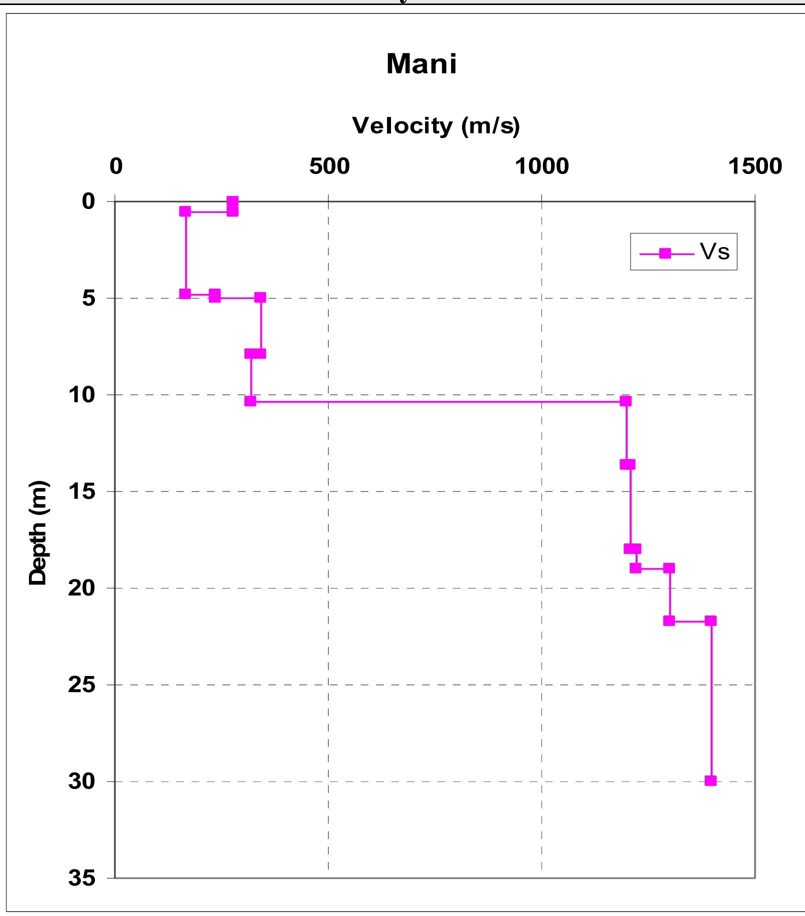
341HWY	
Velocity Profile	
h	Vs
(m)	(m/s)
7.9	122.9
0.1	177.0
7.3	227.7
5.7	366.8
4.7	231.2
4.3	290.9
Vs30 (NEHRP) =	203.3
Soil Type =	D

Figure 3.3 SASW Velocity Profile for Highway PR-341 Site

Maní Site:

After completing the Abonos and PR-341 sites, the SASW testing moved to coastal sites. The Maní site is located along highway PR-341 in the Mayagüez neighborhood known as *El Maní*. This coastal site was relatively leveled and was adjacent to the Maní beach. The interpreted SASW shear wave velocity profile including a table with the interpreted thickness and shear wave velocities for each layer for this site is provided in Figure 3.4. The shear wave velocity in the upper 10 meters was close to 300 m/s. A high shear wave velocity contrast (in the order of 1200 m/s or higher) was found at 10 m depth. Based on available information, this is believed to be related to the presence of weathered rock, but this unit elevation does not necessarily represent a typical condition along the Mayagüez coast. Marine sonar imaging along a N-S profile along the Mayagüez coast have shown variable bedrock elevation (Grindlay 2003). A bedrock outcrop can be found about 2 miles from this test site. High bedrock depth variability is inferred to occur along the Mayagüez coast line. This site classified as NEHRP S_C type with an average shear wave velocity in the upper 30 meters depth of 504.1 m/s.

Velocity Profile



Profile Values

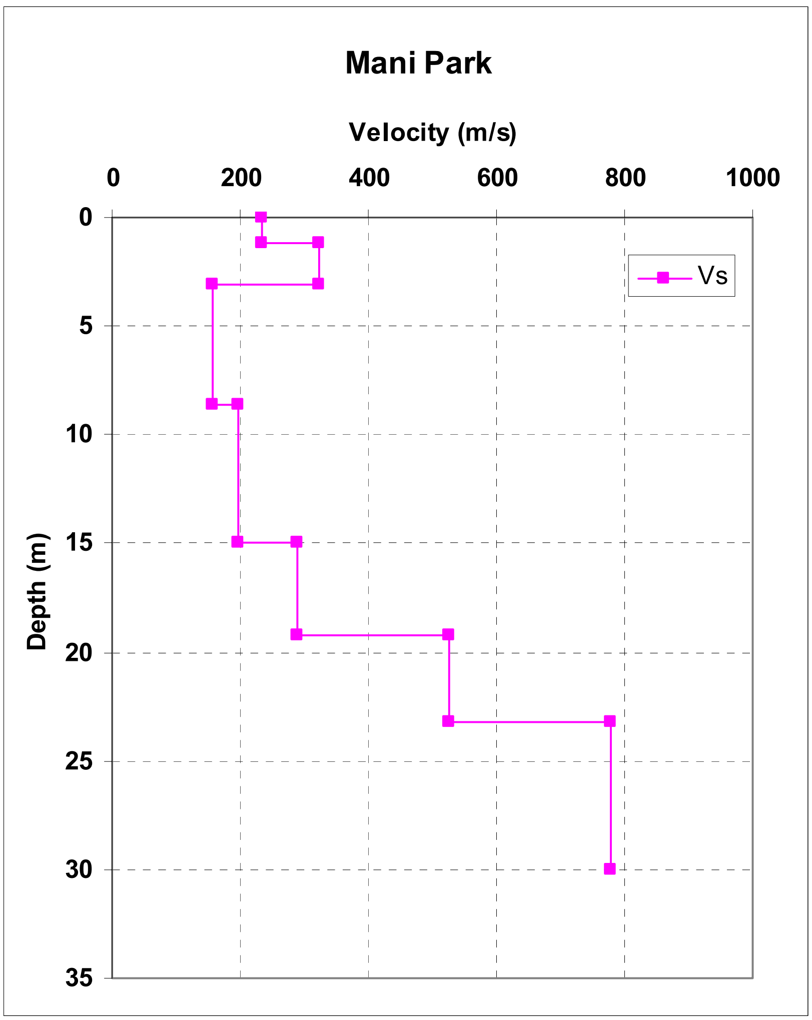
Mani	
Velocity Profile	
h	Vs
(m)	(m/s)
0.5	279.6
4.3	168.5
0.2	238.1
2.9	344.5
2.5	320.0
3.2	1200.0
4.4	1210.0
1.0	1220.0
2.7	1300.0
8.3	1400.0
Vs30 (NEHRP) =	504.1
Soil Type =	C

Figure 3.4 SASW Velocity Profile for Maní Site

Maní Park:

The second coastal site tested was located at the Maní baseball park located along highway PR-341 also in the *El Maní* neighborhood of Mayagüez. The SASW shear wave velocity profile for this site is shown in Figure 3.5. This figure shows that the upper 15 meters had a relatively low shear wave velocity of about 200 m/s. Velocities below 15 meters increased from 290 m/s to 778 m/s at 30 meters depth. This site classified as NEHRP S_D type with an average shear wave velocity of 273.8 m/s.

Velocity Profile	Profile Values



Mani Park	
Velocity Profile	
h	Vs
(m)	(m/s)
1.2	234.7
1.9	323.4
5.5	155.8
6.4	197
4.2	290.5
4	525.9
6.8	778.9
Vs30 (NEHRP) =	273.8
Soil Type =	D

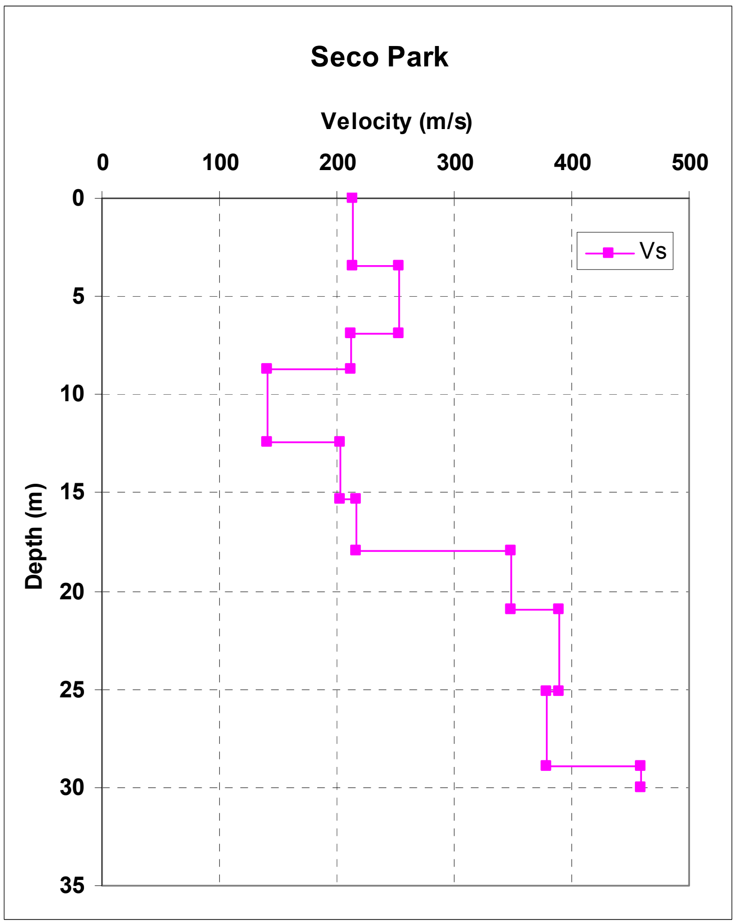
Figure 3.5 SASW Velocity Profile for Maní Park Site

Seco Park:

The third coastal site tested with the SASW technique was the Seco Park Site. This site is to south of the Maní Park site along highway PR-62 in the neighborhood known as *El Seco*.

The shear wave profile for this site is shown in Figure 3.6. It has a similar pattern as the shear wave velocity profile of the Maní Park site. The shear wave velocity of the upper 8.6 m was found to be about 230 m/s. Below 8.6 meters depth the shear wave velocity decreased to 150 m/s to a depth of 10 meters. Below 10 meters, the shear wave velocity increased gradually with depth until reaching a value of 458 m/s at 30 meters. The average shear wave velocity for the upper 30 meters of this site was 243.8 m/s which classifies as a NEHRP soil profile type S_D.

Velocity Profile | **Profile Values**



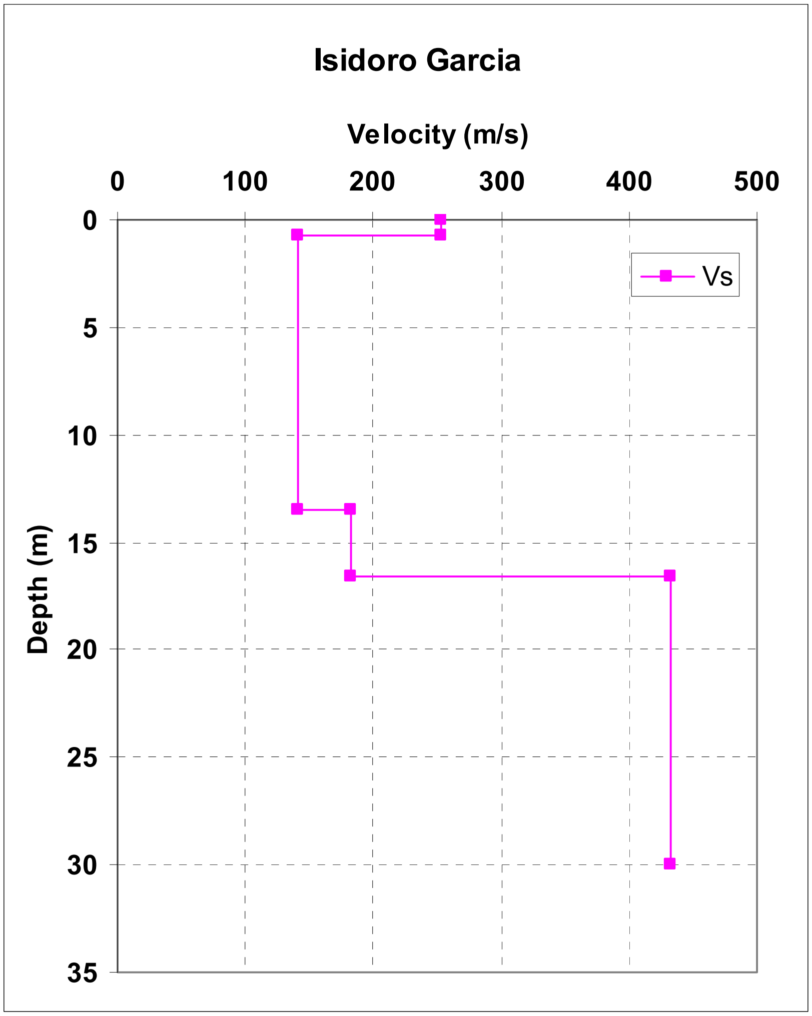
Seco Park	
Velocity Profile	
h	Vs
(m)	(m/s)
3.4	212.9
3.5	253.2
1.7	212.6
3.8	140.7
2.9	202.3
2.6	216.1
3.1	349.0
4.1	389.8
3.9	379.5
1.0	458.6
Vs30 (NEHRP) =	243.8
Soil Type =	D

Figure 3.6 SASW Velocity Profile for the Seco Park Site

Isidoro Garcia Site:

The fourth coastal SASW site was the Isidoro García site located to the south of the Mayagüez downtown adjacent to the coast of Mayagüez at the side of highway PR-102. The test site was outside the Isidoro Garcia Baseball Park and consisted of relatively flat ground. The SASW shear wave velocity profile for this site is shown in Figure 3.7. A relatively low shear wave velocity of 140 m/s was encountered at ground surface extending to a depth of about 13.5 meters. At about 16.6 m depth the shear wave velocity increased to 430 m/s and was inferred to extend to the final depth of 30 meters. The estimated average shear wave velocity for this site was 211.6 m/s which corresponded to a soil profile type S_D according to the NEHRP site classification system.

Velocity Profile	Profile Values



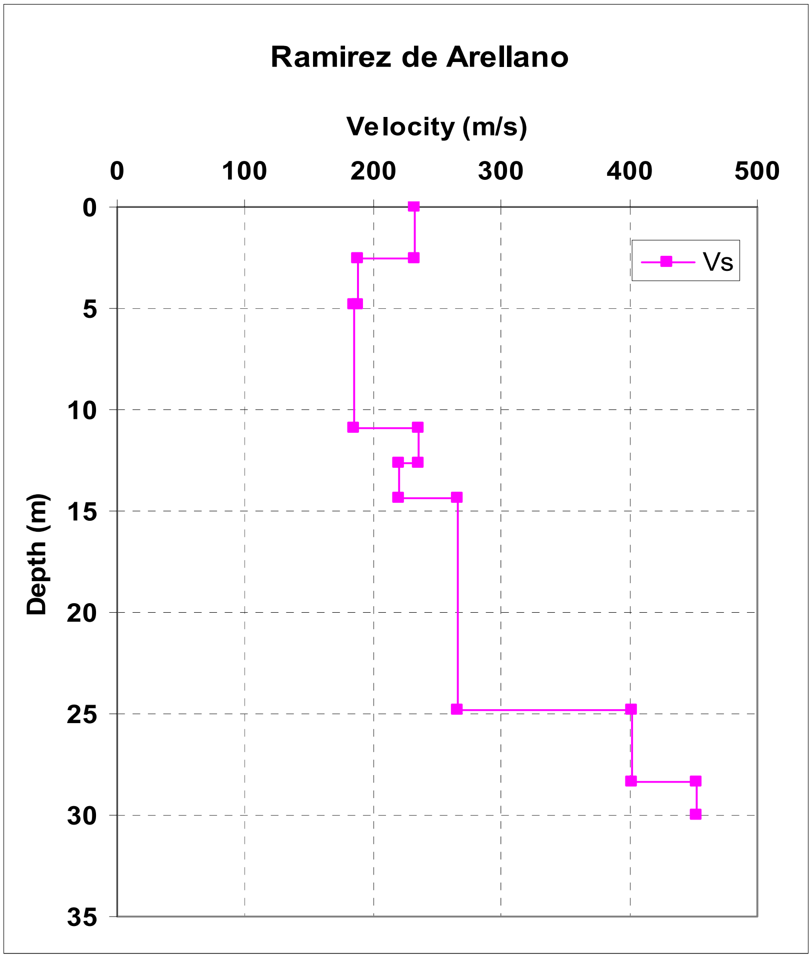
Isidoro Garcia	
Velocity Profile	
h	Vs
(m)	(m/s)
0.7	253.5
12.8	140.6
3.1	183.2
13.4	432.1
Vs30 (NEHRP) =	211.6
Soil Type =	D

Figure 3.7 SASW Velocity Profile for the Isidoro Garcia Site

Ramírez de Arellano Site:

The final coastal site tested is located in the south end of the city of Mayagüez adjacent to the Ramírez de Arellano residential complex and besides highway PR-102. The test site was relatively flat and was about 50 feet east of the beach. The SASW shear wave velocity profile obtained is shown in Figure 3.8. Relatively low shear wave velocities (near 200 m/s) were found in the upper 15 meters. This is consistent with the observations found at other coastal sites. Beyond 15 meters depth the shear wave velocities varied from 265 m/s to 452 m/s at a depth of 30 meters. The average shear wave velocity for the upper 30 meters of this site was estimated to be 244 m/s. This value corresponds to a site classified as soil type S_D according to the NEHRP site classification system.

Velocity Profile	Profile Values



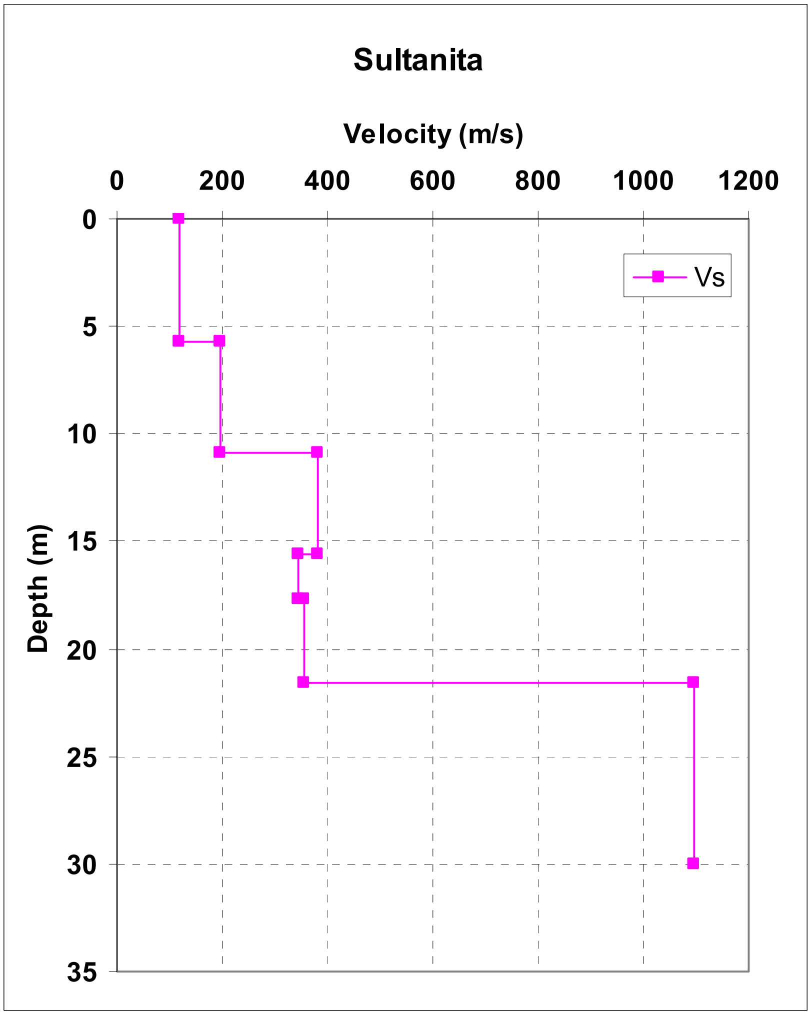
Ramirez de Arellano	
Velocity Profile	
h	Vs
(m)	(m/s)
2.5	232.7
2.3	188.7
6.1	185.3
1.8	235.3
1.7	219.5
10.5	265.5
3.5	401.9
1.7	452.4
Vs30 (NEHRP) =	244.1
Soil Type =	D

Figure 3.8 SASW Velocity Profile for the Ramirez de Arellano Site

Sultanita Site:

The Sultanita site is located in a baseball park of the Sultanita sector located on the west side of Mayagüez in the Sábalos neighborhood. This site is in higher elevation than the other sites as is located in hilly terrain believed to be composed of residual soils. Figure 3.9 presents the velocity profile obtained from the SASW test and a table with the interpreted thickness and shear wave velocities for each layer found at this site. A high shear wave velocity contrast of 1097 m/s was encountered at 21 meters depth. This high velocity layer was believed to be related to the presence of weathered rock. The average shear wave velocity for the upper 30 meters was 270.6 m/s and the resulting NEHRP site classification is S_D.

Velocity Profile	Profile Values



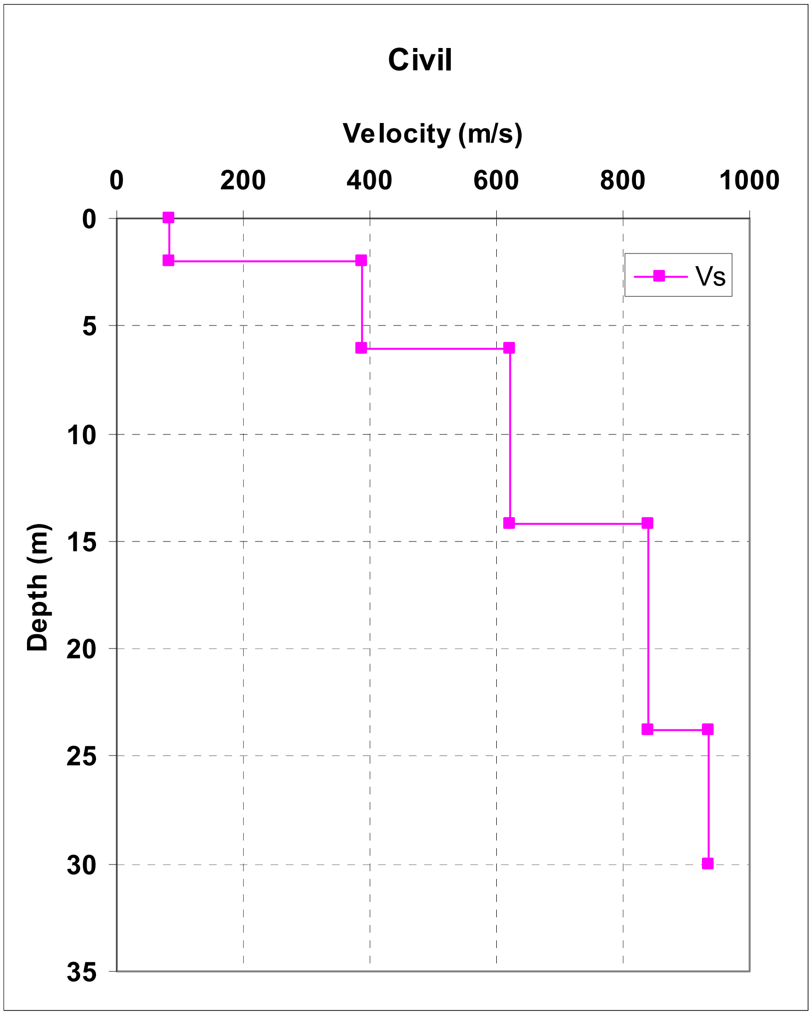
Sultanita	
Velocity Profile	
h	Vs
(m)	(m/s)
5.7	120.0
5.2	197.7
4.7	381.7
2.1	343.3
3.9	355.7
8.4	1097.4
Vs30 (NEHRP) =	270.6
Soil Type =	D

Figure 3.9 SASW Velocity Profile for the Sultanita Site

Civil Engineering Site:

The last site tested with the SASW technique was located next to the building of the Civil Engineering Department of the University of Puerto Rico, Mayagüez Campus. The shear wave velocity profile obtained at this site is shown in Figure 3.10. A relatively low shear wave velocity layer was found near the ground surface, but shear wave velocity increased quickly below this initial layer. At 14 m depth the shear wave velocity was inferred to reach a value of 935 m/s. The average shear wave velocity of the upper 30 meters was estimated as 457.1 m/s. Based on this information the site classified as soil profile type S_C.

Velocity Profile	Profile Values



Civil	
Velocity Profile	
h	Vs
(m)	(m/s)
2.0	83.5
4.1	388.7
8.1	620.2
9.6	839.4
6.2	935.5
Vs30 (NEHRP) =	457.1
Soil Type =	C

Figure 3.10 SASW Velocity Profile for the Civil Engineering Site at UPRM

3.2.2 *Seismic refraction*

Seismic refraction tests were performed at six locations in the Mayagüez area. Sites were chosen at locations where limited or no geotechnical data was available. Figure 3.11 presents a location map showing the seismic refraction test sites. This figure also shows the geological units of Mayagüez. It can be seen that test locations are mostly within the Quaternary Alluvium (Qal) unit. However, the UPRM (Civil Engineering) site and the Matadero site are within the Yauco Formation (Ky) and Sábana Grande Formation (Ksg), respectively. The Quaternary Alluvium (Qal) consists of sand, silt and gravels (Curet, 1986). The Yauco Formation (Ky) consists of calcareous volcanoclastic sandstone, siltstone, claystone, limestone, breccia, and conglomerate (Curet, 1986). The Sábana Grande Formation (Ksg) consists of massive breccia, conglomerate sandstone, siltstone, claystone and limestone (Curet, 1986). The geographic coordinates for each of the seismic refraction test sites are provided in Table 3.3. The seismic refraction carried out for this study is also part of UPRM ME thesis Lugo (In preparation).

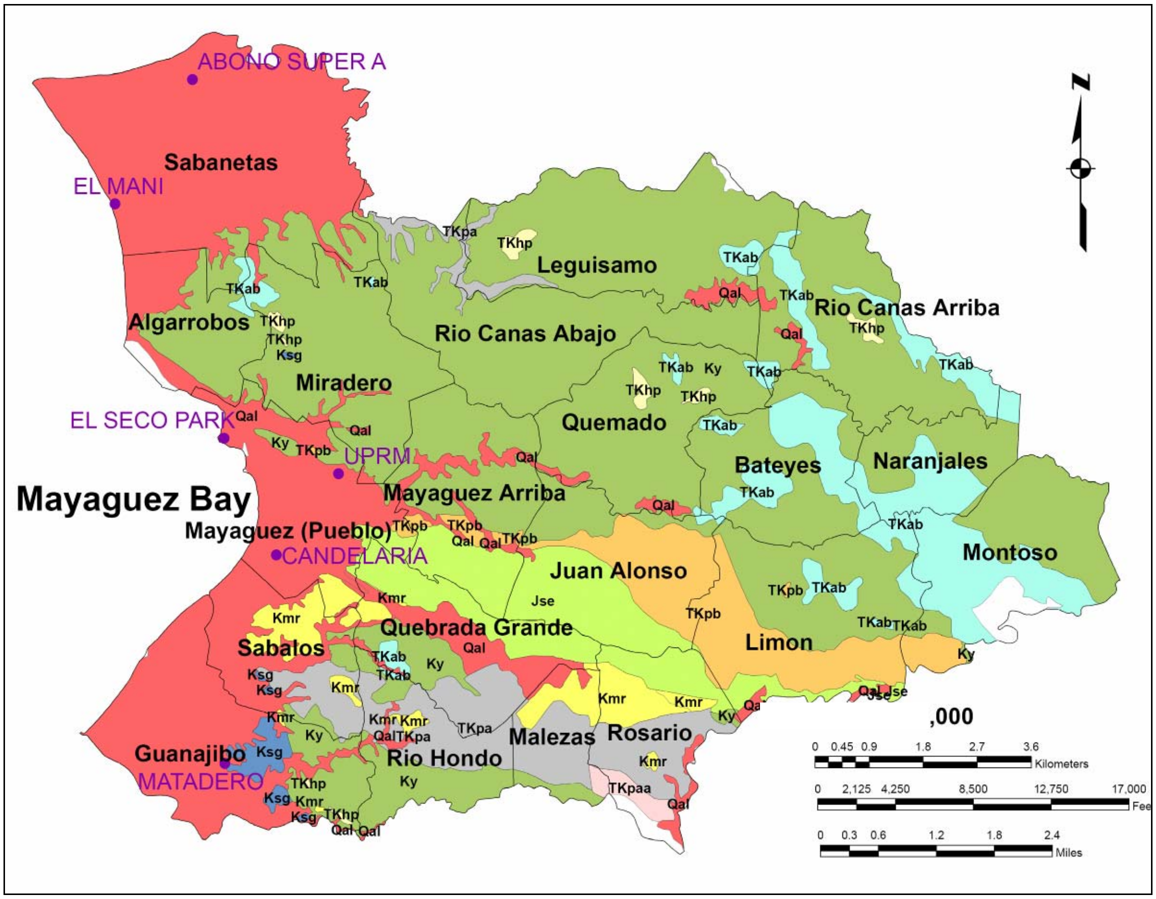


Figure 3.11 Location of Seismic Refraction Test Sites

Table 3.2 Geographic Coordinates of Seismic Refraction Test Sites

Sites	Geographic Coordinates
Abonos Super A	18º16'00.0"N - 67º09'45.0"W
El Maní Park	18º14'53.1"N - 67º10'29.6"W
El Seco Park	18º13'09.6"N - 67º09'34.2"W
UPRM Track field	18º12'25.6"N - 67º08'24.6"W
Candelaria	18º11'42.0"N - 67º09'02.0"W
Matadero	18º09'49.4"N - 67º09'30.7"W

Three of the seismic refraction test sites were carried out at the same location or very close to SASW test sites, these sites were: Abonos, El Maní Park, and El Seco Park. This allowed comparison of results obtained from the two geophysical techniques considered (i.e., SASW and seismic refraction). A comparison of results, including results available form other studies, is presented at the end of this chapter.

The equipment used to perform the seismic refraction tests consisted of a Geometrics ES-2401 seismograph recording system with support cables and geophones property of the Department of Geology at the University of Puerto Rico, Mayagüez Campus. Detailed information about the test procedure, setup, and analysis methodology can be found in Lugo (In preparation).

Seismic refraction results for the six test sites are presented in the following subsections:

Abono Super A Site:

The seismic refraction test site at the Abono Super A factory was the same as the SASW test site. Figure 3.12 shows an aerial view of the site obtained from Google Earth© (2006). As mentioned before, this site is in flat terrain and was mainly used as a cultivation field. The site is located in the Barrio Sabanetas which according to the geologic map is mostly founded on alluvial soils which are reported as extend to depths in excess of 100 ft (Macari, 1994).

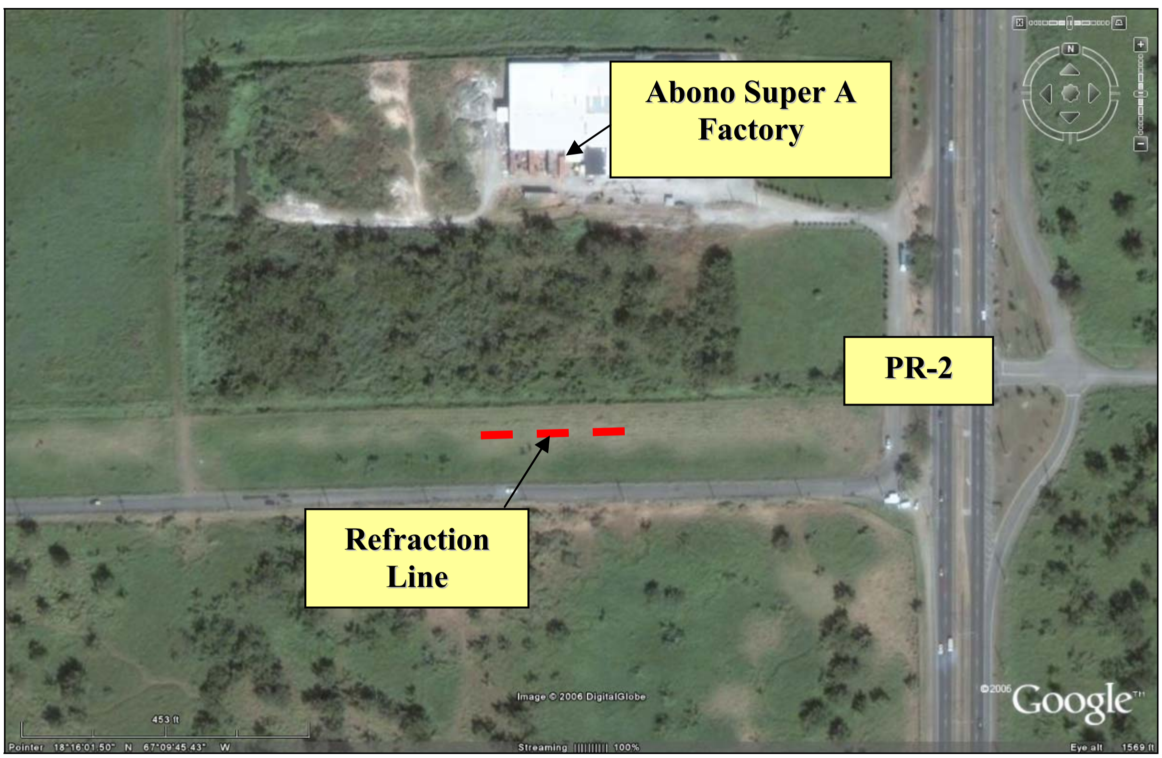
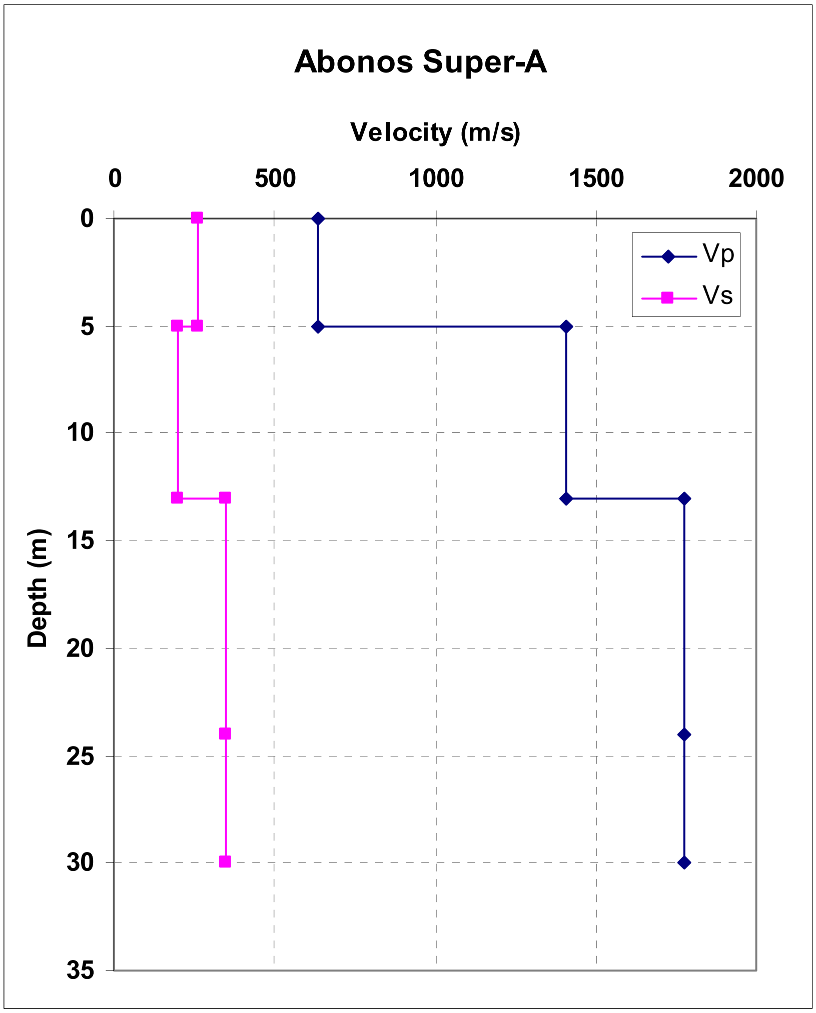


Figure 3.12 Aerial Photo of the Abono Super A Site (base photo from Google Earth 2006)

The seismic refraction results, in the form of compressional and shear wave velocity profiles are shown in Figure 3.13. This figure also includes a table that lists the thicknesses, shear wave, and compressional wave velocities of the layers inferred at this site. To help define the soil profile at this site the geotechnical report labeled MYWS047, from the enclosed database, was used in combination with geology information for the site. The average shear wave velocity for the upper 30 meter depth (Vs_{30}) was 276 m/s and the site classified as soil type S_D according to NEHRP and UBC-97.

Velocity Profile



Profile Values

	Velocity (m/s)	
h (m)	Vp	Vs
5	636	259.6
8	1410	197.4
11	1777	348.5
6	1777	348.5
Vs30 (NEHRP) =		276.4
Soil Type =		D

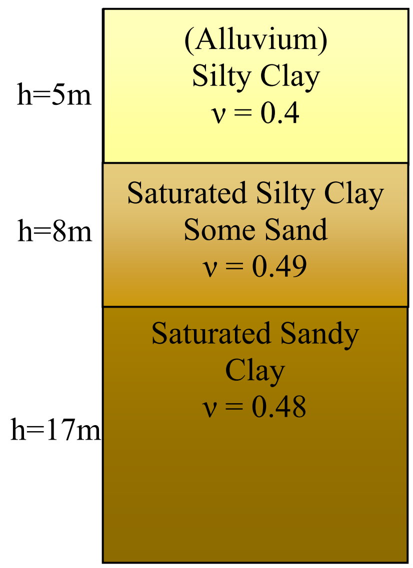


Figure 3.13 Seismic Refraction Velocity Profiles for Abono Super A Site

The El Maní Park Site:

The *El Maní Park* test site, as described before was also tested by means of SASW testing. This site is located in the Barrio Sabanetas near the Mayagüez coastline. The test was performed in the location shown in Figure 3.14 which shows an aerial view of the site based on a air photo from Google Earth© (2006). This site is lowland, flat terrain, composed of alluvial and Holocene beach deposits.

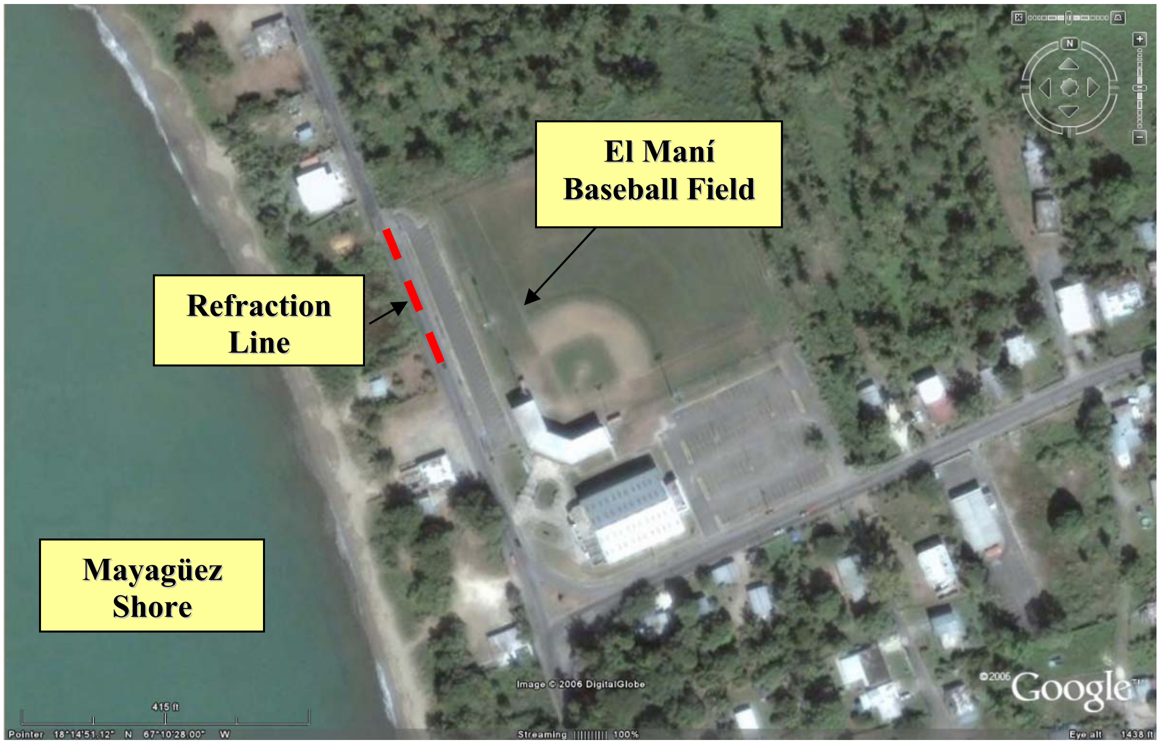
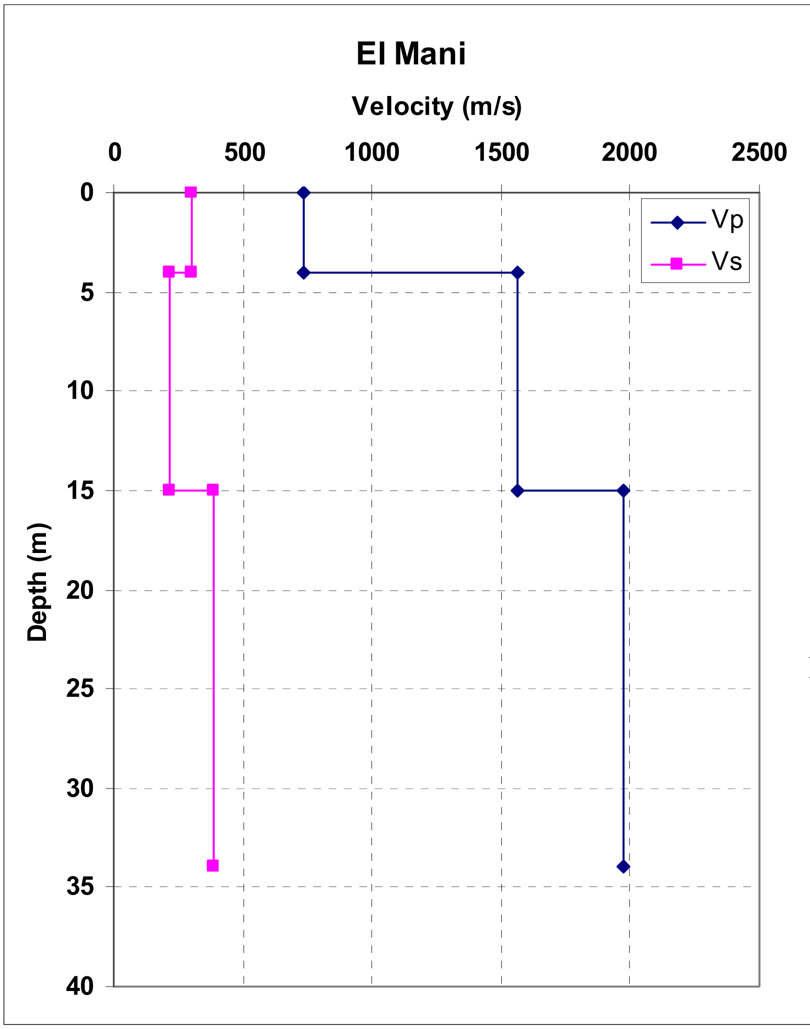


Figure 3.14 Aerial photo of the El Maní Park Site (base photo from Google Earth 2006)

Figure 3.15 shows the seismic refraction velocity profiles obtained at the *El Maní Park* site. This figure also provides thicknesses, shear wave, and compressional wave velocities for each inferred layer. The analysis was based on the geotechnical information from a nearby borehole (report MYWS054 listed in the enclosed geotechnical database), and geology information of the site geology. For this site the average shear wave velocity for the upper 30 meters, Vs_{30}, was estimated as being 293 m/s which is classified as soil type S_D according to NEHRP and UBC-97.

Velocity Profile	Profile Values



	Velocity (m/s)	
h (m)	Vp	Vs
4	737	300.9
11	1566	219.3
15	1971	386.5
Vs30 (NEHRP) =		293.4
Soil Type =		D

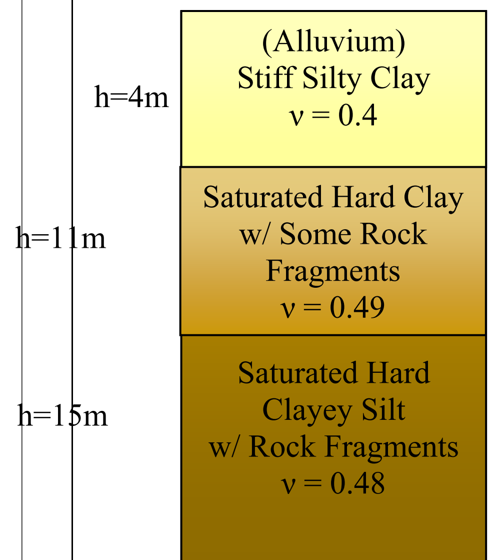


Figure 3.15 Seismic Refraction Velocity Profiles for the El Maní Park Site

El Seco Park Site:

This site was tested using both SASW and seismic refraction techniques. El Seco Park site is located in the Mayagüez neighborhood known as *El Seco*. An aerial photo of the test site is shown in Figure 3.16. This site is relatively flat and is composed of alluvial and Holocene beach deposits (Curet, 1986).

The compressional wave and shear wave velocity profiles obtained from seismic refraction testing at this site are shown in Figure 3.17. Data interpretation was aided with the use of available geological information as well as geotechnical reports MYWS049 and MYWS006, from the enclosed database. For this site the average shear wave velocity, Vs_{30}, was estimated as being 256 m/s which corresponds to a NEHRP soil type S_D.

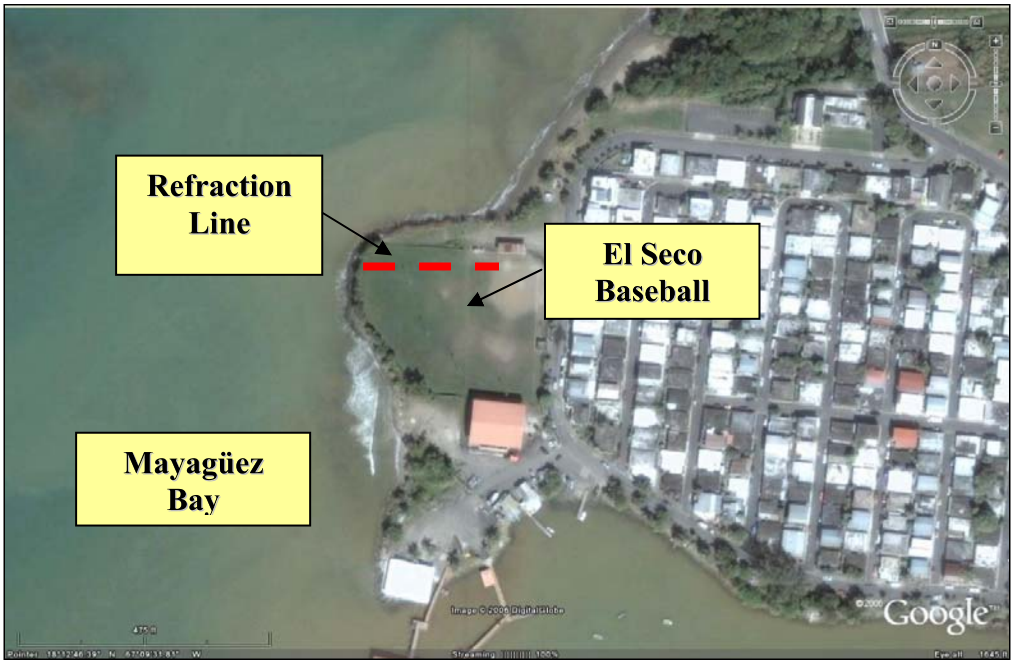
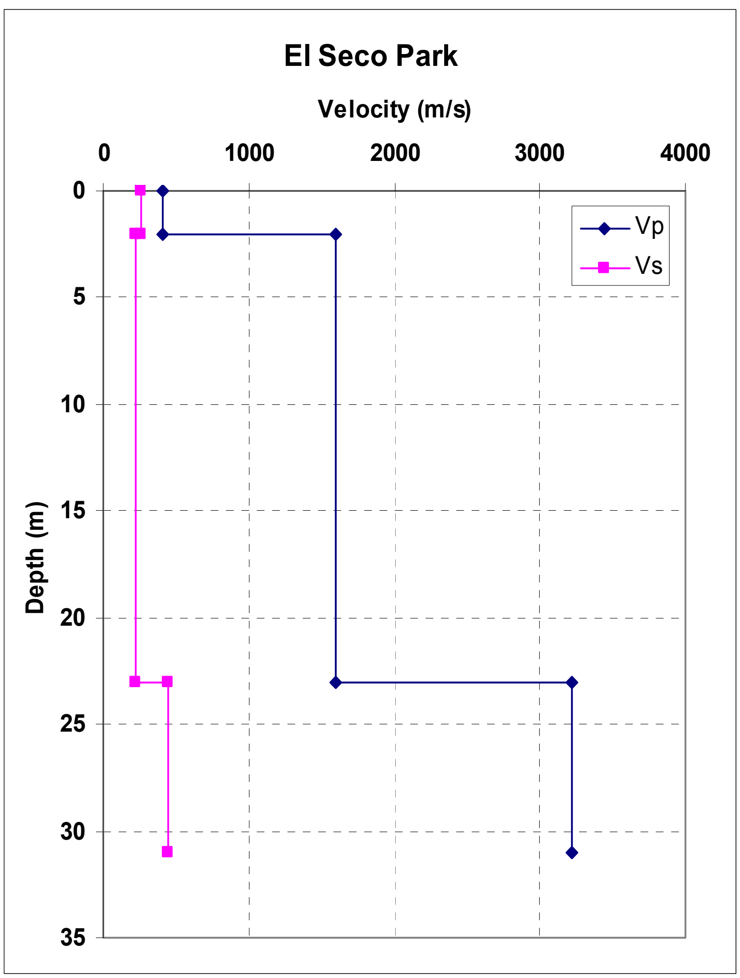


Figure 3.16 Aerial Photo of the El Seco Park Site (base photo from Google Earth 2006)

Velocity Profile	Profile Values



	Velocity (m/s)	
h (m)	Vp	Vs
2	404	259.2
21	1596	223.5
7	3214	450.1
Vs30 (NEHRP) =		255.9
Soil Type =		D

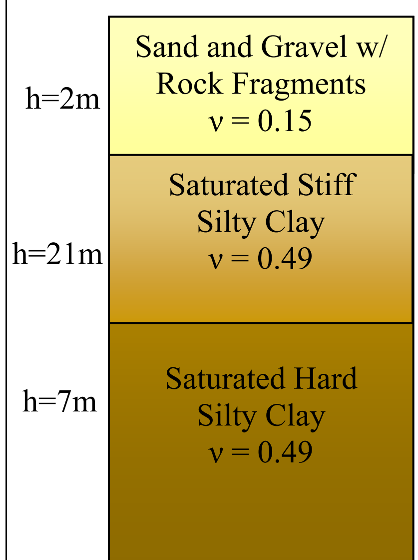


Figure 3.17 Seismic Refraction Velocity Profiles for El Seco Site

<u>*UPRM Track Site:*</u>

The UPRM Track site is located in the track field at the University of Puerto Rico. This site is within downtown Mayagüez (*Pueblo*), and is considered outside of the coastal region. This site is composed of alluvial deposits (Curet, 1986). An air photo of the site is shown in Figure 3.18.

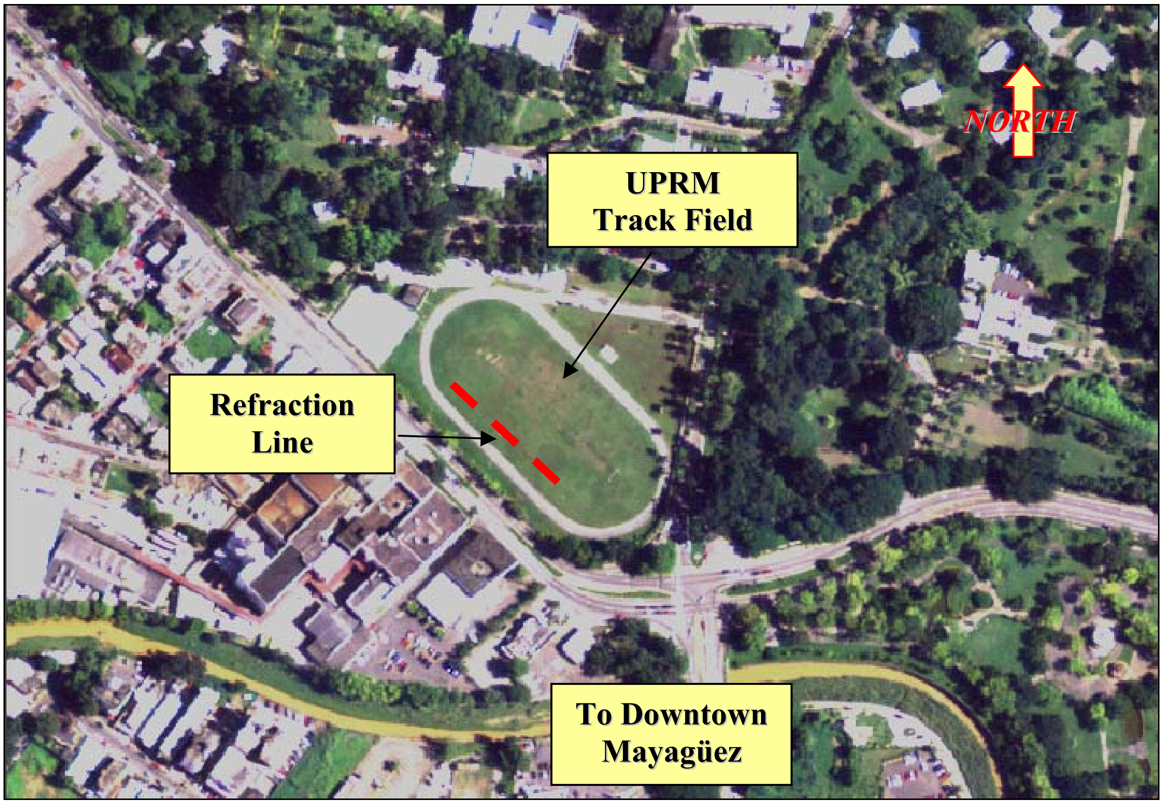
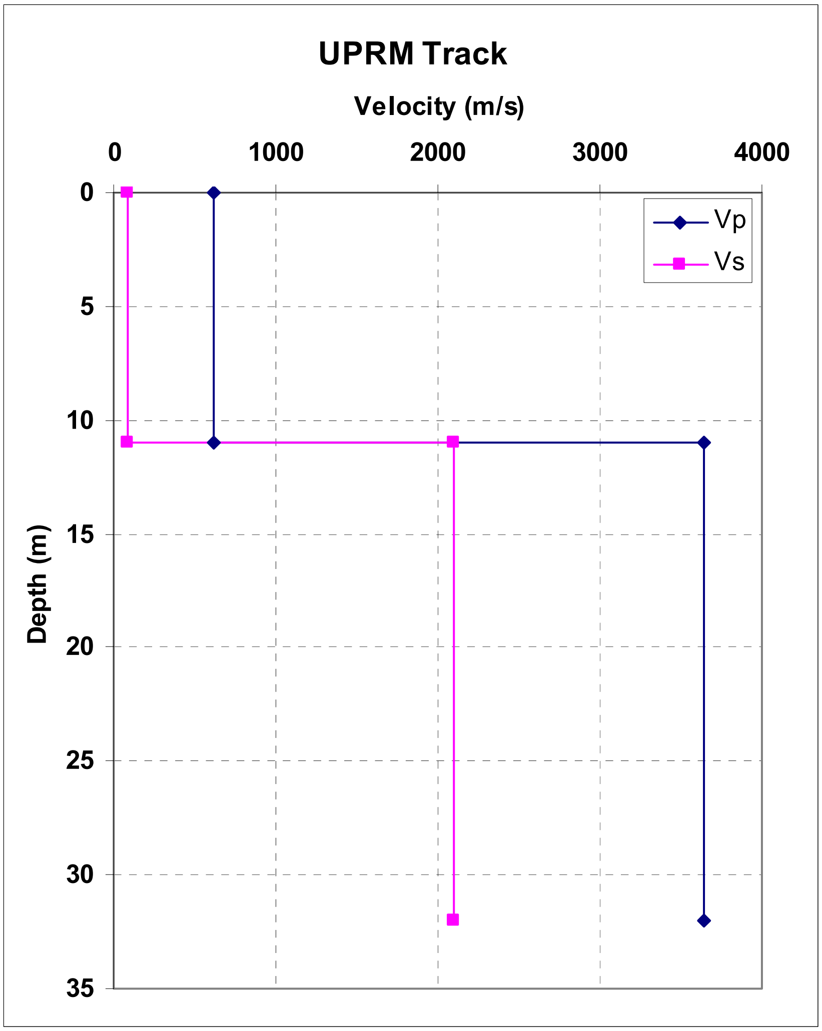


Figure 3.18 Aerial photo of the UPRM Track Test Site

Figure 3.19 summarize the compressional and shear wave velocity profiles obtained for the UPRM Track site. Data interpretation was aided with nearby geotechnical studies stored in the geotechnical database (e.g., study MYJS115) and geology information for the area. For this site the average shear wave velocity in the upper 30 meters, Vs_{30}, was 220 m/s. This Vs_{30} corresponds to an S_D NEHRP soil class.

Geophysical tests were also carried out at this site by Fernandez (2004) (seismic refraction testing), and by Muract (2004) (SASW testing). The test resuts of these two studies had similar results than the ones shown in Figure 3.19.

Velocity Profile	Profile Values



	Velocity (m/s)	
h (m)	Vp	Vs
11	618	86.5
19	3640	2101.6
Vs30 (NEHRP) =		220.3
Soil Type =		D

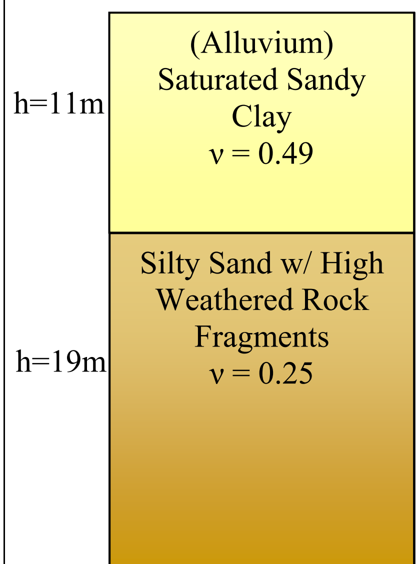


Figure 3.19 Seismic Refraction Velocity Profile for UPRM Track Site

Candelaria Site:

The Candelaria test site is also located in downtown Mayagüez in a neighborhood called Candelaria. The tests were performed in a vacant field with flat ground surface which was immediately to the west of highway PR-2. An aerial view of this site is shown in Figure 3.20. Based on the geotechnical and geological information available this site is considered to consist of alluvial deposits. This site was also tested by the USGS by Odum et al. (in preparation). Comparison of both sets of results is presented later in this chapter.

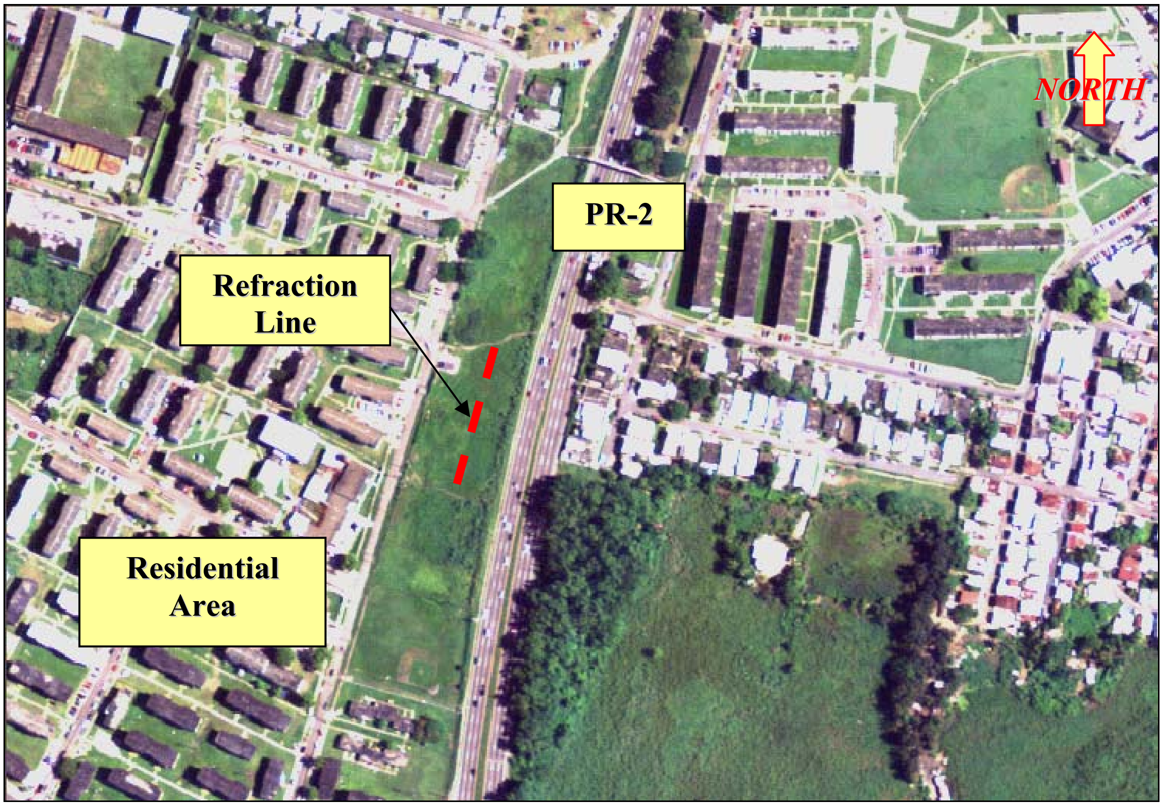
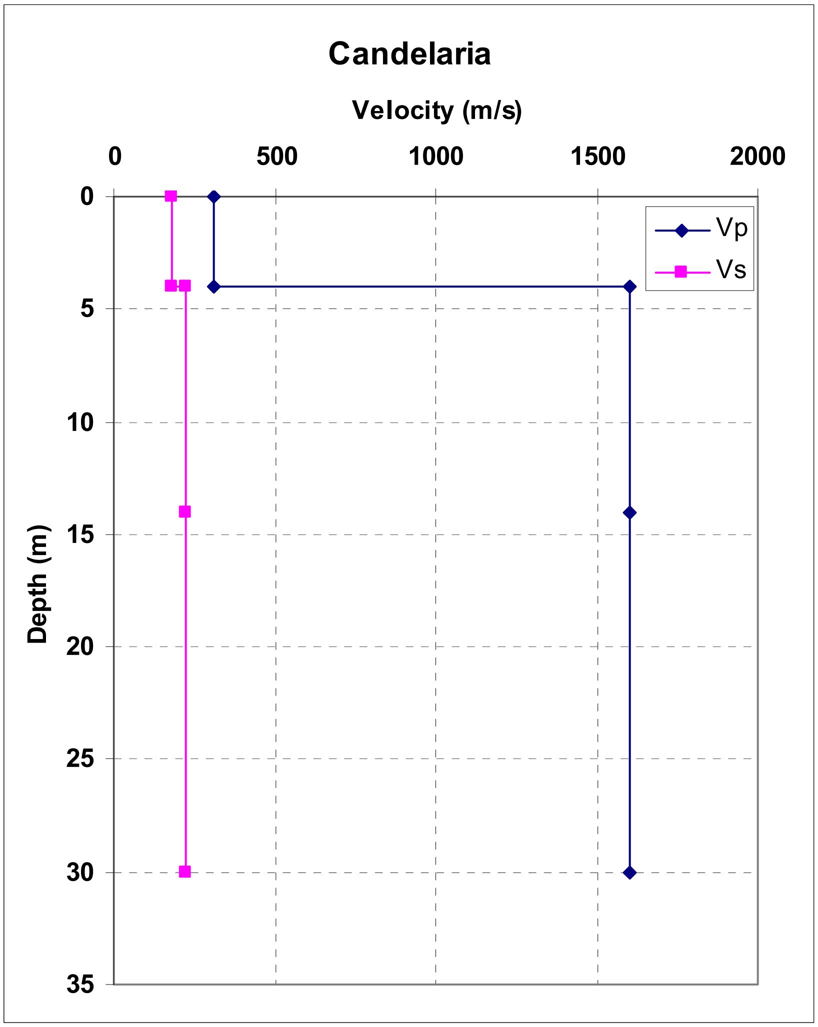


Figure 3.20 Aerial photo of the Candelaria Site (Base photo from www.USGS.gov)

Figure 3.21 shows the compressional wave and shear wave velocity profiles obtained at the Candelaria site. Traffic noise in the area limited the imaging depth resolution at the site to about 14 meters. In order to obtain an estimated average shear wave velocity for the upper 30 m, Vs_{30}, it was assumed that a similar shear wave velocity extended beyond 14 m depth up to 30 meter. Using this assumption, a Vs_{30} of 217 m/s was estimated for this site. This Vs_{30} value corresponds to a NEHRP soil type S_D.

Velocity Profile	Profile Values



	Velocity (m/s)	
h (m)	Vp	Vs
4	313	180.7
10	1601	224.2
16	1601	224.2
Vs30 (NEHRP) =		217.2
Soil Type =		D

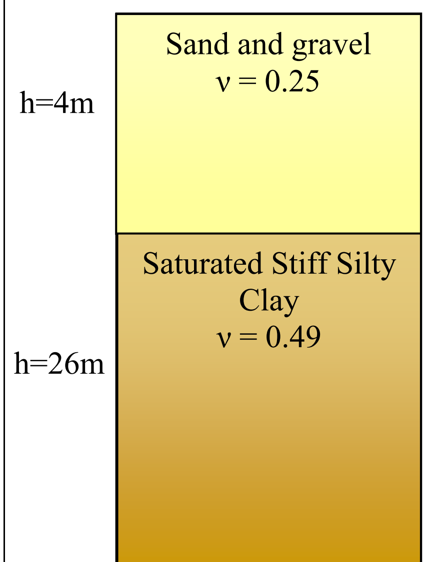


Figure 3.21 Seismic Refraction Velocity Profiles for Candelaria Site

Matadero Regional Site:

The Matadero Regional site is located in the Barrio Guanajibo located on the south part of Mayagüez. The tests were performed in a relatively flat surface ground located in the backyard of the Matadero Regional Office. Figure 3.22 shows an aerial view of the site taken from Google Earth© (2006). Based on available information, this site is considered to be on Quaternary alluvium and in an area with mangrove and swamp deposits.

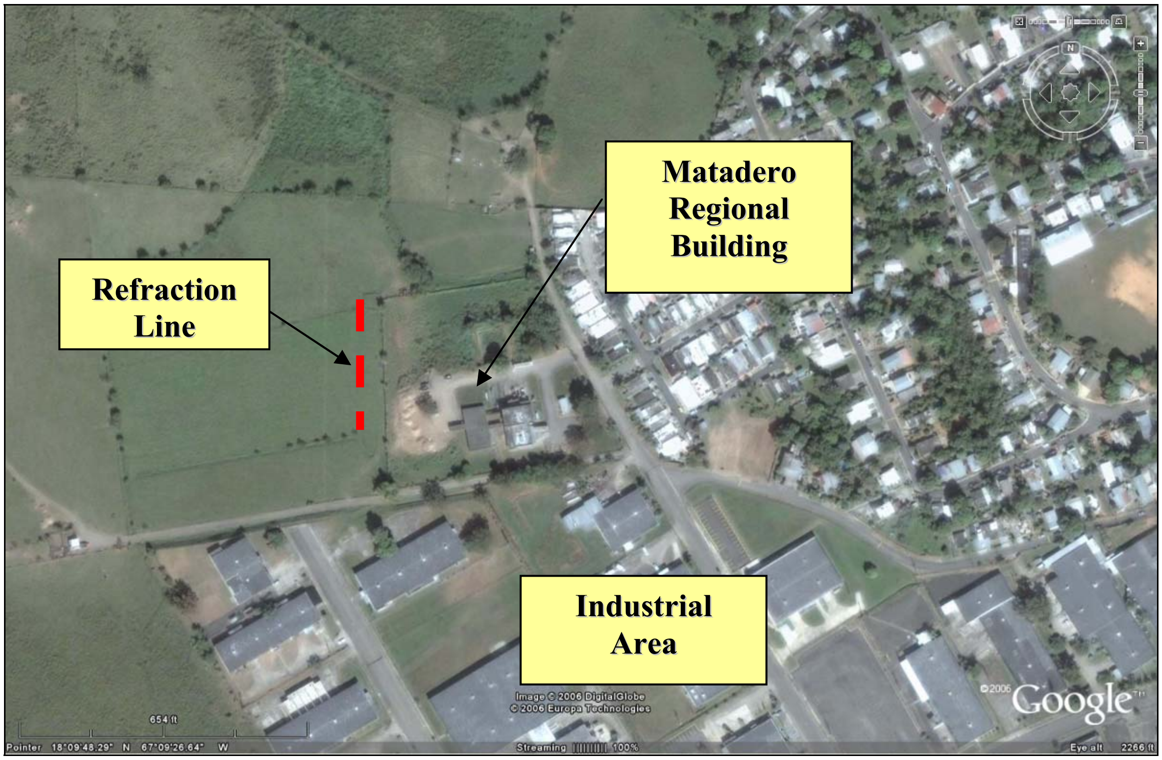
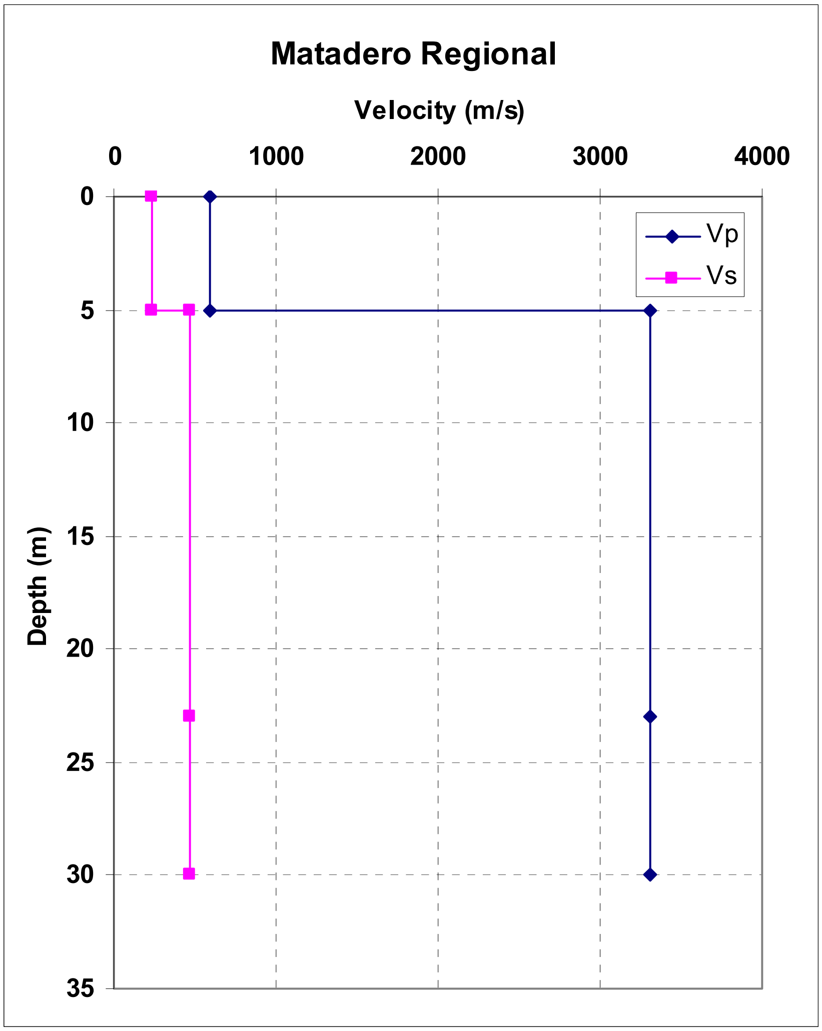


Figure 3.22 Aerial photo of the Matadero Regional Site (Base photo from Google Earth 2006)

Figure 3.23 shows the compressional wave and shear wave velocity profiles obtained for the Matadero Regional site. For this site the Vs_{30} was estimated as being about 402 m/s which corresponds to a NEHRP classification type S_C.

Velocity Profile | **Profile Values**



	Velocity (m/s)	
h (m)	Vp	Vs
5	589	240.5
18	3311	463.6
7	3311	463.6
Vs30 (NEHRP) =		401.5
Soil Type =		C

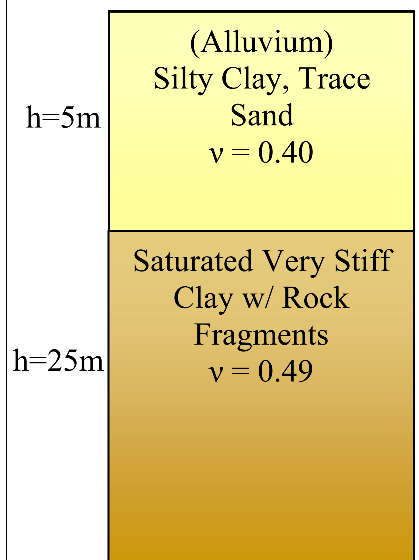


Figure 3.23 Seismic Refraction Velocity Profiles for the Matadero Regional Site

3.3 *Other Available Geophysical Tests for the City of Mayagüez*

3.3.1 *Tests by Odum et al. (In preparation)*

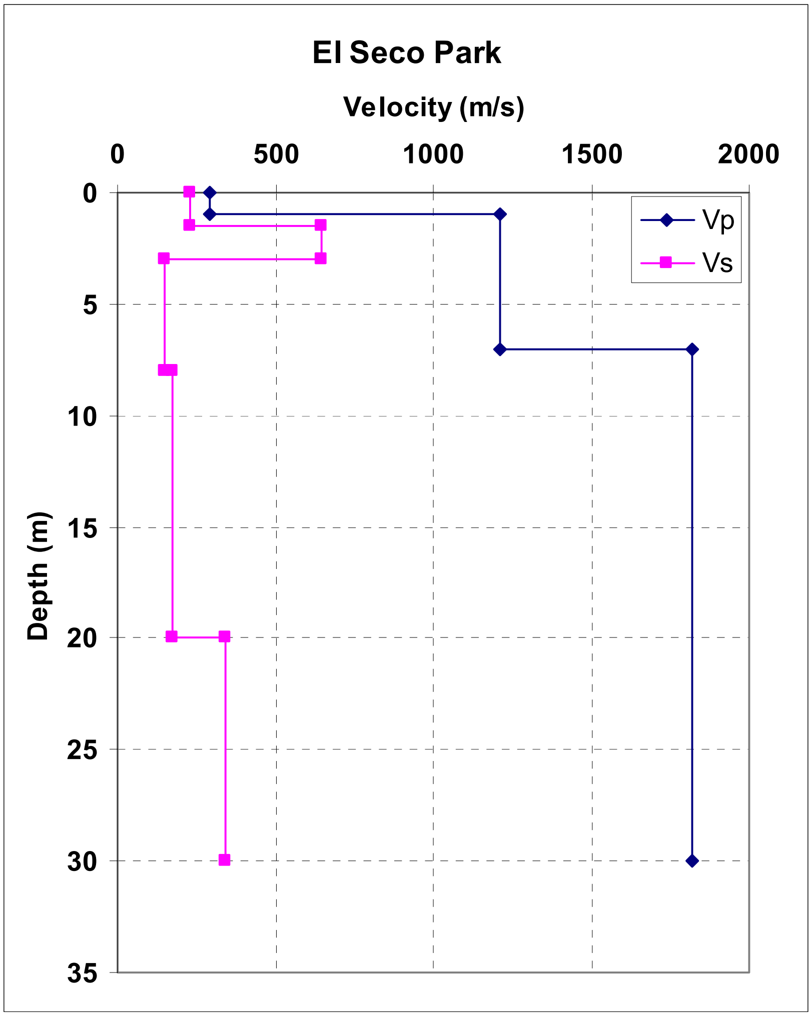
During the summer of 2003 the United States Geological Survey (USGS) carried out several geophysical tests in Puerto Rico in collaboration with the Puerto Rico Seismic Network and the Puerto Rico Strong Motion Program. These tests consisted of seismic refraction and refraction microtremor (ReMi) tests. This section presents a summary of the relevant results from this study. Detailed information can be found in Odum et al. (In preparation).

Odum et al. carried out geophysical tests at three sites in the Mayagüez area, including: El Seco Park, UPRM track field, and the Candelaria. The results for these three sites are presented below.

El Seco Park Site:

Figure 3.24 presents the compressional wave and shear wave velocity profiles obtained from seismic refraction and ReMi tests for this site. Although six shear wave velocity layers were identified, the authors interpreted only three primary geologic units within the 30 m depth. They interpreted the first two layers (0 m to 1.5 m, Vs=230 m/s and 1.5 m to 3.0 m, Vs =648 m/s) as a layer of artificial fill where the uppermost layer is composed of compacted soil and the lower unit is likely composed of large boulder-sized and smaller rock pieces (Odum et al., In preparation). Beneath the fill layer they interpreted a section of unconsolidated alluvial (in terms of geology terminology) and near-shore marine material (Qal) (3.0 m to 8.0 m, Vs=150 m/s and 8.0 m to 20.0 m, Vs=172 m/s). The authors related this slight velocity increase at 8.0 m to the presence of an older, more consolidated unit and/or a change in lithology (Odum et al., in preparation). The lower layer, between 20 and 30 m depth, with an average shear wave velocity of about 340 m/s, was interpreted as being weathered Ky bedrock (Odum et al., in preparation). The authors calculated an average shear wave velocity, Vs_{30}, for this site of 212 m/s, which corresponds to a NEHRP soil type S_D.

Velocity Profile	Profile Values



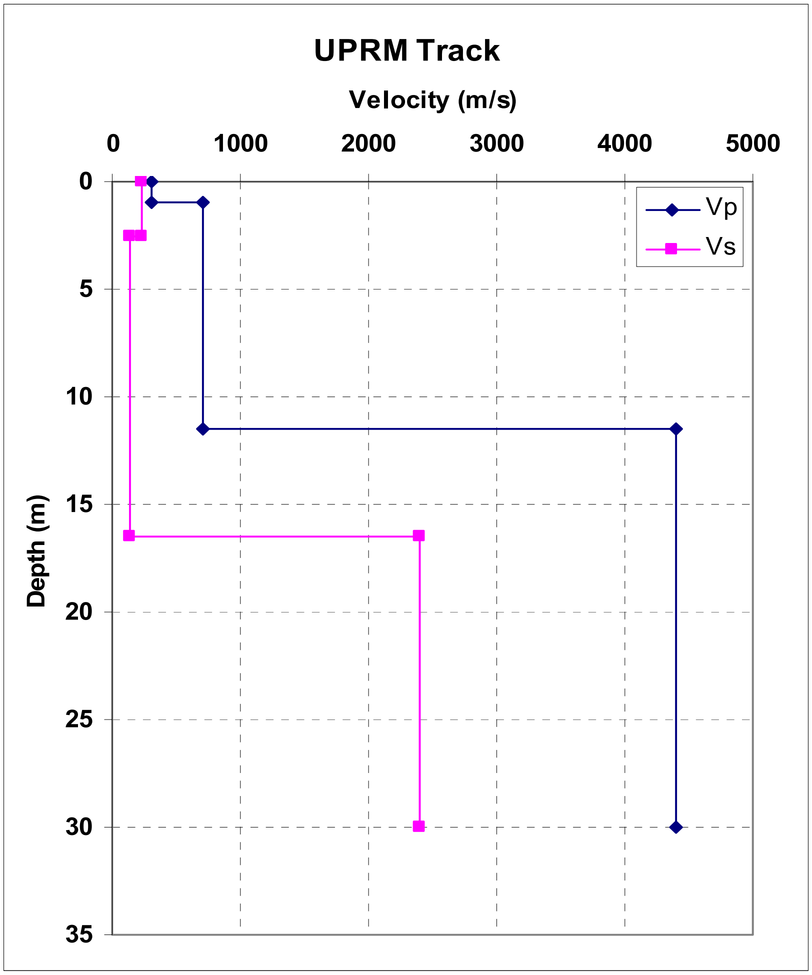
El Seco Park	
Vp	
h(m)	Velocity (m/s)
1	290
6	1210
23	1820
Vs	
h(m)	Velocity (m/s)
1.5	230
1.5	648
5	150
12	172
10	340
Vs30 (NEHRP) =	212
Soil Type =	D

Figure 3.24 Velocity Profiles for El Seco Park Site from Odum et al. (in preparation)

UPRM Track Site:

The interpreted results for this site are shown in Figure 3.25. For this site, Odum et al. identified three distinct velocity layers. The first layer extended from the ground surface to a depth of about 2.5 m and has an average shear wave velocity of Vs=230 m/s. This layer was interpreted as consisting of modified soil and artificial fill (Odum et al., in preparation). The intermediate layer, extending from 2.5 m to 16.5 m depth, had a shear wave velocity of Vs=140 m/s and was interpreted as consisting of saprolite derived from weathering of the Yauco Formation (Ky). Odum et al. interpreted a distinct physical property at approximately 16 m depth which they believe is within bedrock and is related to a dramatic increase in shear-wave velocity from 140 m/s to 2400 m/s. The calculated average Vs30 velocity for this site was 200 m/s, which corresponds to a S_D NEHRP soil type.

Velocity Profile	Profile Values



UPRM Track	
Vp	
h(m)	Velocity (m/s)
1.0	300
10.5	700
19.5	4400
Vs	
h(m)	Velocity (m/s)
2.5	230.0
14	140.0
13.5	2400.0
Vs30 (NEHRP) =	257.5
Soil Type =	D

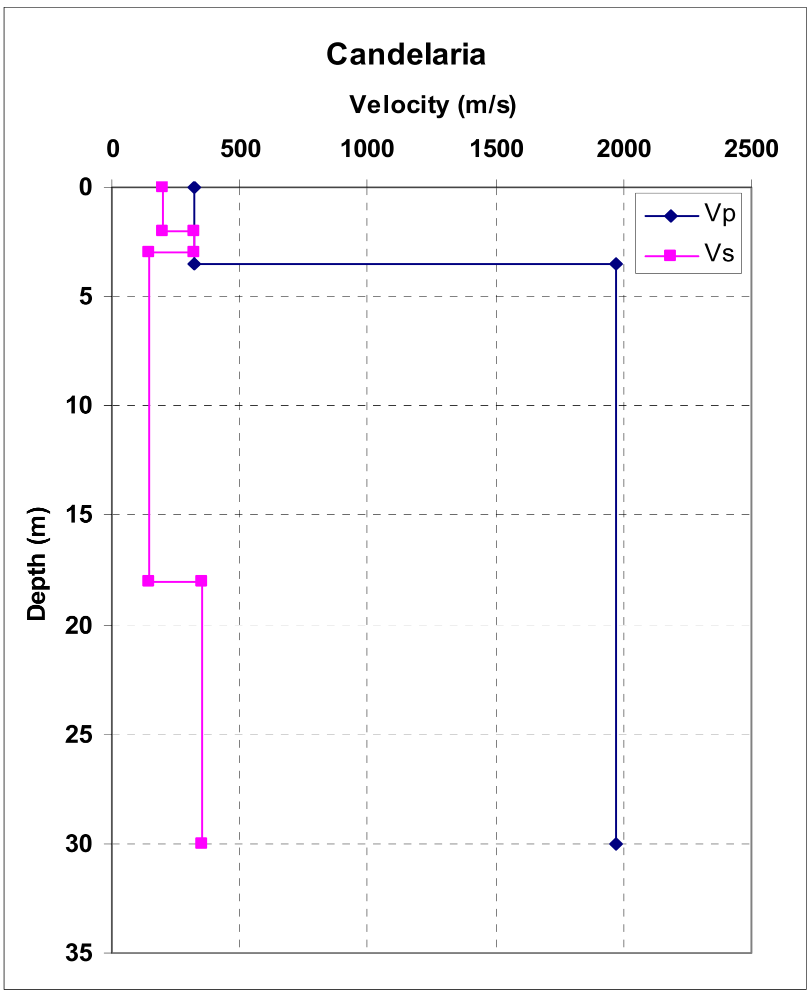
Figure 3.25 Velocity Profiles for UPRM Track Site from Odum et al. (in preparation)

The interpretation of the presence of a Saprolite layer by Odum et al., at about 16 m depth, was related to the pronounced shear wave velocity increased measured at this depth. A similar shear wave velocity increase was measured for this USGS NEHRP project (Figure 3.19). The north end of the UPRM Track site is in a cut of the original hill. In fact the entrance road behind the UPRM track is a steep road that goes up several tenths of meters to reach the hill top where the UPRM Mechanical building is located. The partial cut could explain the presence of a competent layer with high shear wave velocity values. However, as shown in Figure 3.18, it important to point out that the UPRM track is very close to the Yagüez river which flows just to the south. Available borings from the India Brewery (including CPT soundings from Macari 1994), which is adjacent to the south of UPRM track, indicate presence of thick alluvial soils that extend beyond 100 ft depth. Large lateral variation of the soil profiles at this site is expected when moving from the cut area (residual soils) towards the Yagüez river (alluvial soils).

Candelaria Site:

The third site tested in Mayagüez by Odum et al. was the Candelaria site described earlier. The interpreted velocity profiles for this site is provided in Figure 3.26. As shown, the authors identified two velocity layers in the upper three meters of this site. They interpreted the shear wave velocity from 0 m to 2 m, Vs=200 m/s, to be artificial fill. This layer overlies a 1 m thick layer, Vs=325 m/s, which they interpreted to be another fill layer. Beneath the fill layers this study indicates presence of a 15 m thick Qal layer with an average shear wave velocity of Vs=145 m/s. From 18 m to 30 m depth, the authors interpreted the presence of saprolite (weathered Ky bedrock) with an average shear wave velocity of Vs=355 m/s. The calculated average Vs_{30} velocity for this site was 200 m/s, which corresponds to a NEHRP soil type S_D.

Velocity Profile | **Profile Values**



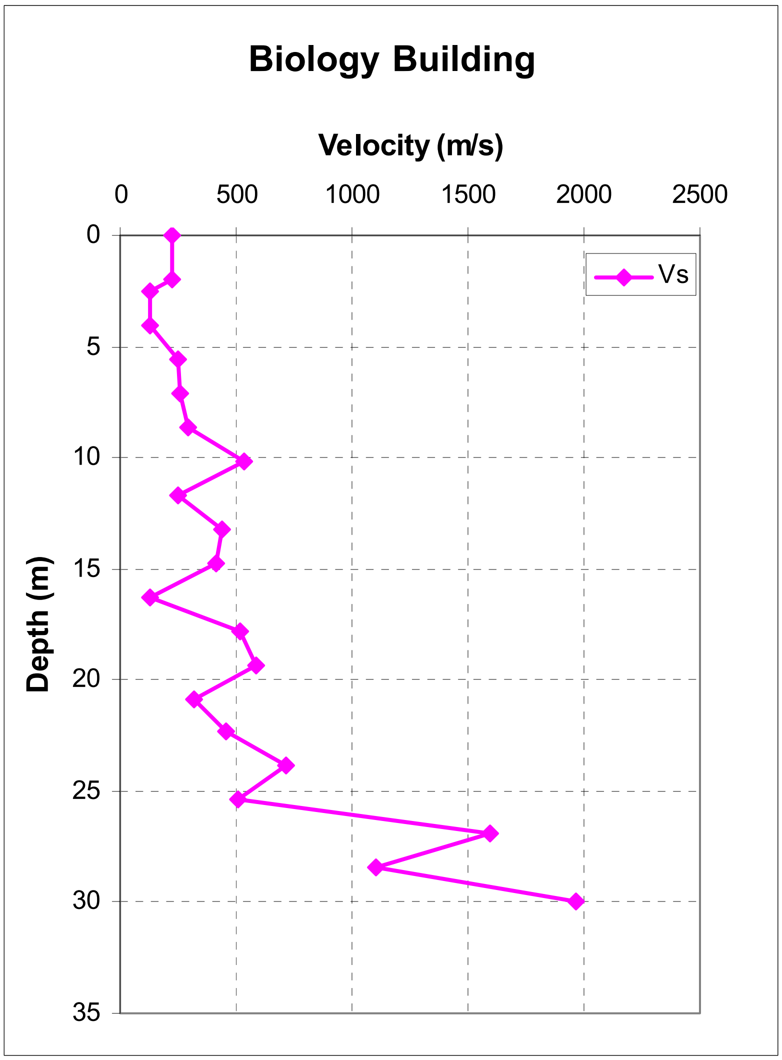
Candelaria	
Vp	
h(m)	Velocity (m/s)
3.5	300
26.5	700
Vs	
h(m)	Velocity (m/s)
2	200
1	325
15	145
12	355
Vs30 (NEHRP) =	200
Soil Type =	D

Figure 3.26 Velocity Profiles for Candelaria Site from Odum et al. (in preparation)

3.3.2 *Downhole tests by the Puerto Rico Strong Motion Program*

On 2002, the Puerto Rico Strong Motion Program carried out downhole tests for six of their seismic stations. The actual drilling was carried out by the local geotechnical company Jaca & Sierra and the downhole tests were carried out by a geophysical subcontractor from mainland USA. One of the geotechnical explorations was performed at a seismic station located near the Biology Building of the University of Puerto Rico at Mayagüez. The shear wave velocity profile from the downhole test is shown in Figure 3.27. The calculated Vs_{30} velocity for this site was 313 m/s, which corresponds to a NEHRP soil type S_D.

Velocity Profile



Profile Values

Biology Building	
Vs	
h(m)	Velocity (m/s)
0	222.5
1.9	222.5
2.5	131.1
4.1	128.0
5.6	253.0
7.1	256.0
8.6	295.7
10.2	533.4
11.7	249.9
13.2	435.9
14.7	414.5
16.3	128.0
17.8	515.1
19.3	588.3
20.8	323.1
22.4	457.2
23.9	713.2
25.4	512.1
26.9	1594.1
28.5	1106.4
30.0	1962.9
Vs30 (NEHRP) =	313
Soil Type =	D

Figure 3.27 Shear Wave Velocity results for Biology Building Site for PRSMP study

3.4 *Comparison of Results*

This section presents a brief comparison of the results of geophysical tests carried out for this study and those from Odum et al. (in preparation). Comparison was done only for common sites that were no more than a hundred meters from each other. Three of the tests sites tested in this study were close enough to those tested by Odum et al. (in preparation). Three sites were tested using both SASW and seismic refraction.

Table 3.3 presents a summary of the calculated average shear wave velocity (Vs_{30}) results from the different techniques, i.e., refraction, SASW and ReMi (by the USGS group). This table shows consistent and comparable average shear wave velocity values as well as the NEHRP site classifications. The percent of difference between seismic refraction and the other geophysical methods (SASW and ReMi) ranged from 5.1% to 33.5%. Even though, there were differences in the average shear wave velocity values obtained, there were no differences in the resulting NEHRP soil type classifications. Differences in velocity values are expected and could be attributed to many factors including lateral variations of soil characteristics (particularly in sites with residual soils). Some of the differences could also be related to differences in the alignments in the instrumentation arrays, i.e. north-south vs. east-west direction, inherent differences of the geophysical methods, and differences related to processing and interpretation.

Table 3.3 Comparisons of Geophysical Test Results

	Refraction (This study)		**SASW (This study)**		**Refraction/ReMi USGS (Odum et al., In preparation)**		**Average**		**% Difference of Refraction with**	
Site	**Vs**	**Soil Type**	**Vs**	**Soil Type**	**Vs**	**Soil Type**	**Vs**	**Soil Type**	**SASW**	**Odum**
Abonos	276.4	D	196.9	D	---	---	236.7	D	33.5	---
El Maní Park	293.4	D	273.8	D	---	---	283.6	D	6.9	---
El Seco Park	255.9	D	243.8	D	212.0	D	237.2	D	5.1	18.5
UPRM Track	220.3	D	---	---	257.5	D	238.9	D	---	15.6
Candelaria	217.2	D	---	---	200.0	D	208.6	D	---	8.3

CHAPTER 4 Geotechnical Database for Mayagüez Area

4.1 *Introduction*

This chapter presents information about the geotechnical database developed for this study. General information on how to access and navigate the database is provided. The chapter also presents a description of the information stored in the database including a list of the different GIS layers.

The geotechnical database prepared as part of this research project organized all available information using ArcView GIS 3.2© (Environmental Systems Research Institute, 1996) and ESRI® ArcMap 9.0 (Environmental Systems Research Institute, 2004). This involved digitalizing borehole data, maps, and many types of layers. Creation of the database required adding layers such as geophysical tests, wetlands, flood zones, groundwater wells, etc. All information was geo-referenced using geographic coordinates in the UTM NAD 27 Zone 19 system.

Readers interested in a detailed review of the database content can access the database provided in the enclosed DVD. Additional copies of the DVD can be obtained by contacting the PIs.

4.2 *General Instructions to Access and Navigate the Geotechnical Database*

The enclosed geotechnical database includes a user interface developed using DemoShield® 7.5 (Install Shield Software Corporation, 2002). This interface permits the user to access the database directly from the DVD where it is located, avoiding loss of information. The interface, shown in Figure 4.1, runs automatically once the DVD with the database is inserted.

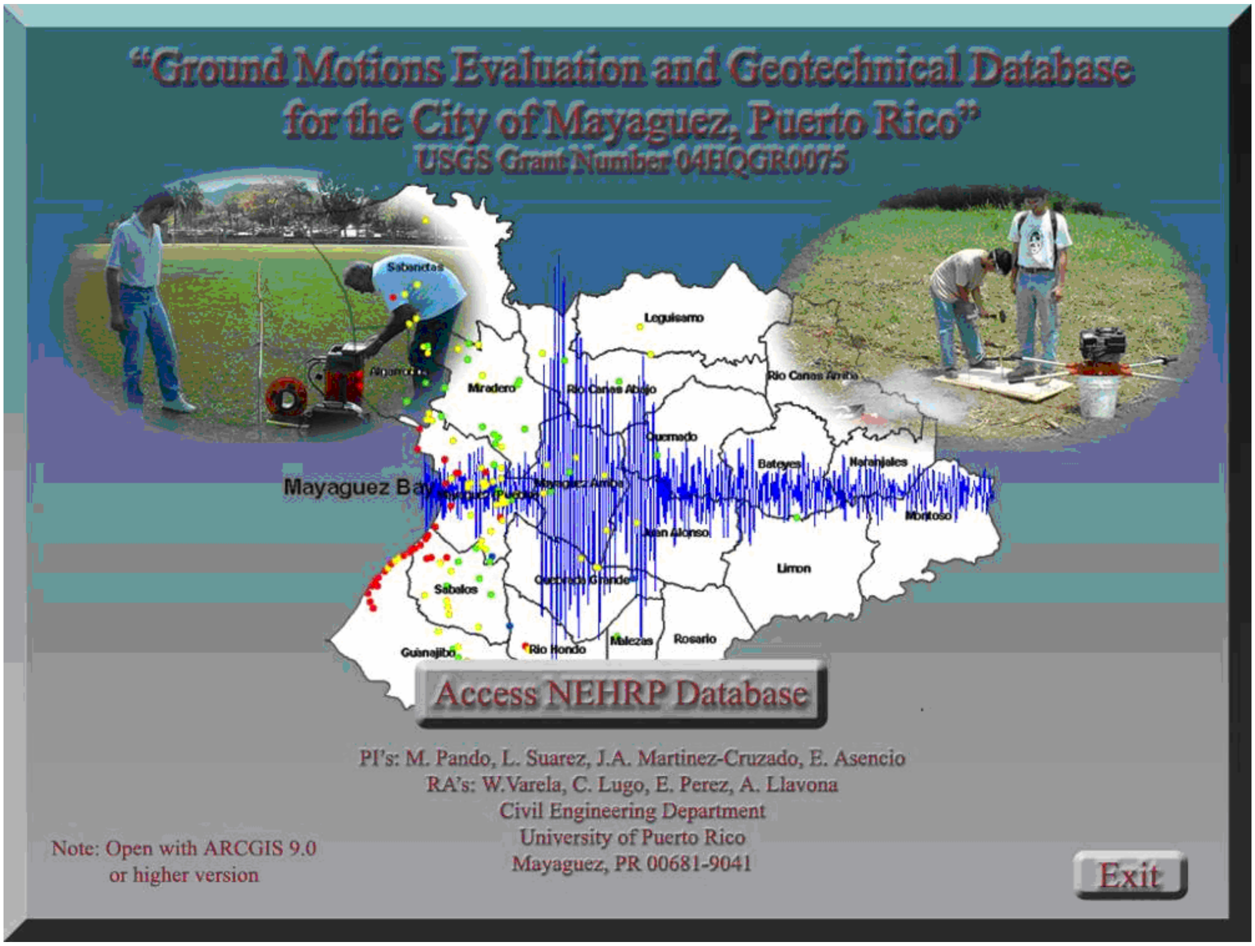


Figure 4.1 Interface Developed to Access Mayagüez Geotechnical Database

To access the database the user must click the "*Access NEHRP Database*" button that appears on the interface screen. This action will open the database automatically on the program ArcMap 9.0 (or higher version). It is important to note that the computer must have this program installed. By default the database is set to open showing a general map of Mayagüez that shows all the counties and location points for all the geotechnical studies collected. Each study is color coded to show the NEHRP classification. Points labeled as S_F include sites requiring a site specific study or represent a site identified as liquefiable. As mentioned before, this liquefaction assessment was based on using a peak ground acceleration of 0.34g (Llavona, 2004). Use of a lower PGA may result in some sites changing from NEHRP class S_F to S_E as they may become non-liquefiable due to lower cyclic stresses induced when having a lower PGA. Figure 4.2 shows the initial screen when the geotechnical database is accessed.

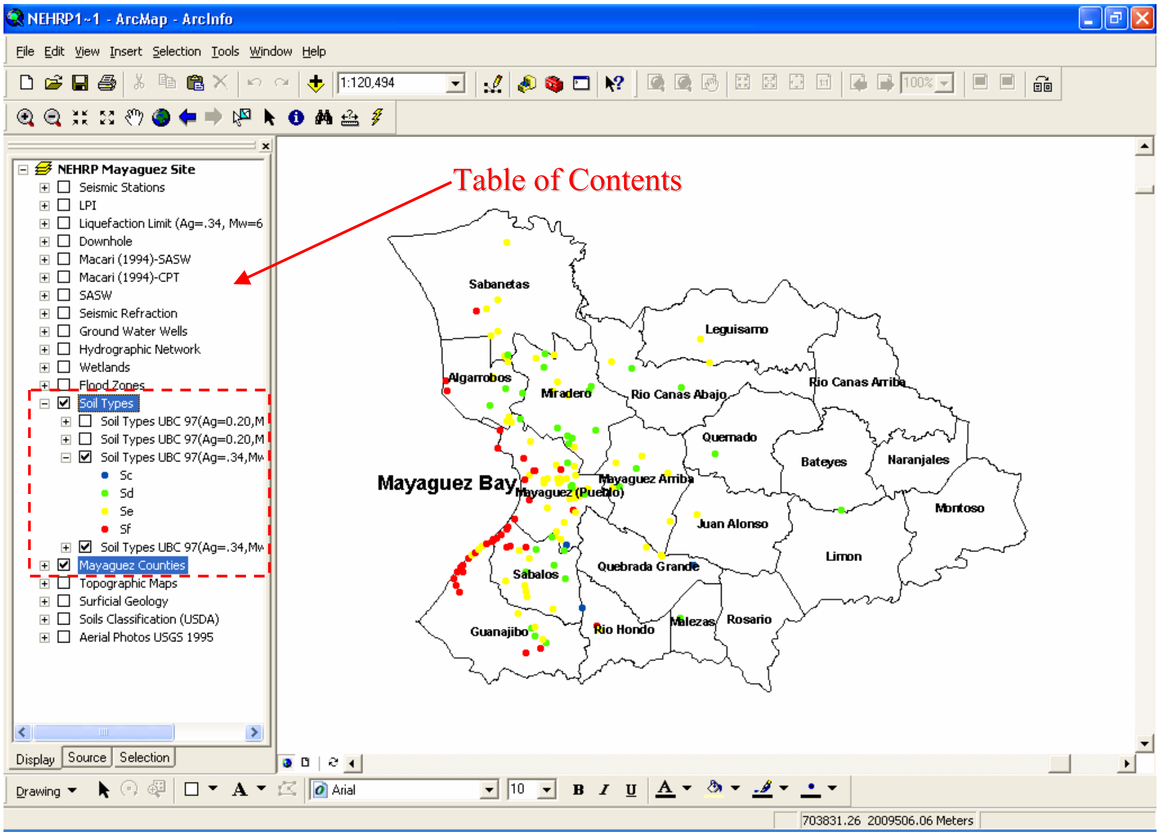


Figure 4.2 Initial View of Geotechnical Database

The first step recommended to start working with the NEHRP database is to set the tools that will help the user to perform the most common tasks. In addition to the Main menu and the Standard toolbar, it is recommended to have active other toolbar options like, Draw, Layout, and Tools. To do this, the user needs to select these applications from the toolbars list in the View menu (See Figure 4.3). A check mark next to the toolbar name indicates this option is active and visible. After selecting the toolbar options, the application displays the toolbar as a floating toolbar on the desktop or if the toolbar was previously turned on, it returns to its last specified position.

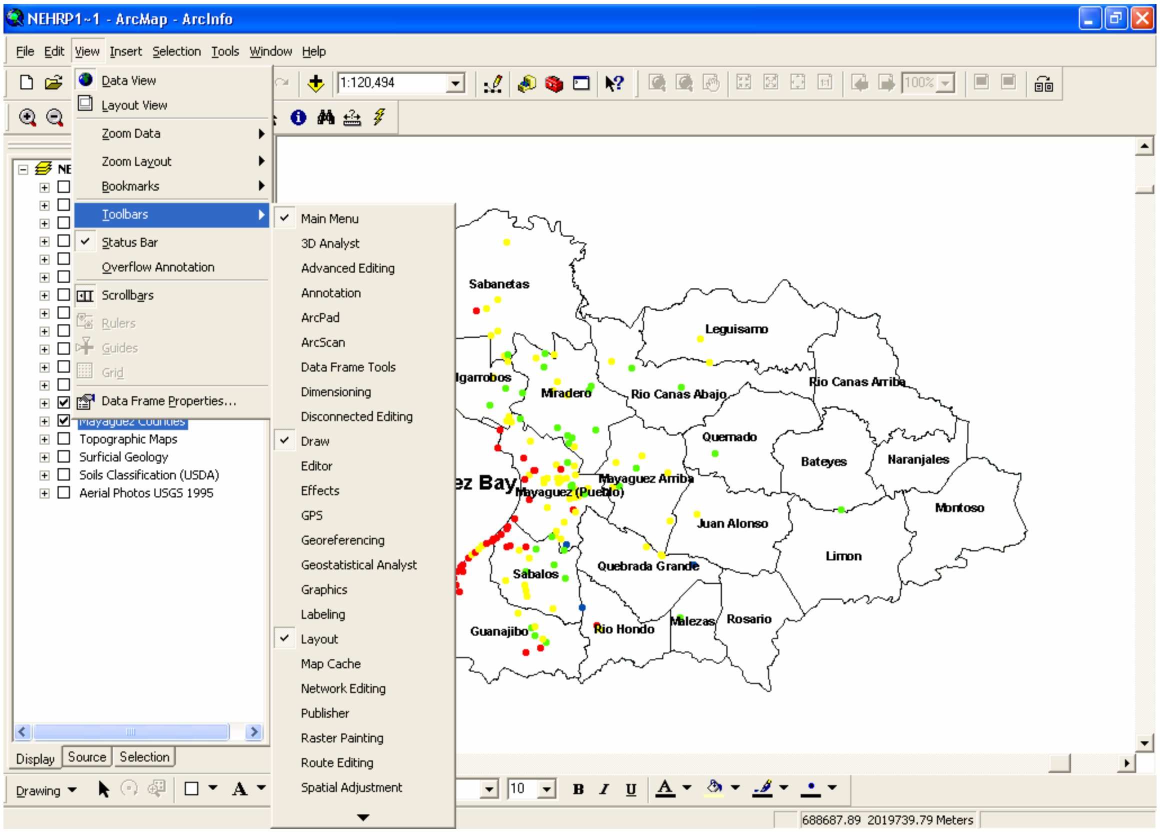


Figure 4.3 Settings Toolbars

For this database the Tools menu (see Figure 4.4) is one of the menus most frequently used by the user. The Tools menu contains the most needed features that will permit the user to access, interpret, and study the geotechnical model and database. For example, it contains the zoom in and zoom out tools, select features tool, identify tool and hyperlink tool.

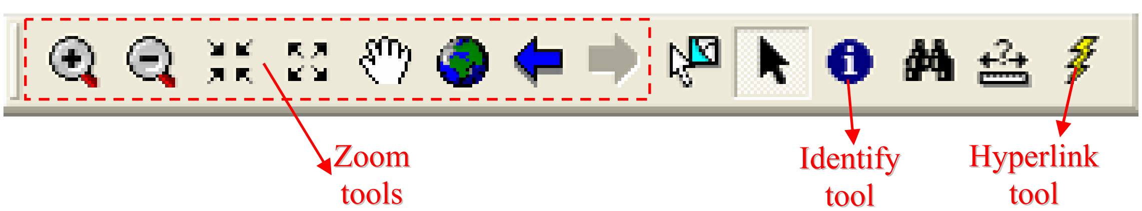


Figure 4.4 Tools Menu Features

After the user defines the tools needed to work in ArcMap 9.0, the next step is to explore or browse the data collected and stored in the geotechnical model and database. The zoom tools can be used to easily change how the user views the data in the map in order to investigate different areas and features.

Another useful feature is to use the Identify tool which can be used to access information about a feature displayed in the map. It allows the user to see the attributes or information related to the data. The Identify tool is considered an easy way to learn something about a location in a map. Usually, the information that can be accessed with the Identify tool is information stored in the input file or input table that is linked to that particular data or feature presented in the map. Examples of attributes for a point on the map are its coordinates. As soon as the user clicks the Identify tool, the Identify Results window opens, shown in Figure 4.5. The user can then click a location in the map and the Identify Results dialog box will display the available data stored for that location.

The default option is to show the information of the topmost layer in the table of contents for the location. If more than one feature was identified, the user can click any of the features in the left panel of the Identify Results window to see the attributes of that feature. If the user can use the Layers dropdown list at the top of the Identify Results dialog box to choose from several other options in addition to the topmost layer: *Visible layers*, *Selectable layers*, *All layers*, or any other specific layer in the map. The Identify tool will act on whatever is chosen in the Layers dropdown list.

The hyperlink tool, shown in Figure 4.6, is used for accessing documents stored in the database. To do this, the user must select the hyperlink tool on the Tools menu. Once the user selects the hyperlink tool option, blue dots (see Figure 4.6) will appear in the map for all the points that contain additional data in the form of a linked document. When the user selects or clicks over a specific blue dot the linked document or file associated with this point will be opened. The file will be launched using the application for which that file type is currently associated, for example a pdf file will likely open through Acrobat Reader.

Once the user is familiar with the basic tools required to navigate and work with the ArcMap 9.0 program, he or she can readily explore the Mayagüez NEHRP database and all the information contained in it. This will allow the user to access geotechnical information stored for an specific site.

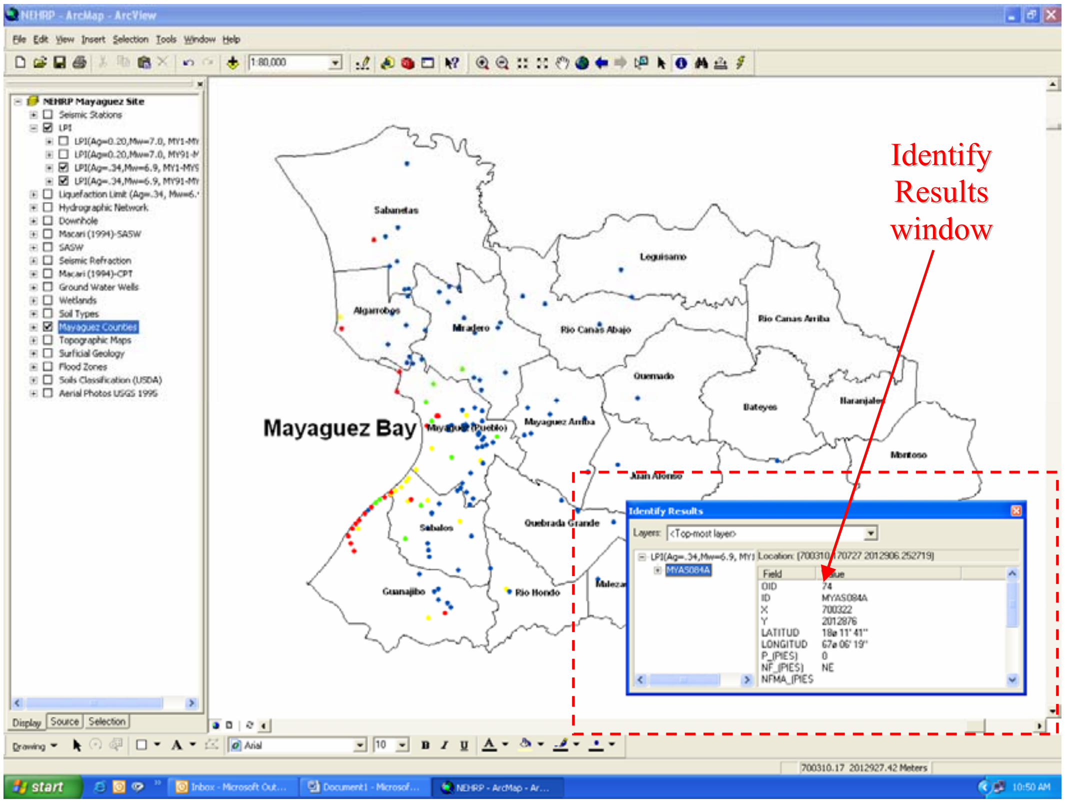


Figure 4.5 Identify Results Window

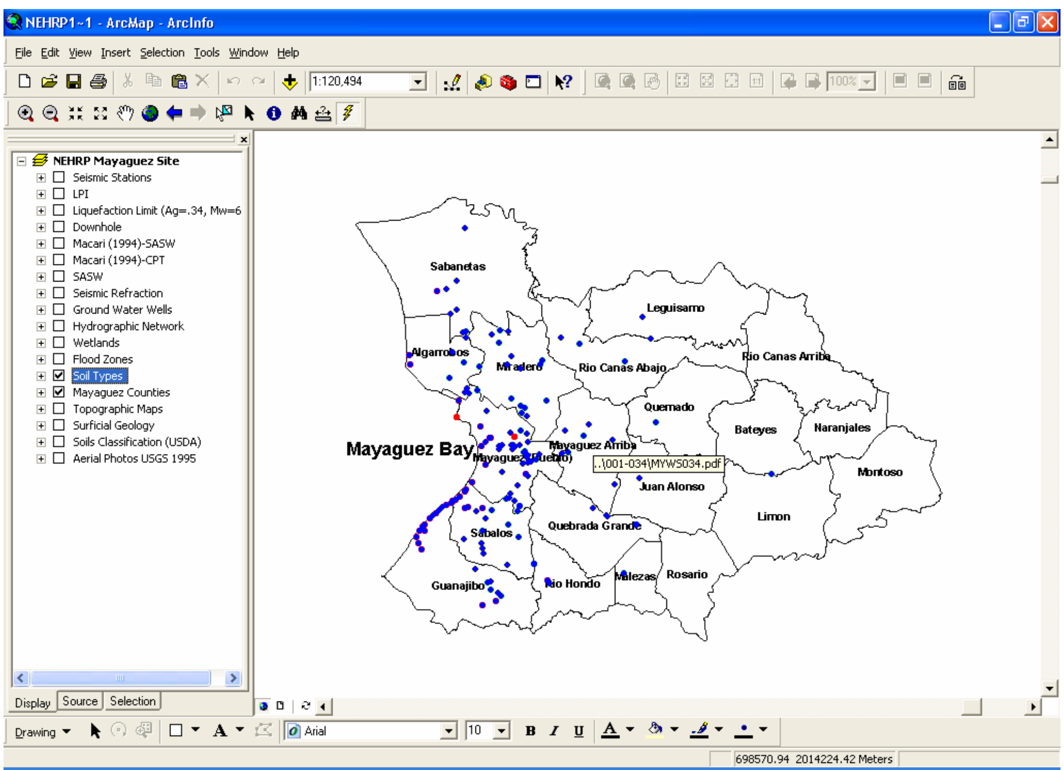


Figure 4.6 Hyperlink Tool Selected

4.3 *Description of the Geotechnical Database Content*

This section presents a general overview of the content of the database. More detailed information is available by directly accessing the enclosed DVD with the database. The geotechnical model for Mayagüez includes nineteen layers that contain specific data for the Mayagüez area. The layers included in the ArcView database model are as follows:

- Location of Seismic Stations
- LPI (Liquefaction Potential Index values)
- Extent of the Liquefiable Soils Zone: The limits of the zone identified in Mayagüez as having a high liquefaction potential is shown in Figure 4.7. As mentioned earlier, this evaluation was carried out by Llavona (2004).
- SASW from Macari (1994)
- Downhole study for the PRSMP (Biology building)
- CPT soundings from Macari(1994)
- SASW for this USGS-NEHRP study: This layer shows the location of the ten SASW tests performed as part of this study (shown in Figure 4.8).
- Seismic Refraction tests for this USGS-NEHRP study: This layer shows the location of six seismic refraction studies made for this project (shown in Figure 4.9).
- Location of available USGS ground water wells
- Hydrographic Network: This layer presents the hydrographic network for the Mayagüez area (Figure 4.10).
- Wetlands
- Flood Maps (Figure 4.11).
- NEHRP Soil Classifications
- Mayagüez Counties
- Topographic Maps
- Surficial Geology
- USDA Soils
- Aerial Photos (from USGS 1995 and USGS 2004)

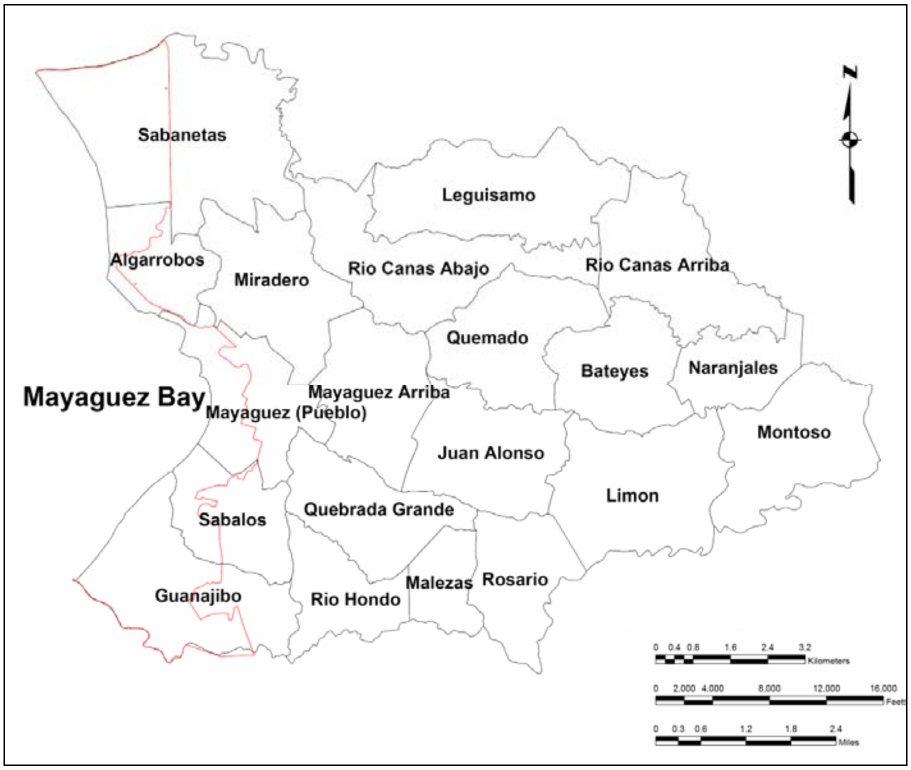


Figure 4.7 Extent of zone identified as highly susceptibility liquefaction

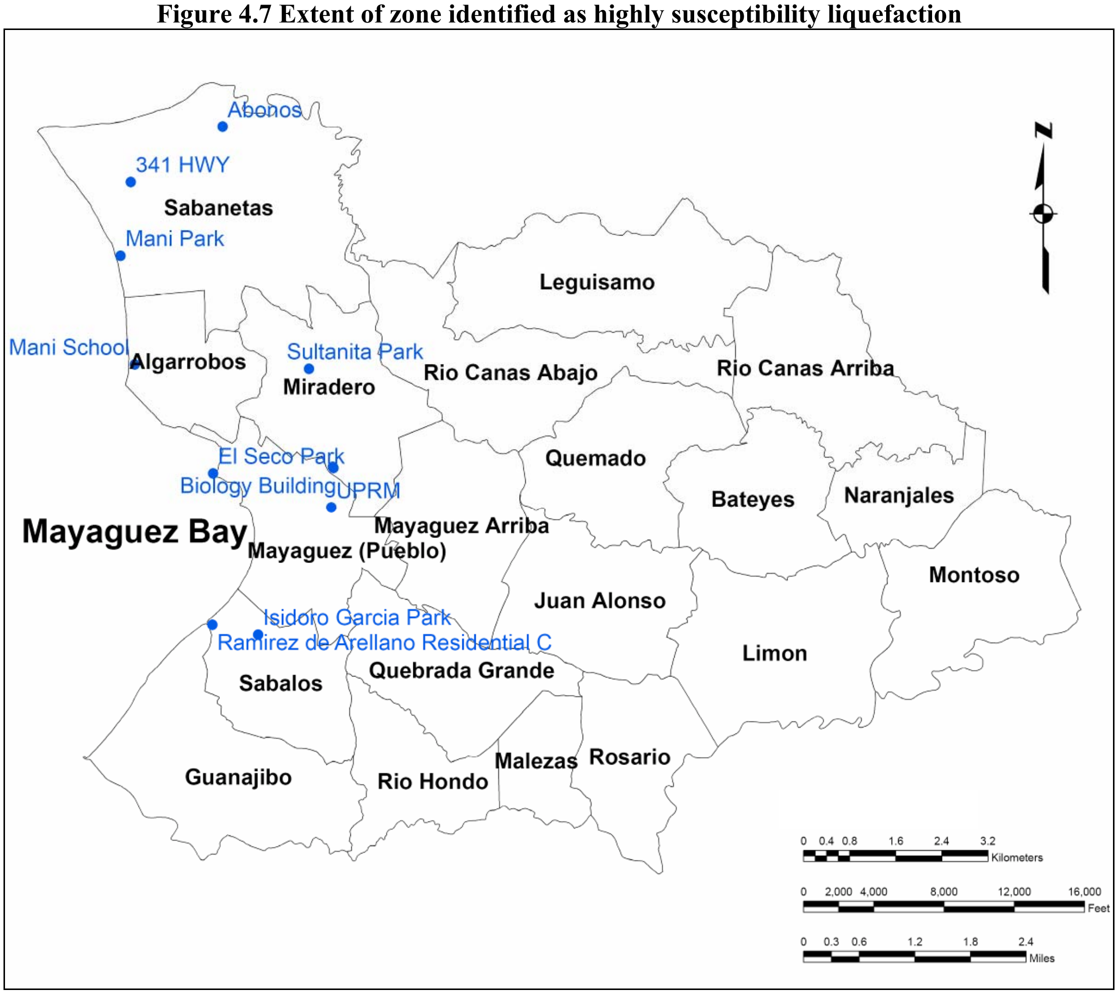


Figure 4.8 Location of SASW Test Performed for this study

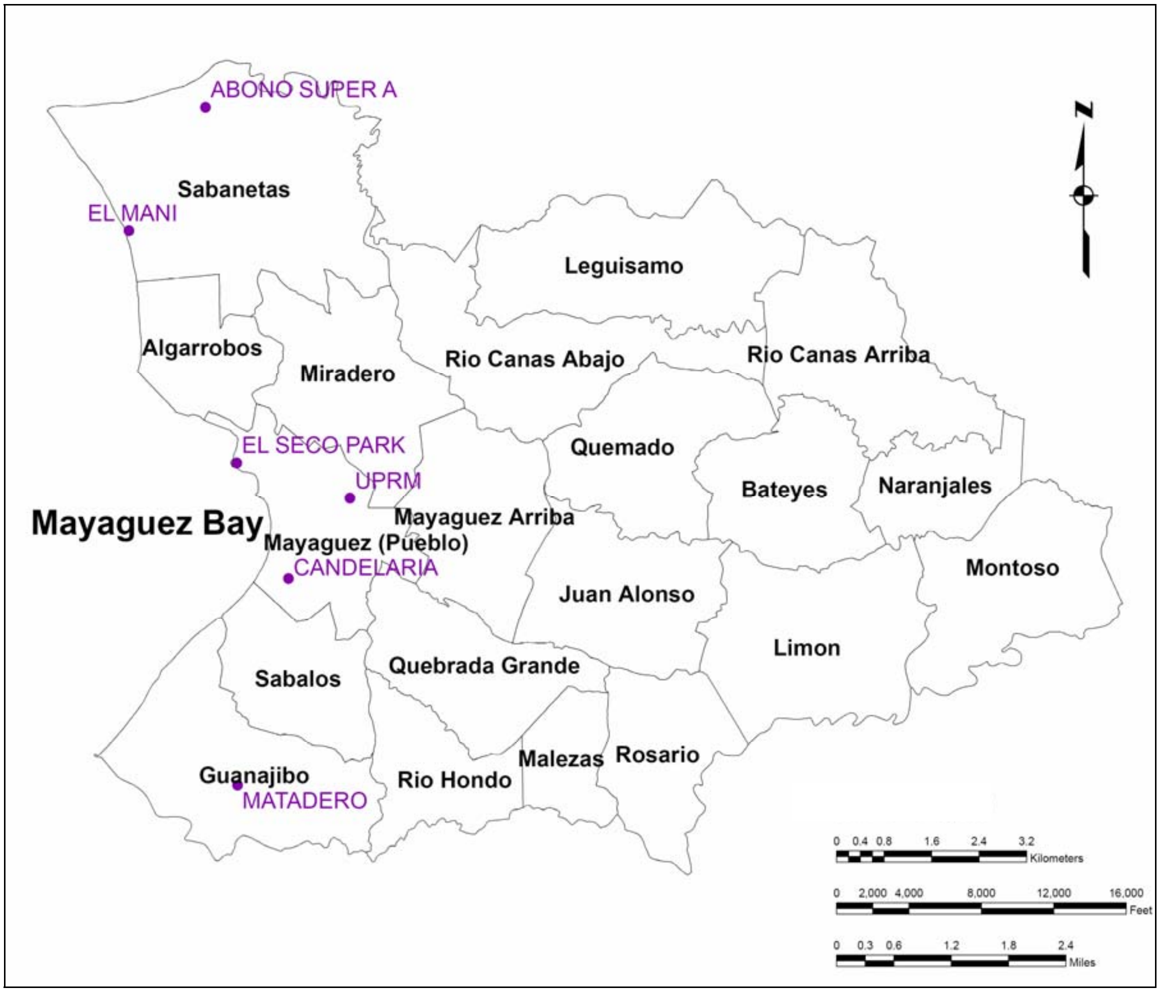


Figure 4.9 Location of Seismic Refraction Tests performed for this study

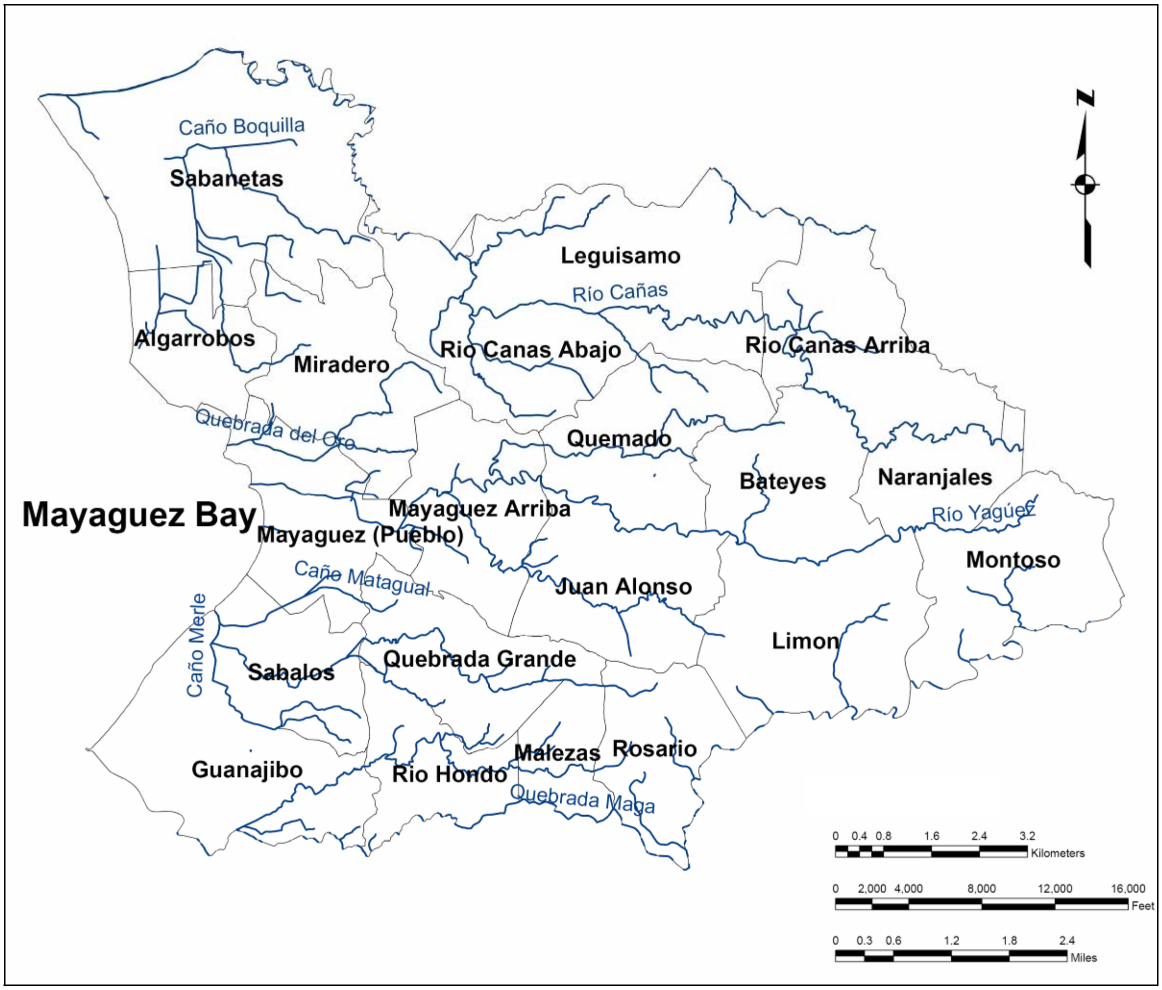


Figure 4.10 Mayagüez Hydrographic Network

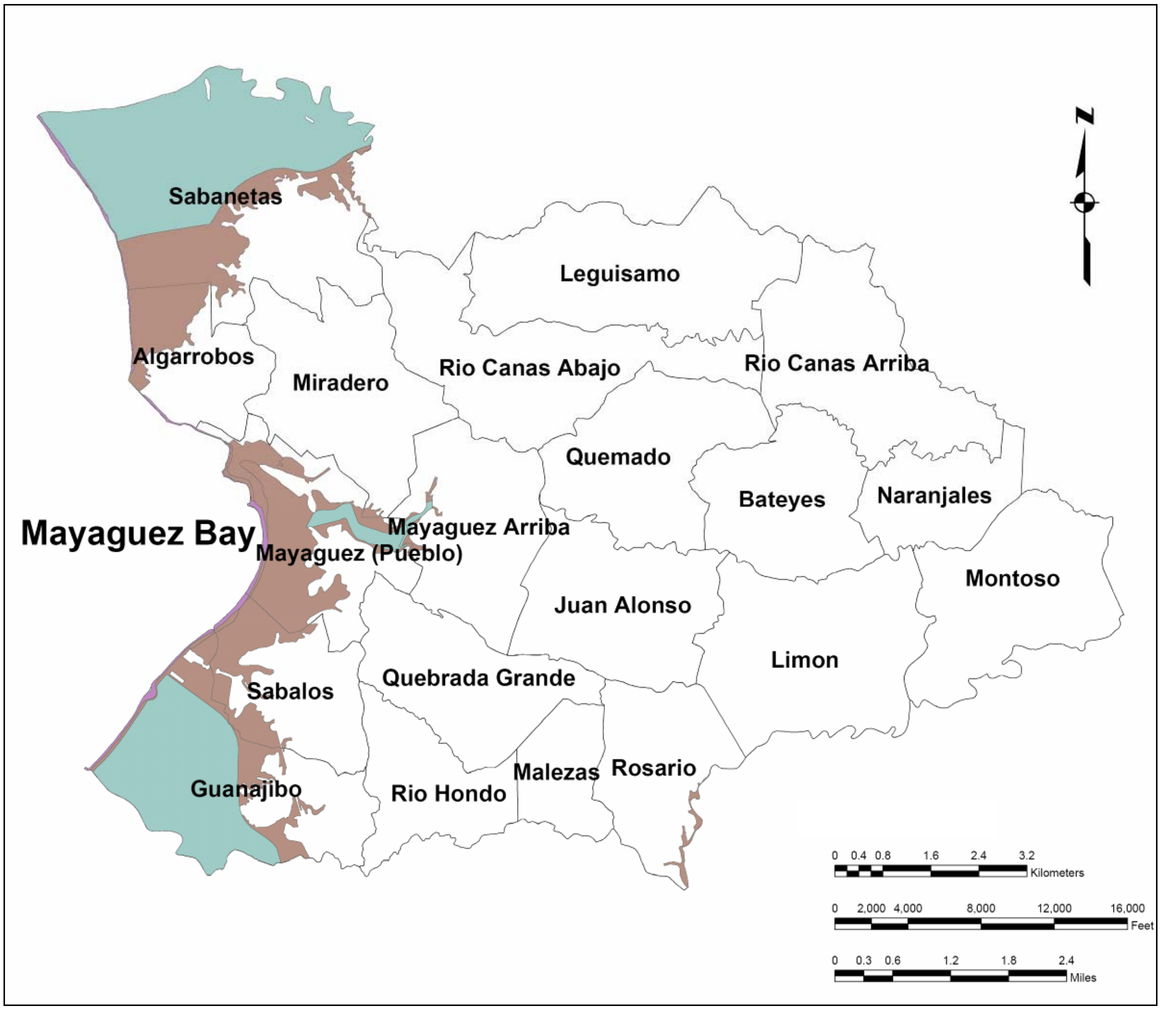


Figure 4.11 Flood Zones for Mayagüez

CHAPTER 5 Ground Response Analysis for the Mayagüez Area

5.1 *Introduction*

This chapter presents a summary of the results from one dimensional ground response analyses carried out for fifteen sites in the city of Mayagüez. The sites were selected for analysis based on available geophysical and geotechnical information (from the geotechnical database described in Chapter 4). In terms of NEHRP classification, the fifteen sites included four class S_c sites, nine sites class S_d, and two sites class S_e. These sites are representative of the typical soil conditions of Mayagüez. Analyses were performed to assess possible seismic ground motions amplifications due to local site conditions. Due to the existing gaps in geotechnical and geological information two dimensional analyses were not considered appropriate at this moment. This chapter presents the computed ground response spectra at the surface for each site analyzed as well as comparisons with the recommended design spectra from current codes applicable in Puerto Rico. Additional details regarding the ground response analyses carried out for this project can be found in Perez (2005).

5.2 *Methodology used for ground response analysis*

In this research project, equivalent linear one-dimensional analysis were carried out using the computer program SHAKE2000 (Ordónez, 2003). The following is a brief explanation of the method used. The reader interested in detailed information on this topic can find it in Kramer (1996) and SHAKE (2003).

The term one-dimensional refers to the assumption that the soil profile extends to infinity in all the horizontal directions and the bottom layer is considered a half space. In this type of analysis, only the vertical propagation of seismic waves can be considered, usually shear waves. The equivalent linear one-dimensional analysis is an approximate linear method of analysis. The non linear behavior of the soil is accounted by means of an iterative process in which the soil damping ratio and shear modulus are changed so that they are consistent with a certain level of shear strain calculated with linear procedures. The soil nonlinearities are not implicitly considered as in fully non linear methods; rather at each iteration cycle the equations of motion solved are those of an equivalent linear model. The input data necessary are the time history of an earthquake, the soil profile, and the dynamic soil properties. The earthquake time history can be a corrected accelerogram recorded by seismic station or a synthetic or artificial ground motion. The soil profile consists of the layers and their corresponding thicknesses, initial damping ratio, unit weights, and shear moduli or shear wave velocities. The dynamic soil properties are defined by means of a damping ratio and shear modulus degradation curves. These are curves of the variation of the equivalent damping ratio and secant shear modulus with strain.

This method of analysis has proved to give good approximations of the response of leveled soil deposits subjected to an earthquake and it had been successfully compared with finite element method and fully non-linear analysis. A recent comparison made with the finite elements non-linear codes was performed in a seismic amplification study in Lotung, Taiwan (Borja, et.al., 2002) reporting good results.

5.3 *Dynamic soil properties for Mayagüez sites*

In the equivalent linear one dimensional analysis, implemented in the computer program SHAKE 2000, the dynamic soil properties are defined by the damping ratio and shear modulus degradation curves. Researchers had developed these types of curves for different soil materials. Example of this curves for sand and clay are those proposed by Seed and Idriss (1970) and Seed and Sun (1989), for gravel the ones proposed by Seed et al. (1986), and the damping ratio and shear modulus degradation curves for rock proposed by Schnabel (1973).

Identification of soil types and selection of the appropriate property curves for the analyses was based on thorough review of the available geotechnical information in the geotechnical database for Mayagüez. Figure 5.1 shows the location of the sites were ground response analyses were performed. The sites analyzed were classified in three groups according to the site information available. Table 5.1 summarizes the groups created in this study with their description and the sites assigned to each group. Those sites where shear wave velocity data and geotechnical boring information was available were assigned to Group A. For sites where geotechnical information from a nearby boring was not available, soil materials were inferred from geology and USDA maps and correlations with shear wave velocity as prepared by ASTM and the U.S. Army Corps of Engineers (USACE 1995). These sites were assigned to Group B. From the geotechnical exploration database three sites were found in Mayagüez where the exploration reached 100 ft depth or higher. These sites, for which only geotechnical information was available, were assigned to Group C. For sites in Group C, shear wave velocity was estimated using correlations of Vs with SPT N values or CPT qc if available (e.g., Imai and Yoshimura, 1970).

Table 5.1: Groups created and sites designation for the ground response analysis.

Group	Description	Sites
A	Sites with shear wave velocity profile and geotechnical boring logs near the site.	Abonos, Maní, Biología, Civil Engineering, and Viaducto
B	Sites with shear wave velocity profile only.	HWY341, Maní Park, Seco Park, Ramírez de Arellano, Isidoro García, and Sultanita
C	Sites with geotechnical boring logs only.	*El Castillo, El Bosque, India, and Marina*

Figure 5.1 Location map of sites where ground response analyses were performed.

Tables 5.2 through 5.4 shows a summary of the damping ratio and shear modulus reduction curves used for each of the ground response analysis groups carried out for this project.

Table 5.2: Dynamic soil properties assigned to Group A (see Table 5.1)

Dynamic Soil Properties-Abonos site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Clayey Silt	Damping for Clay, Average (Seed & Idriss 1970)	G/Gmax Clay (Seed & Sun 1989) upper bound
2	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Dynamic Soil Properties-Maní site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Sand	Sand Avg. (Seed & Idriss 1970)	Sand Avg. (Seed & Idriss 1970)
2	Weath. Rock	Gravel Avg. (Seed 1986)	Gravel Avg (Seed 1986)
3	ROCK	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Dynamic Soil Properties-Biología site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Silty Clay	Damping for Clay, Lower bound (Seed & Idriss 1970)	G/Gmax Clay (Seed and Sun 1989) upper bound
2	Silty Sand	Damping for Sand, Upper Bound (Seed & Idriss 1970)	G/Gmax Sand, Upper Bound (Seed & Idriss 1970)
3	Weath. Rock	Gravel Avg. (Seed 1986)	Gravel Avg (Seed 1986)
4	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Dynamic Soil Properties-Viaducto site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Clay	Damping for Clay, Average (Seed & Idriss 1970)	G/Gmax Clay (Seed & Sun 1989) upper bound
2	Limstone	Damping for Gravelly soils (Seed et al 1988)	G/Gmax Gravel Average (Seed et al 1986)
3	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)
Dynamic Soil Properties-UPRM Civil Engineering Building site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Silty Clay	Damping for Clay, Lower bound (Seed & Idriss 1970)	G/Gmax Clay (Seed and Sun 1989) upper bound
2	Silty Sand	Damping for Sand, Upper Bound (Seed & Idriss 1970)	G/Gmax Sand, Upper Bound (Seed & Idriss 1970)
3	Weath. Rock	Gravel Avg. (Seed 1986)	Gravel Avg (Seed 1986)
4	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Table 5.3: Dynamic soil properties assigned to Group B (see Table 5.1)

Dynamic Soil Properties-341HWY site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Clayey Silt	Damping for Clay, Average (Seed & Idriss 1970)	G/Gmax Clay (Seed & Sun 1989) upper bound
2	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Dynamic Soil Properties-Maní Park site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Sand	Sand Avg. (Seed & Idriss 1970)	Sand Avg. (Seed & Idriss 1970)
2	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Dynamic Soil Properties-Seco Park site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Sand	Sand Avg. (Seed & Idriss 1970)	Sand Avg. (Seed & Idriss 1970)
2	Weath. Rock	Gravel Avg. (Seed 1986)	Gravel Avg. (Seed 1986)

Dynamic Soil Properties-Isidoro García site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Sand	Sand Avg. (Seed & Idriss 1970)	Sand Avg. (Seed & Idriss 1970)
3	Weath. Rock	Gravel Avg. (Seed 1986)	Gravel Avg. (Seed 1986)

Dynamic Soil Properties-Ramírez de Arrellano site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Sand	Sand Avg. (Seed & Idriss 1970)	Sand Avg. (Seed & Idriss 1970)
3	Weath. Rock	Gravel Avg. (Seed 1986)	Gravel Avg. (Seed 1986)

Dynamic Soil Properties-Sultanita site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Clay	Damping for Clay, Average (Seed & Idriss 1970)	G/Gmax Clay (Seed and Sun 1989) upper bound
2	Weath. Rock	Gravel Avg. (Seed 1986)	Gravel Avg. (Seed 1986)
3	Rock	Damping for Rock (Shcnabel 1973)	Rock (Schnabel 1973)

Table 5.4: Dynamic soil properties assigned to Group C (see Table 5.1)

Dynamic Soil Properties-El Bosque site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Silty Clay	Damping for Clay, Lower bound (Seed & Idriss 1970)	G/Gmax Clay (Seed and Sun 1989) upper bound
2	Clayey Silt	Damping for Clay, Average (Seed & Idriss 1970)	G/Gmax Clay (Seed and Sun 1989) upper bound
3	Weath. Sandstone	Gravel Avg. (Seed 1986)	Gravel Avg. (Seed 1986)
4	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Dynamic Soil Properties-El Castillo site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Clayey Silt	Damping for Clay, Average (Seed & Idriss 1970)	G/Gmax Clay (Seed and Sun 1989) upper bound
2	Weath. Sandstone	Gravel Avg. (Seed 1986)	Gravel Avg. (Seed 1986)
3	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

Dynamic Soil Properties-India Brewery site			
Soil ID	**Soil Type**	**Damping ratio reduction**	**Shear modulus reduction**
1	Sandy Clay	Sand Avg. (Seed & Idriss 1970)	Sand Avg. (Seed & Idriss 1970)
2	Silty Clay	Damping for Clay, Lower bound (Seed & Idriss 1970)	G/Gmax Clay (seed and sun 1989) upper bound
3	Silty Sand	Sand Avg. (Seed & Idriss 1970)	Sand Avg. (Seed & Idriss 1970)
4	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

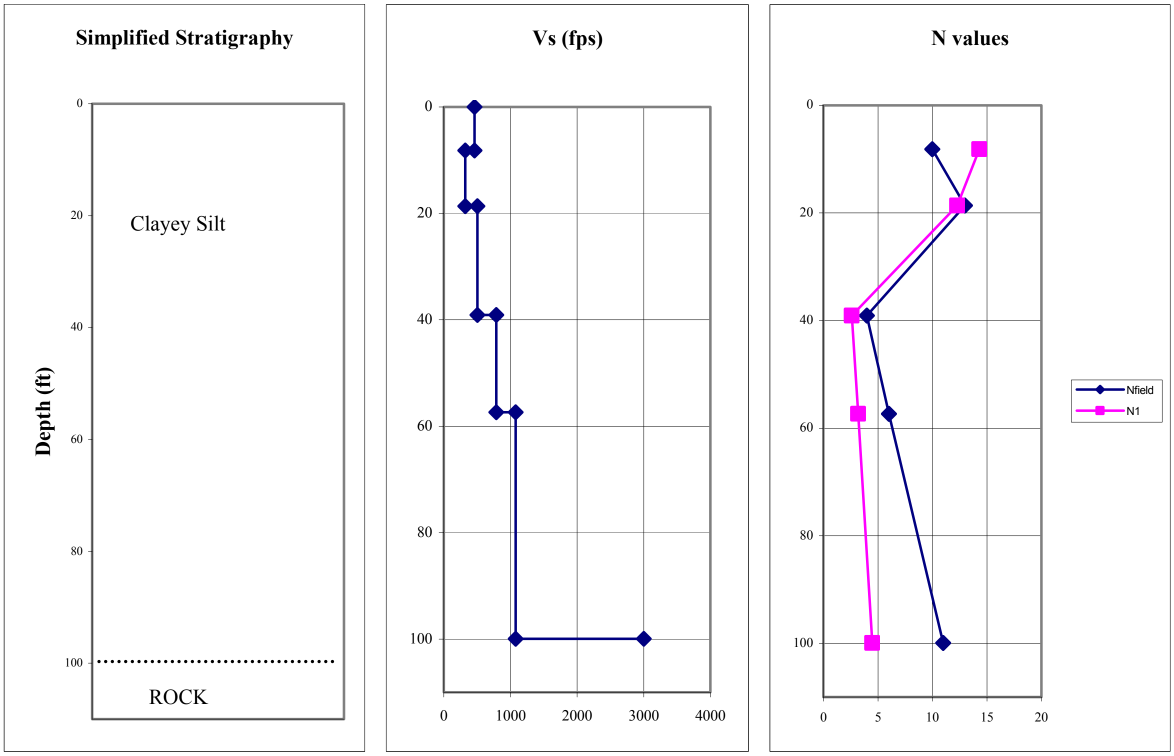
Dynamic Soil Properties-Marina Post Office Site			
Soil ID	**Soil Type**	**Damping Ratio**	**Modulus Reduction**
1	Clayey silt	Damping for Clay, Average (Seed & Idriss 1970)	G/Gmax Clay (Seed and Sun 1989) upper bound
2	Weathered Rock	Gravel Average. (Seed 1986)	Gravel Average (Seed 1986)
3	Rock	Damping for Rock (Schnabel 1973)	Rock (Schnabel 1973)

5.4 *Generalized simplified Soil profiles for the sites analyzed*

Using the available information, including geophysical tests carried for this study, idealized soil profiles were constructed for the fifteen sites analyzed. As mentioned before, the sites were classified in three groups depending on the information available for each site. Group A comprised sites with shear wave velocity data and geotechnical information. The sites in which only shear wave velocity information was available were assigned to Group B. In Group C were assigned sites where only geotechnical information was available. The additional information necessary to perform the ground response analysis was estimated using correlations. This section presents a summary of the simplified soil profiles used for ground response analyses for each site. For sites were bedrock was not encountered, situation for most sites, bedrock was assumed to be located at the bottom of the geotechnical model (at 30 m depth). This assumption is a simplification that at this stage is considered sufficient given the knowledge gaps identified in this study. For example there is a lack of reliable, or sufficient, information regarding bedrock depth, and its soil-bedrock interface characteristics. This is a major hurdle in order to perform reliable ground response analysis for this region. More research in this area is recommended.

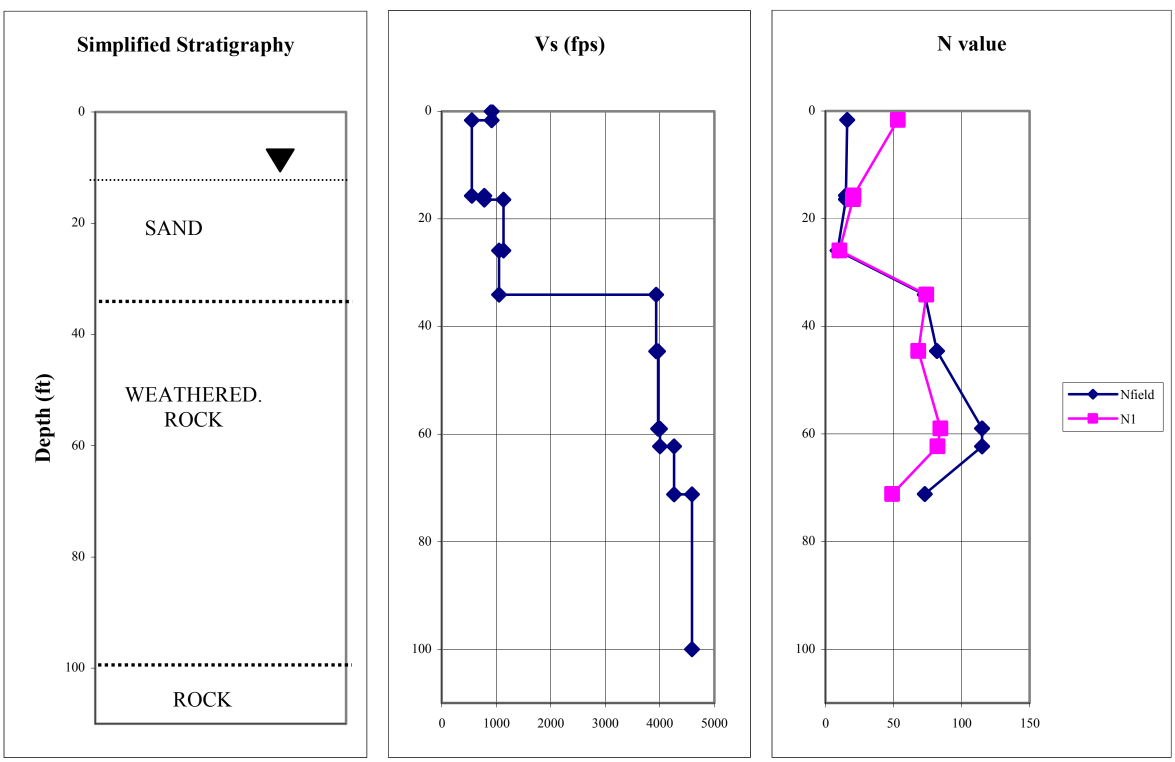
5.4.1 *Group A soil profiles*

Figures 5.2 to 5.6 show the generalized simplified profiles for the Group A sites including information of V_s and SPT N data. This group had three S_c sites and two S_d sites. The Abonos site profile is shown in Figure 5.2. This site is located in the Añasco valley and consists of a deep clayey silt to silty clay alluvial soils with relatively low shear wave velocities (NEHRP Class S_d). Macari (1994) reported this site as comprised of loose alluvial deposits that may extend beyond 30 m depth. The next Group A site is the Maní site located near the coast of Mayagüez. The profile used for this site is presented in Figure 5.3. A geotechnical boring available from a nearby location showed presence of weathered rock beginning at a depth of about 35 ft that had SPT N values above 50 blows per foot. This agrees with the high shear wave velocity observed at this depth from the SASW tests (about 1,200 m/s). This site was classified as NEHRP class S_c. The third and fourth sites in Group A are the UPRM-Biology and the Viaducto sites, shown in Figures 5.4 and 5.5, respectively. The Biology sites was classified as NEHRP S_c and the Viaducto as S_d. Macari (1994) reported SASW tests near the Viaducto site in the area around the Darlington Building. In his study, Macari found that the shear wave velocity increased to about 460 m/s at 24 m depth where the geotechnical exploration shows presence of weathered rock. The last site for Group A is located in the Civil Engineering Department of UPRM, and is shown in Figure 5.6. This site was classified as NEHRP S_c.



(a) (b) (c)

Figure 5.2 Abonos site profile (a) Soil materials, (b) shear wave velocities, and (c) N values



(a) (b) (c)

Figure 5.3 Maní site profile (a) Soil materials, (b) shear wave velocities, and (c) N values

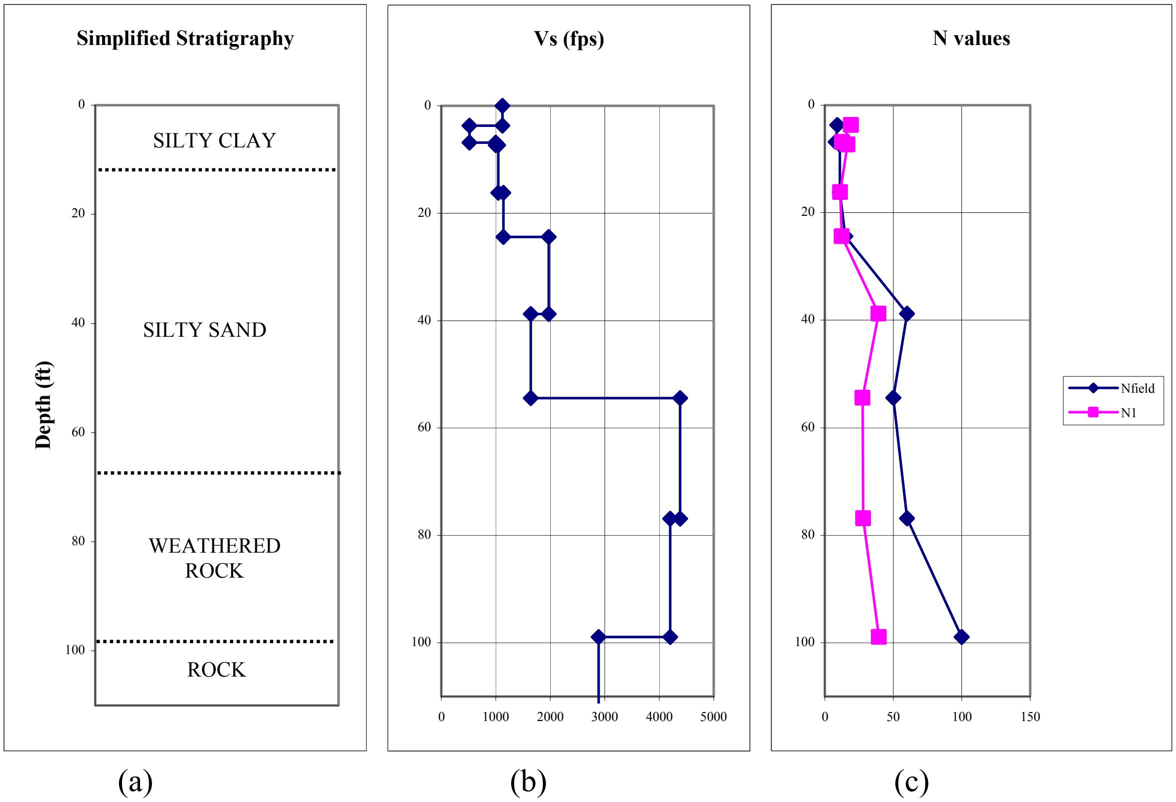


Figure 5.4 Biología site profile (a) Soil materials, (b) shear wave velocities, and (c) N values

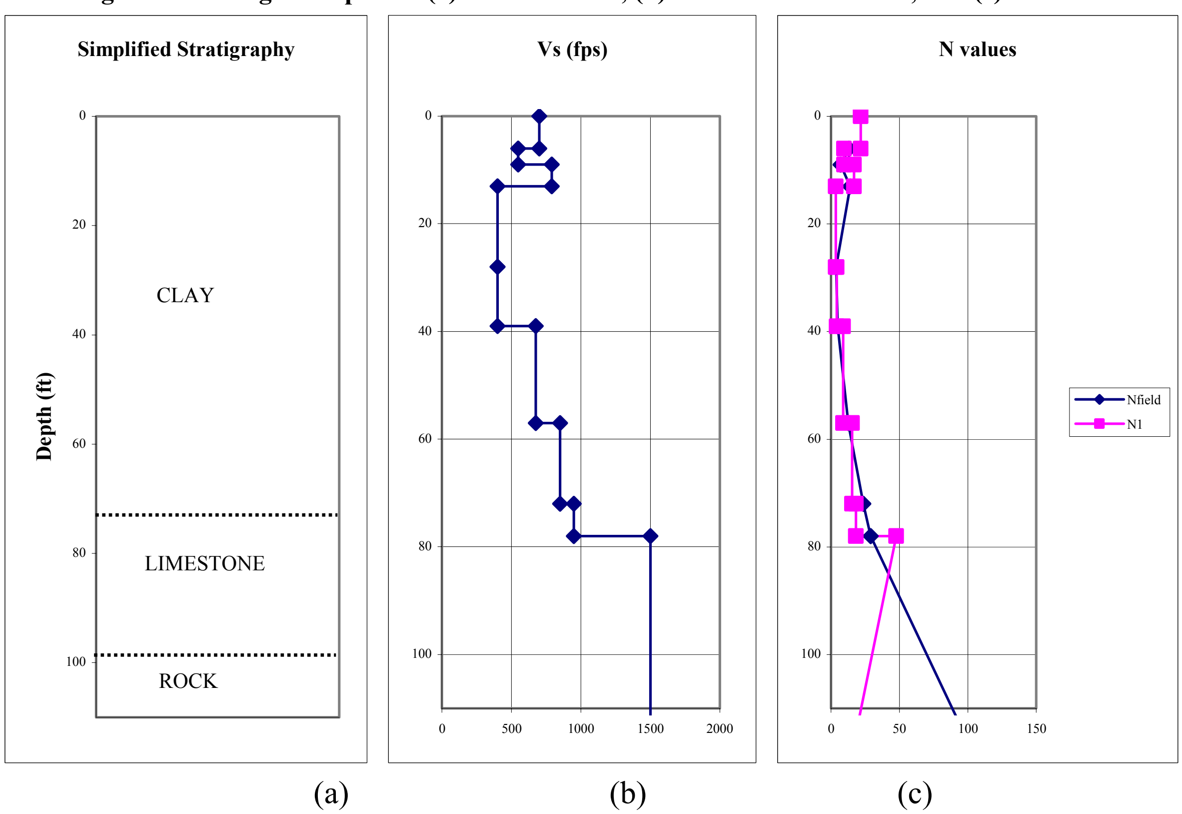


Figure 5.5 Viaducto site profile (a) Soil materials, (b) shear wave velocities, and (a) N values.

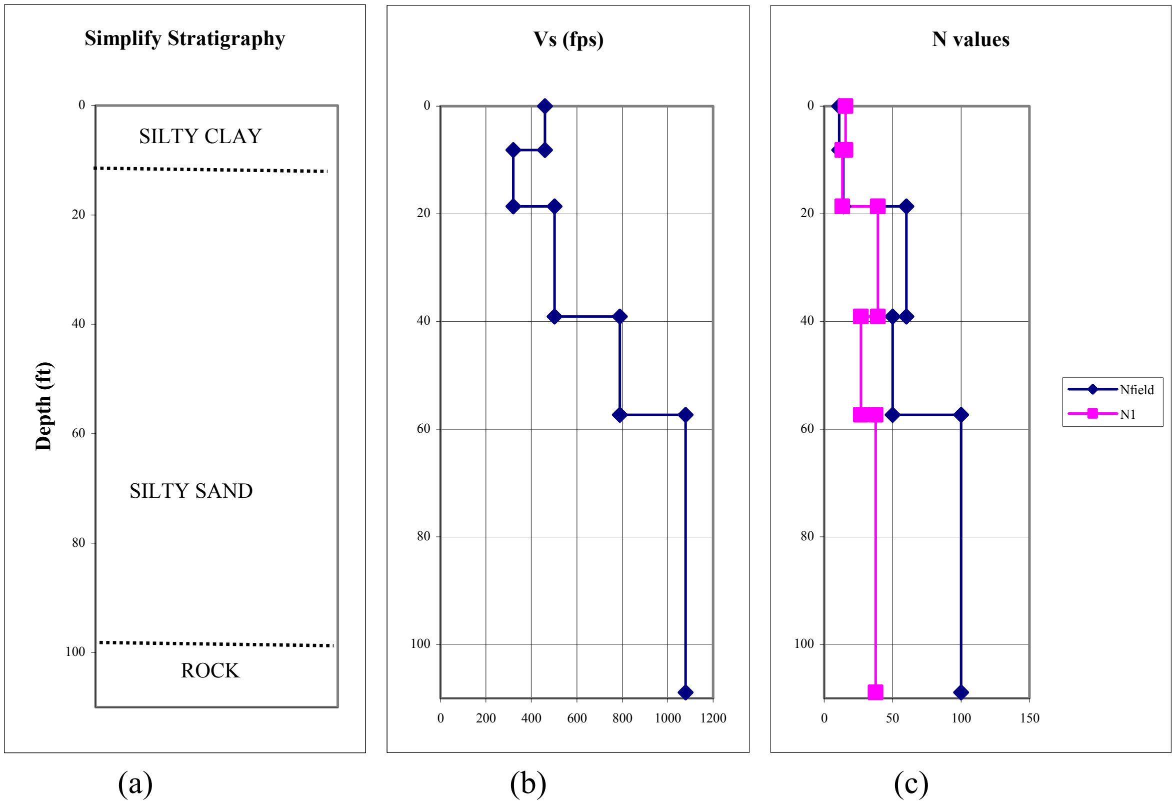


Figure 5.6 Civil site profile (a) Soil materials, (b) shear wave velocities, and (c) N values

5.4.2 *Group B soil profiles*

Group B sites were those for which a shear wave velocity profile was available and the soil information was inferred from geology and USDA soils maps and from correlations with shear wave velocity. Six sites are in Group B, all classified as NEHRP sites S_d, and their simplified interpreted soil profiles are shown in Figures 5.7 through 5.12. The Highway 341 site is shown in Figure 5.7. This site is located in the Añasco valley and consists of very deep alluvial soils. The second site in Group B, the Maní Park, is located near the coast of Mayagüez and is believed to consist mainly of sandy soils. The simplified stratigraphy and S-wave velocity profile information for this site is shown in Figure 5.8. The profile for the Seco Park site is shown in Figure 5.9. Similarly to the Maní Park site, this site was inferred to be predominantly sandy soils. The fourth and fifth sites are the Isidoro García and Ramírez de Arellano sites are shown in Figures 5.10 and 5.11, respectively. These sites have similar shear wave velocity profiles, with values ranging between 270 and 460 m/s. The sixth and last site in Group B is the Sultanita lot located in the east side of the city of Mayagüez in mountainous terrain. From the geology of the area and the shear wave velocity profile obtained from the SASW tests, a clayey residual soil was assigned to this site. Competent bedrock was not found in any of the geophysical tests of these six sites, hence as a first approximation it was assumed to be located at the base of each model (30 m depth). This simplified assumption may not be conservative, but further analysis of other bedrock alternatives including evaluation of the sensitivity of the results to bedrock depth was not considered for this project. At this stage the analyses presented herein are considered sufficient given the quality of the existing information, the level of uncertainty of many of the parameters, and the important information gaps that still need to be resolved before attempting more detailed analyses.

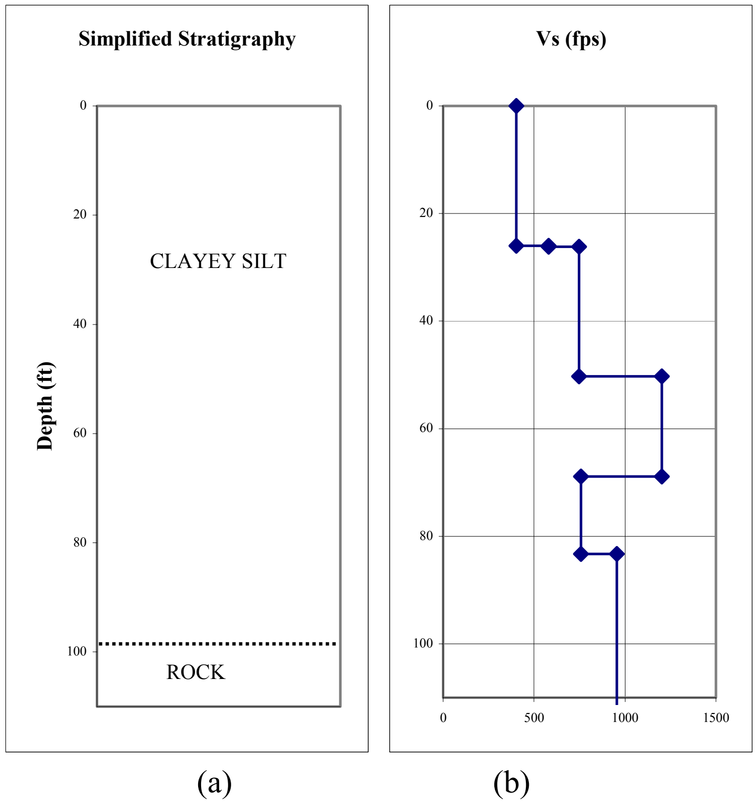
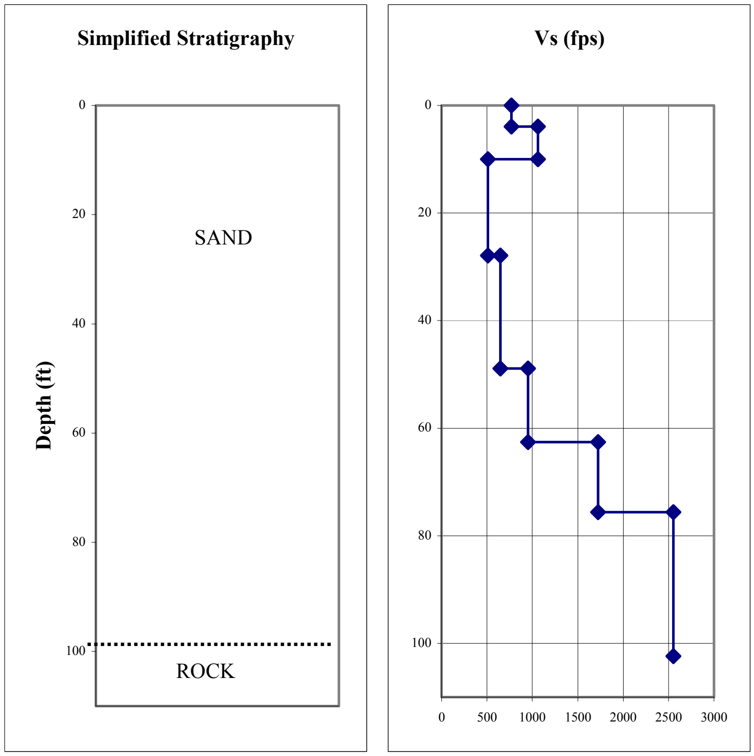
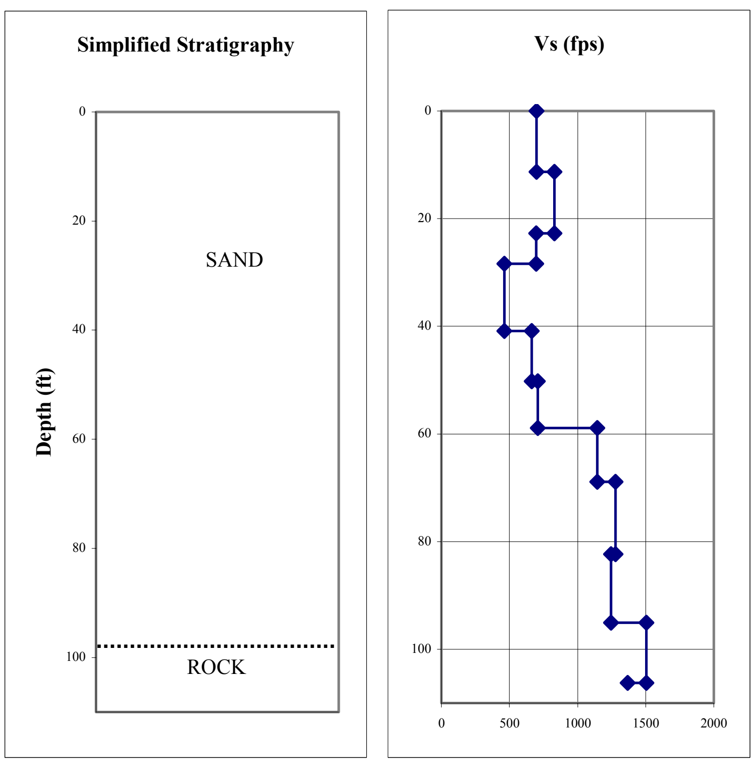


Figure 5.7: Profile for Hwy 341 site (a) Soil materials and (b) shear wave velocity profile



(a) (b)

Figure 5.8 Profile for Mani Park site (a) Soil materials and (b) shear wave velocity profile



(a) (b)

Figure 5.9 Profile for the Seco Park site (a) Soil materials and (b) shear wave velocity profile

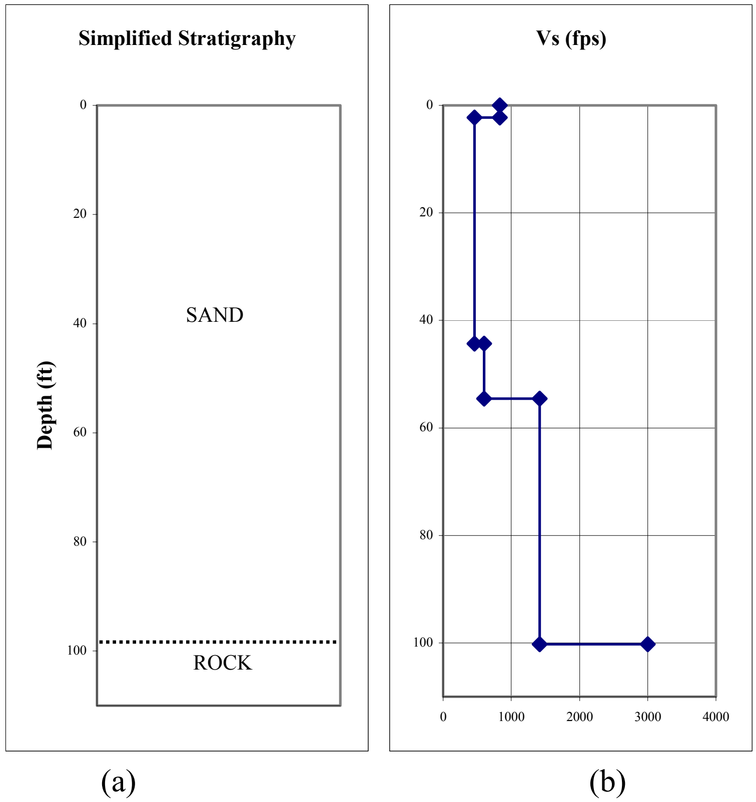


Figure 5.10 Profile for the Isidoro Garcia site (a) Soil materials and (b) shear wave velocity profile

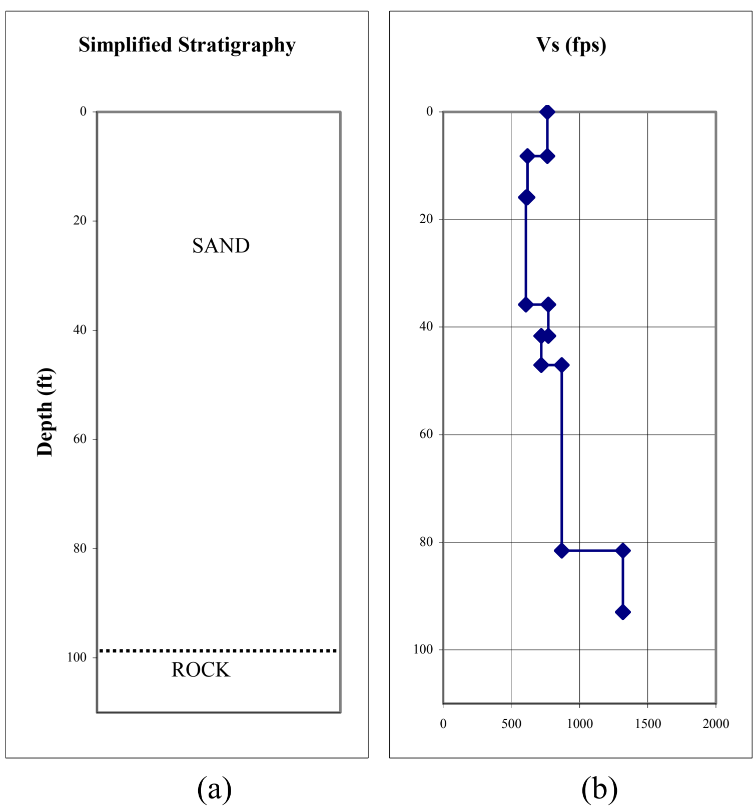
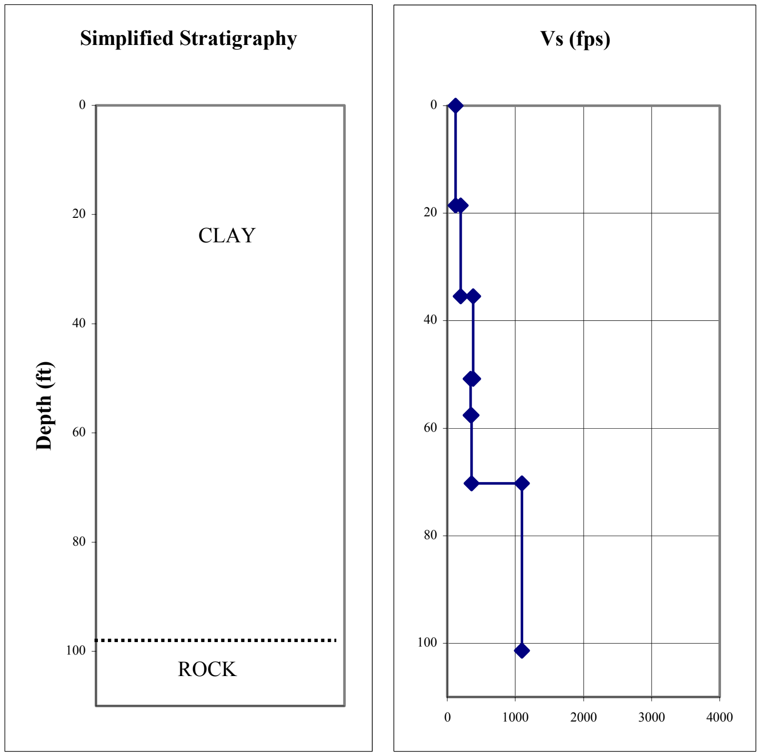


Figure 5.11 Profile for the Ramirez de Arellano site a) Soil materials and (b) shear wave velocity profile



(a) (b)

Figure 5.12 Profile for the Sultanita site (a) Soil materials and (b) shear wave velocity profile

5.4.3 *Group C soil profiles*

Four sites were assigned to Group C (El Bosque, El Castillo, India Brewery, and La Marina). These sites only had available geotechnical boring log information. For these sites the shear wave velocity profiles were estimated using borehole data (e.g., correlations with SPT N data), geology and soil maps. For Group C, one site classified as NEHRP class S_c (El Castillo), one as S_d (El Bosque), and two as S_e (India Brewery and La Marina).

The El Bosque site consisted of clayey silt and silty clay (Class S_d). Sandstone bedrock was found at 24.4 m depth (See Figure 5.13). The profile for the El Castillo site is shown in Figure 5.14. This site consisted of clayey silt underlain by weathered rock at a depth of about 7.6 m and was classified as S_c. The India brewery site, located near the Yagüez river, consists of deep alluvial soils comprised of sandy and silty clays, as shown in Figure 5.15. This site classified as NEHRP class S_e. The generalized profile for the Marina site is shown in Figure 5.16. This site comprised of very thick deposits of clayey silt and classified as NEHRP class S_e. Information regarding SPT N values for Group C sites is included in Figures 5.13 through 5.16.

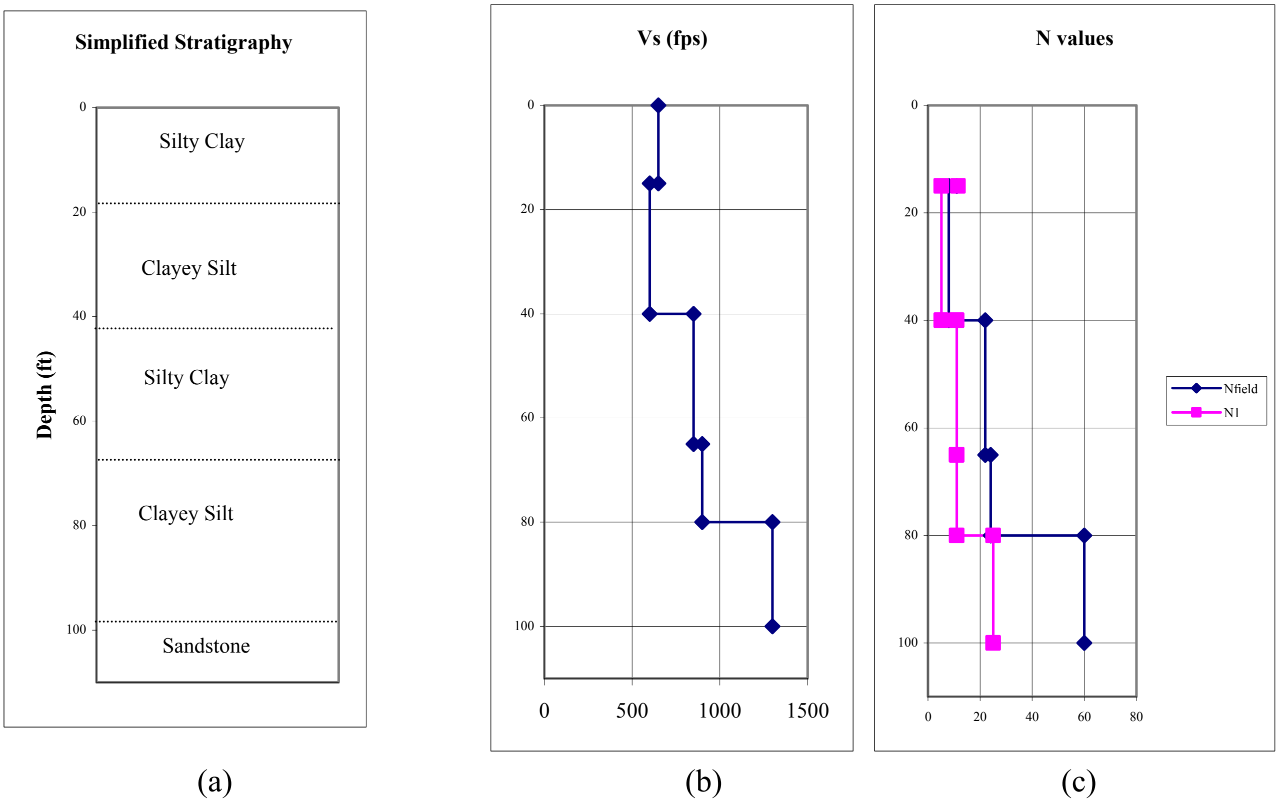


Figure 5.13 Profile for El Bosque site (a) Stratigraphy, (b) Estimated shear wave velocities, and (c) N values

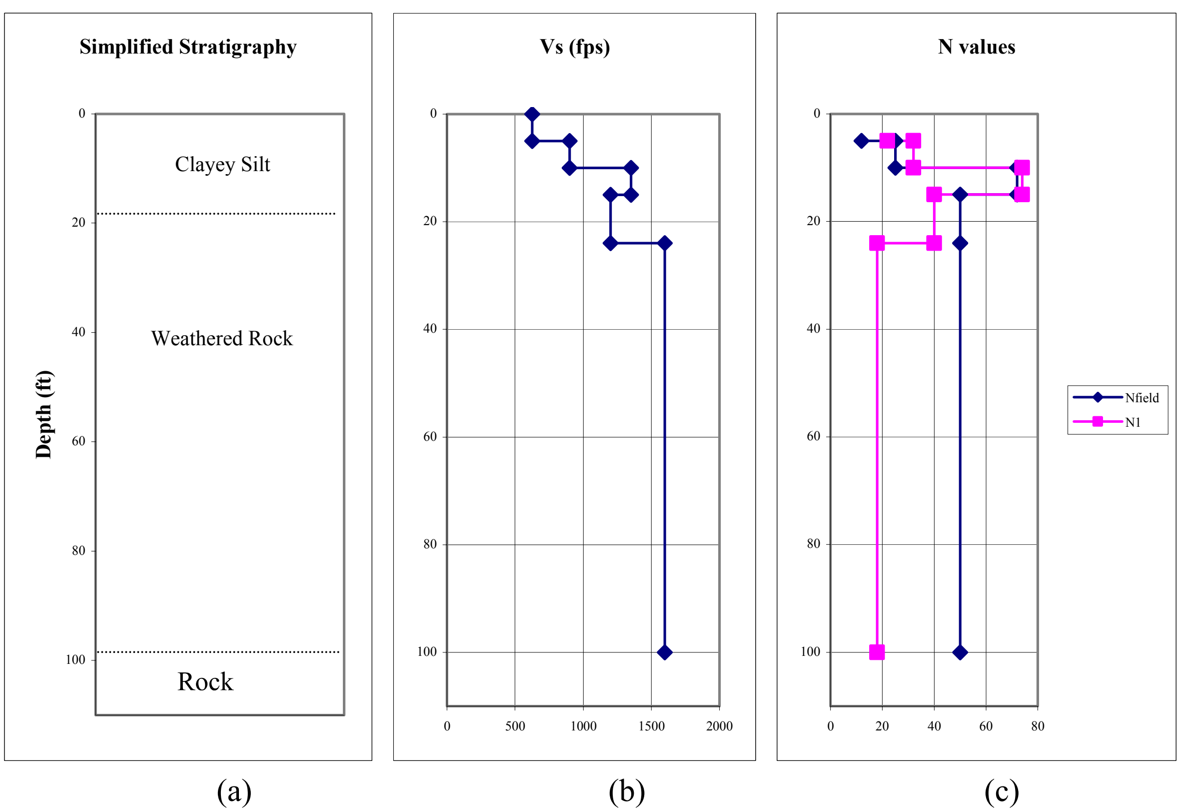
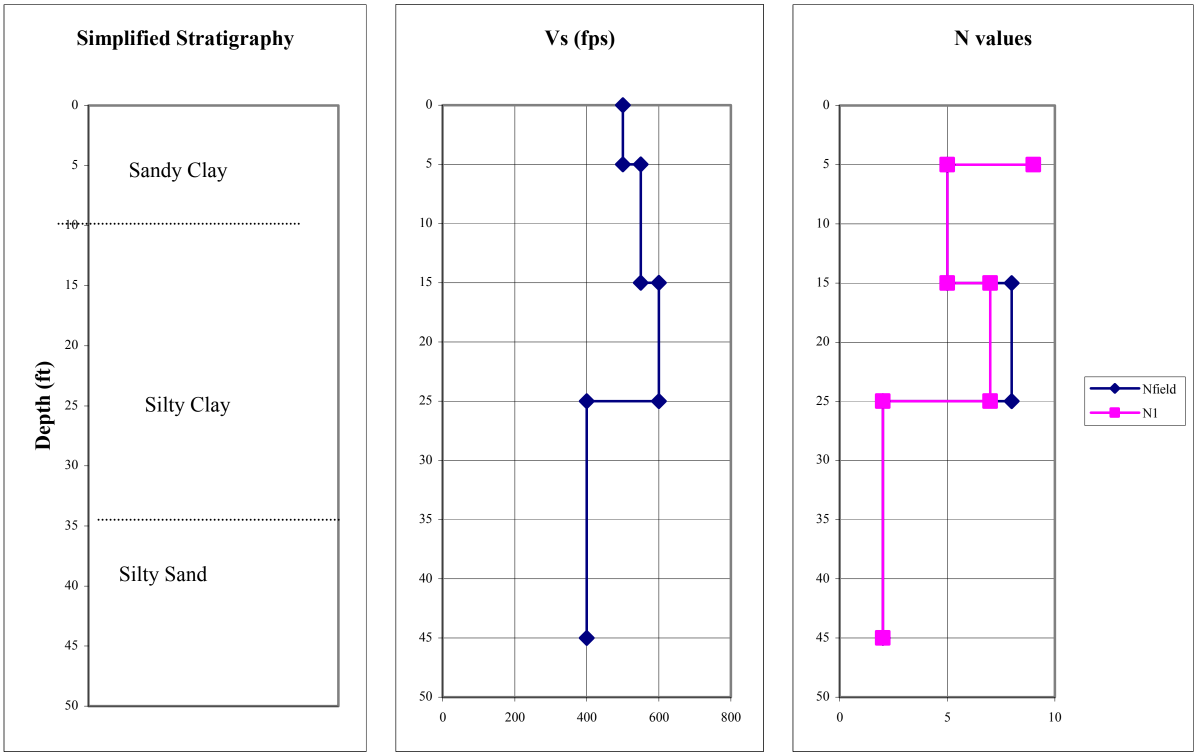
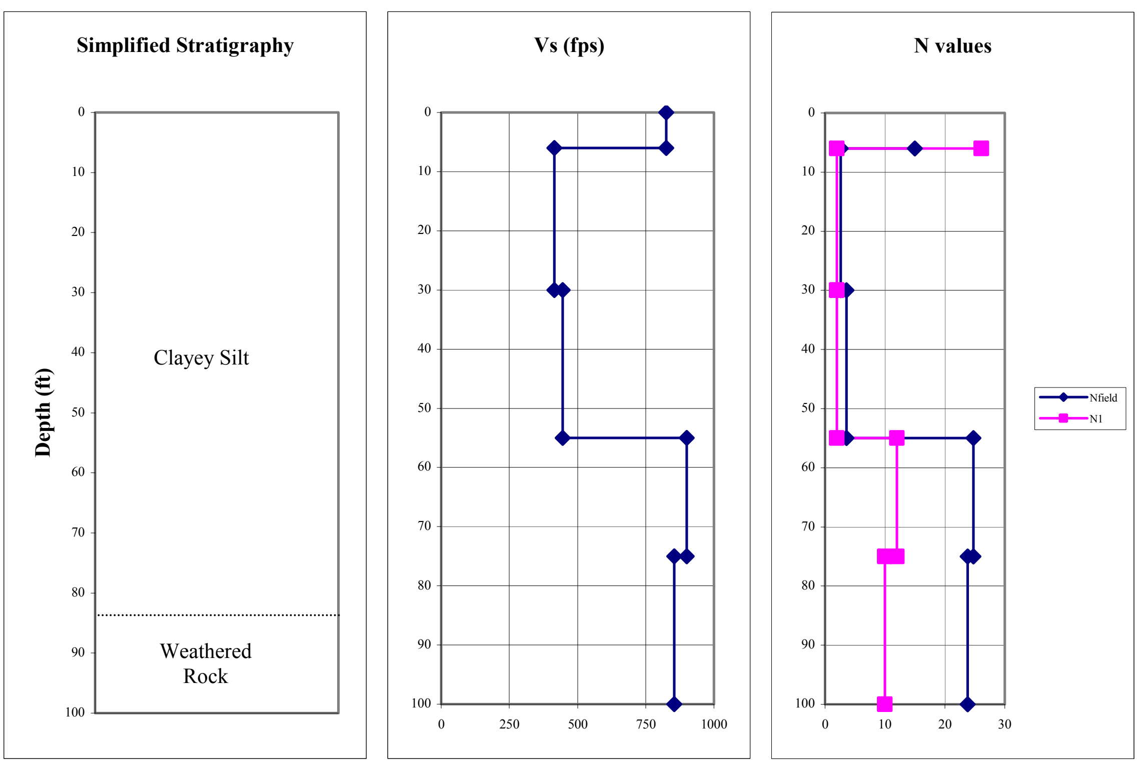


Figure 5.14: Profile for El Castillo site (a) Stratigraphy, (b) Estimated shear wave velocities, and (c) N values



(a) (b) (c)

Figure 5.15 Profile for La India Brewery site (a) Stratigraphy, (b) Estimated shear wave velocities, and (c) N values



(a) (b) (c)

Figure 5.16 Profile for La Marina site (a) Stratigraphy, (b) Estimated shear wave velocities, and (c) N values

5.5 *Input Ground Motions*

Strong motion records from earthquake registered in Puerto Rico are not available since the last large earthquake occurred in 1918. Therefore, ground response analyses carried out for this study used input ground acceleration time histories based on four artificial ground motions time histories and one real earthquake record. The artificial ground motions were generated using the methodology proposed by Montejo (2004) and were made compatible with the UBC-97 design response spectrum for seismic Zone 3 in a NEHRP soil type S_b with 5% damping. The real earthquake accelerogram used was the El Salvador earthquake of October 10, 1986 obtained from the Geotechnical Investigation Center instrument in the north-west direction. This earthquake record was found by Martinez et al. (2001) to be the dominant one among many earthquakes analyzed for a seismic hazard study for Western Puerto Rico. The 1986 El Salvador earthquake has a response spectrum reasonably close to the design spectrum recommended by the UBC-97 for Zone 4. As mentioned in Chapter 2, Martinez et al. (2001) found UBC-97 for Zone 4 to be more appropriate for Mayagüez. The main characteristics of the five input ground motions used for this study are summarized in Table 5.5.

Table 5.5 Summary of characteristics of input ground motions

ID	PGA (g)	Peak velocity (in/s)	Frequency (Hz)	Predominant Period (s)	Bracketed Duration (s)	Type	Station
1	0.37	10.39	1.94	0.52	9.4	Modified[1] Coalinga,CA May 9/83 Ms = 4.7	1608 Oil Field Fire St.
2	0.39	11.45	2.22	0.45	21.5	Modified[1] Loma Prieta, CA Oct. 18/89 Ms = 7.1	58117 Treasure Island
3	0.37	10.80	1.64	0.61	10.9	Modified[1] Coyote Lake, CA Aug. 6/79 Ms = 5.6	57217 C.L. Dam
4	0.34	13.45	2.77	0.36	6.6	Modified[1] Friuli, Italy Sept. 15/76 Ms=5.7	8014 Forgaria C.
5	0.42	23.62	1.45	0.69	6.4	**Not modified** El Salvador Oct. 10/86 Mw = 5.4	Geotech Res. Center N-W direction

Note: (1): Modified using methodology by Montejo (2004) to make it compatible to UBC-97 design response spectrum for Zone 3, Soil Sb.

Figure 5.17 shows the UBC-97 design spectrum for seismic Zone 3 in rock and the response spectra for the first four artificial input ground motions modified to become compatible with the design spectrum. As shown in Table 5.5, the dominant periods of the artificial time histories ranged from 0.36 seconds to 0.61 seconds. The peak ground acceleration varied from 0.34g to 0.39g. More details on these artificial ground motions can be found in Perez (2005).

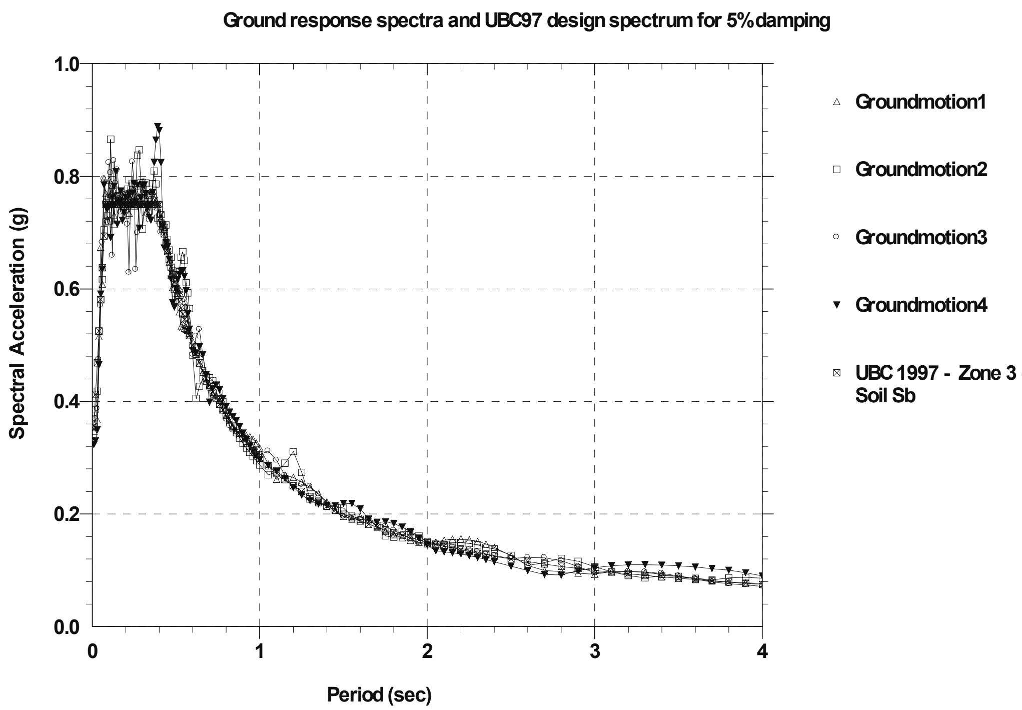


Figure 5.17: Response spectra of artificial accelerograms and UBC 97 design spectrum for rock in zone 3.

Martínez et al. (2001) found in their study that for the city of Mayagüez the design spectrum prescribed in the UBC-97 for zone 3 underestimates the seismic demand for this area. Therefore, they recommended use of the UBC-97 design spectrum for Zone 4. For this purpose the authors found the El Salvador earthquake of October 10, 1986 to be very compatible, as shown in Figure 5.18. Table 5.5 lists the characteristics of the acceleration time history of the El Salvador earthquake. The dominant period for this earthquake record is 0.69 seconds and it has a peak ground acceleration of 0.42g.

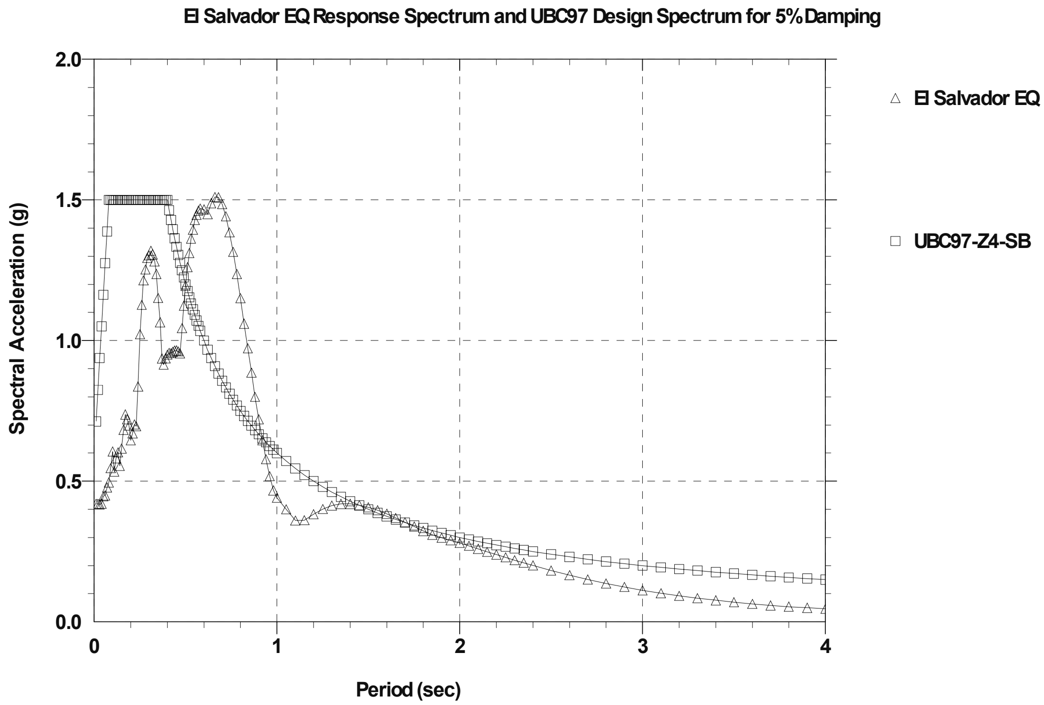


Figure 5.18: El Salvador earthquake response spectrum and the UBC 97 design spectrum for rock in zone 4.

5.6 *Ground response analysis results*

This section presents the results obtained from the equivalent linear one dimensional ground response analyses. As mentioned before, all the sites were assigned to one of three groups depending of the information available for the analysis. The analyses were performed by using as input the four artificial ground motions compatible with the UBC-97 design spectrum for rock in zone 3 and the El Salvador earthquake record which has a response spectrum comparable to the UBC-97 spectrum for rock in zone 4. For each site the following quantities were calculated: the soil deposit fundamental period, the peak acceleration at the ground surface, and the response spectrum at the ground surface for a 5% damping ratio. The main results of the analyses are presented in the following subsections. Additional details can be found in Perez (2005).

5.6.1 *Results for Group A*

Sites in Group A were those having shear wave velocity information from field tests as well as geotechnical information. In this group three were Sc (Maní, Biology, and Civil) and two sites were Sd (Abonos and Viaducto). The results from the four artificial ground motions were arithmetically averaged and they are presented in Table 5.6. Table 5.7 summarizes the results obtained for the El Salvador earthquake accelerogram input.

Table 5.6: Summary of average results for Group A sites subjected to artificial ground motions.

Site ID	$\bar{V}_s$ [a] m/s	UBC-97 Classification	T_s [b] (linear) sec	T_s [b] (non linear) sec	UBC-97[c] Acc. g	Max. Acc.[d] (non linear) g
Abonos	197	Sd	0.51	0.59	0.36	0.65
Maní	503	Sc	0.38	0.62	0.33	0.32
Biología	572	Sc	0.17	0.22	0.33	0.77
Viaducto	216	Sd	0.50	0.74	0.36	0.46
Civil	451	Sc	0.54	0.75	0.33	0.33

a. Represents an average wave velocity in upper 30m (100ft) as defined in UBC-97.

b. Soil periods (Ts) are average values for the four artificial ground motions.

c. UBC-97 ground acceleration for seismic zone 3 (seismic coefficient Ca).

d. The maximum accelerations (Max. Acc.) reported are the average values at the surface of the soil deposit.

Table 5.7: Summary of results for Group A sites subjected to the El Salvador earthquake record.

Site ID	$\bar{V}_s$ [a] m/s	UBC-97 Classification	T_s [b] (linear) sec	T_s [b] (non linear) sec	UBC-97[c] Acc. g	Max. Acc. (non linear) G
Abonos	197	Sd	0.51	0.67	0.44	1.06
Maní	503	Sc	0.38	0.77	0.40	0.34
Biología	572	Sc	0.17	0.24	0.40	0.97
Viaducto	216	Sd	0.50	0.88	0.44	0.67
Civil	451	Sc	0.54	0.98	0.40	0.51

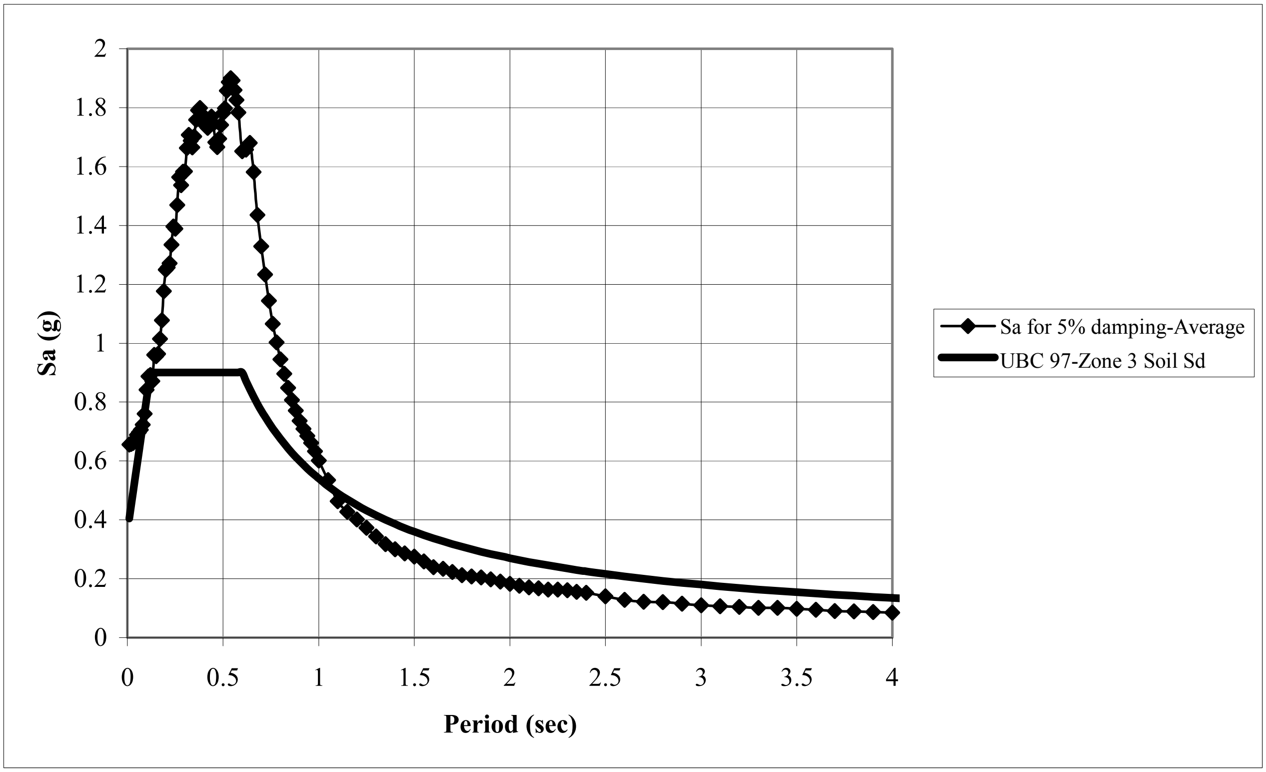
a. Represents an average wave velocity in upper 30m (100ft) as defined in UBC-97.

b. Soil periods (Ts) are average values for the four artificial ground motions.

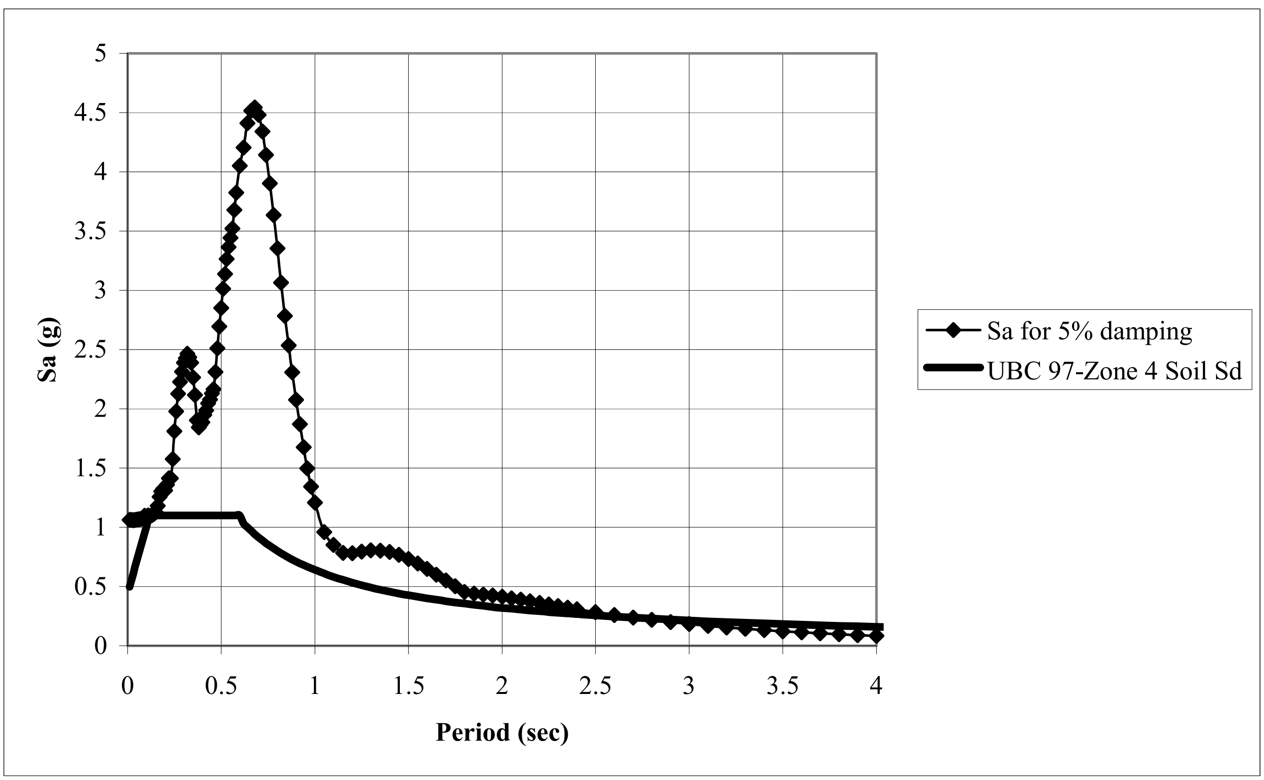
c. UBC-97 ground acceleration for seismic zone 4 and near source factor Na = 1.0 (seismic coefficient Ca).

The results show that the UBC-97 spectrum under predicts in some cases the seismic acceleration at the surface. Relatively high acceleration values were obtained because the initial (linear) period of the soil deposit is close to the dominant periods of the earthquakes. The Maní and Biología site which have the stiffest profile had the smaller increase in period (or degradation) after the analysis iterations, and this is believed to have resulted in higher responses. The same trend was obtained with the El Salvador earthquake as shown in Table 5.9.

Using the acceleration time histories obtained at the surface, ground response spectra for a 5% damping ratio were developed for each site of Group A. The ground response spectra for each site are shown in Figures 5.19 through 5.23. Part (a) of each of these figures presents the average response spectrum from the four artificial input ground motions and compares it with the UBC-97 design spectrum for zone 3 for the corresponding NEHRP soil profile classification. Part (b) of Figures 5.19 to 5.23 display the response spectrum obtained with the 1986 El Salvador earthquake accelerogram and compares it with the UBC-97 design spectrum for seismic zone 4 and the corresponding NEHRP soil profile type.

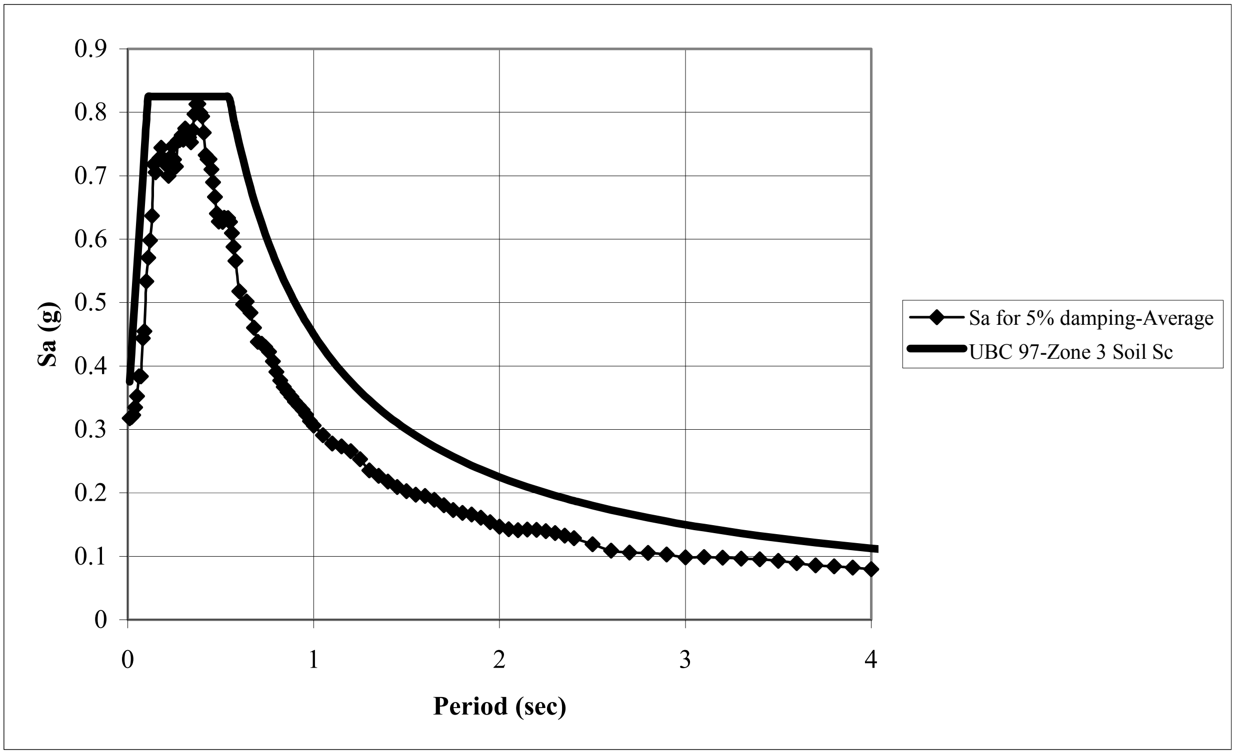


(a) Artificial ground motions

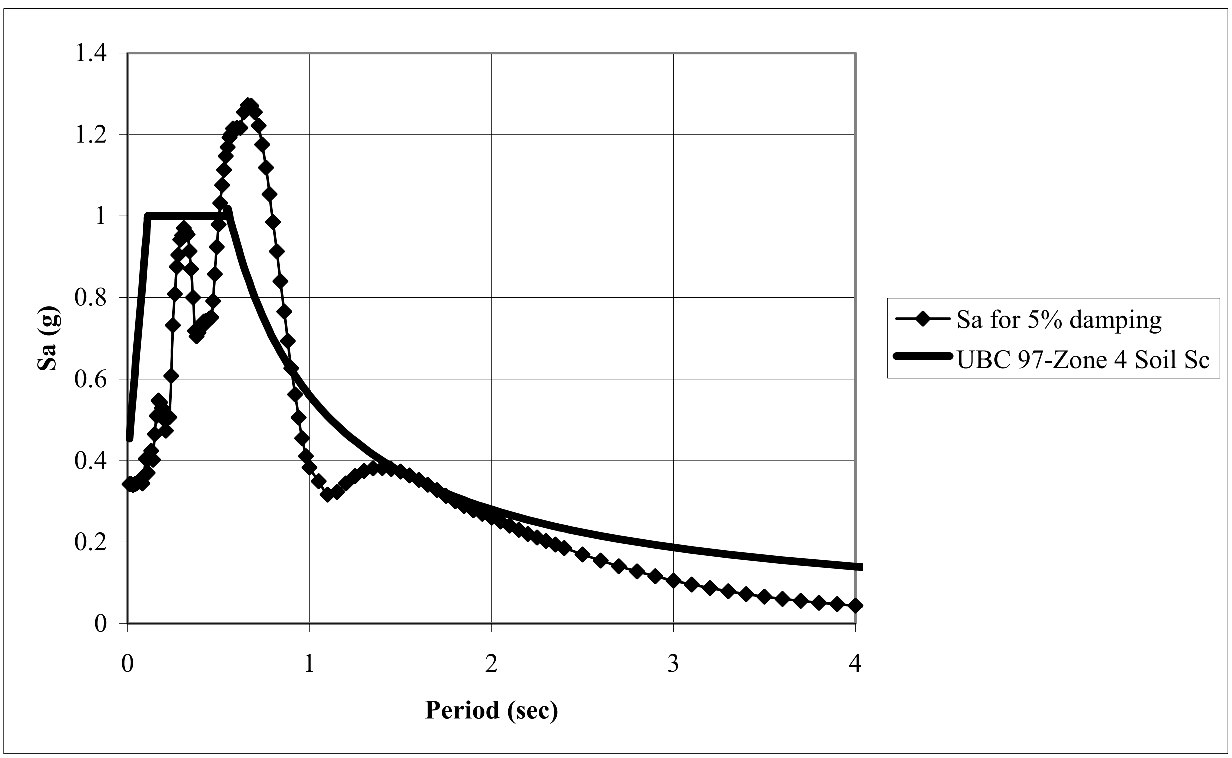


(b) El Salvador earthquake

Figure 5.19: Response spectrum at surface of the Abonos site from analyses and UBC 97 design spectrum.

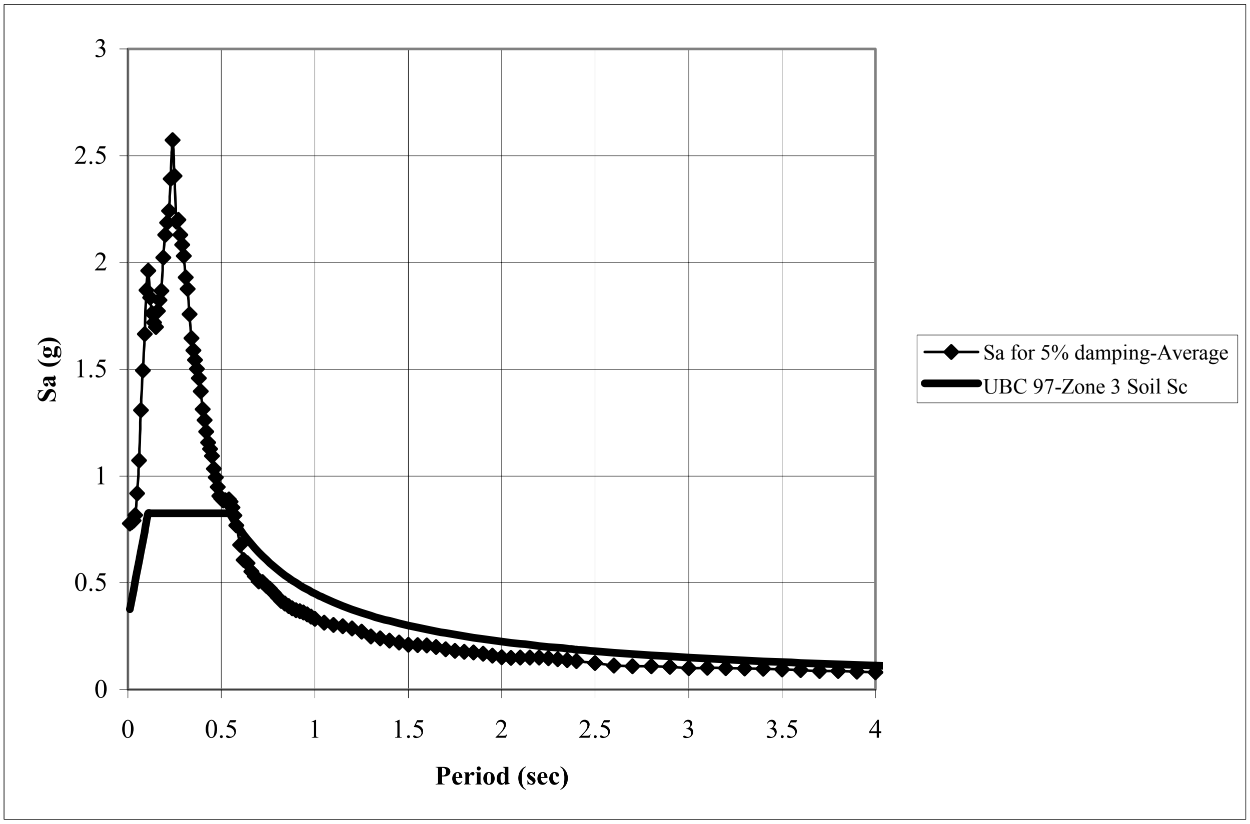


(a) Artificial ground motions

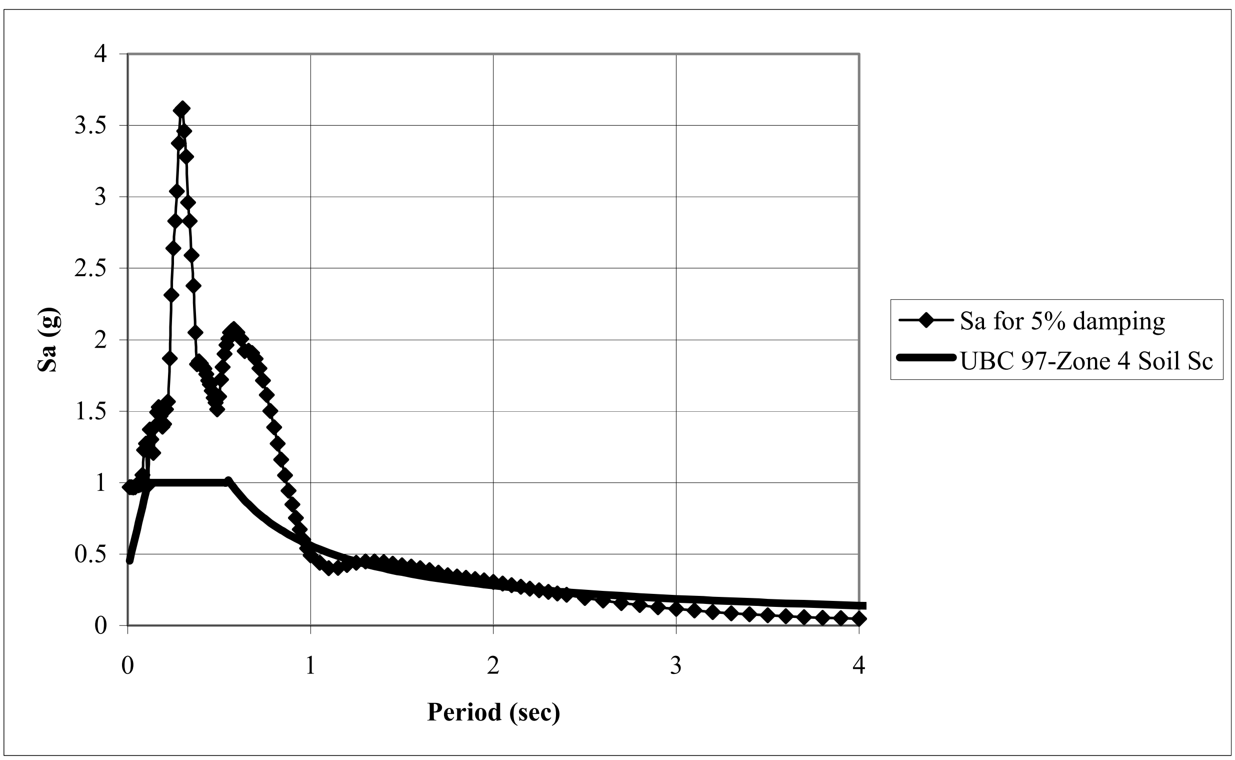


(b) El Salvador earthquake

Figure 5.20: Response spectrum at surface of the Maní site from analyses and UBC 97 design spectrum.

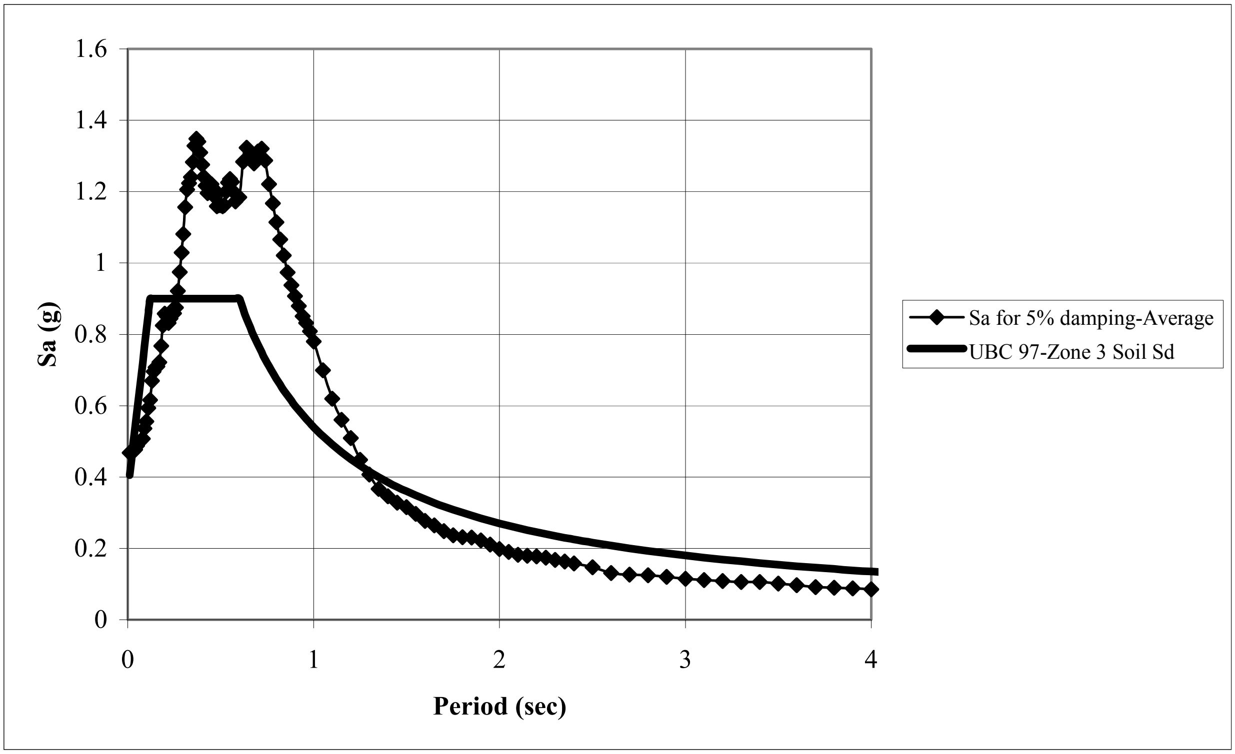


(a) Artificial ground motions

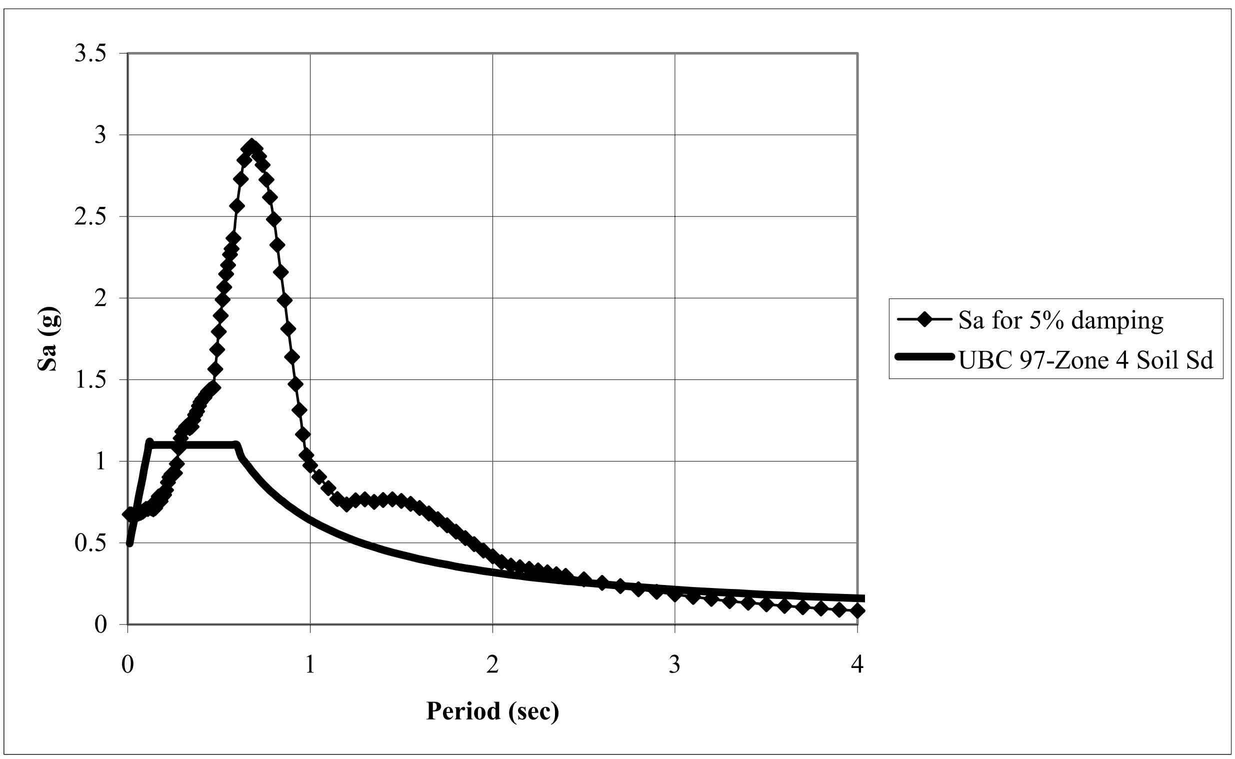


(b) El Salvador earthquake

Figure 5.21: Ground response spectrum at surface of the Biología site from analyses and UBC 97 design spectrum.

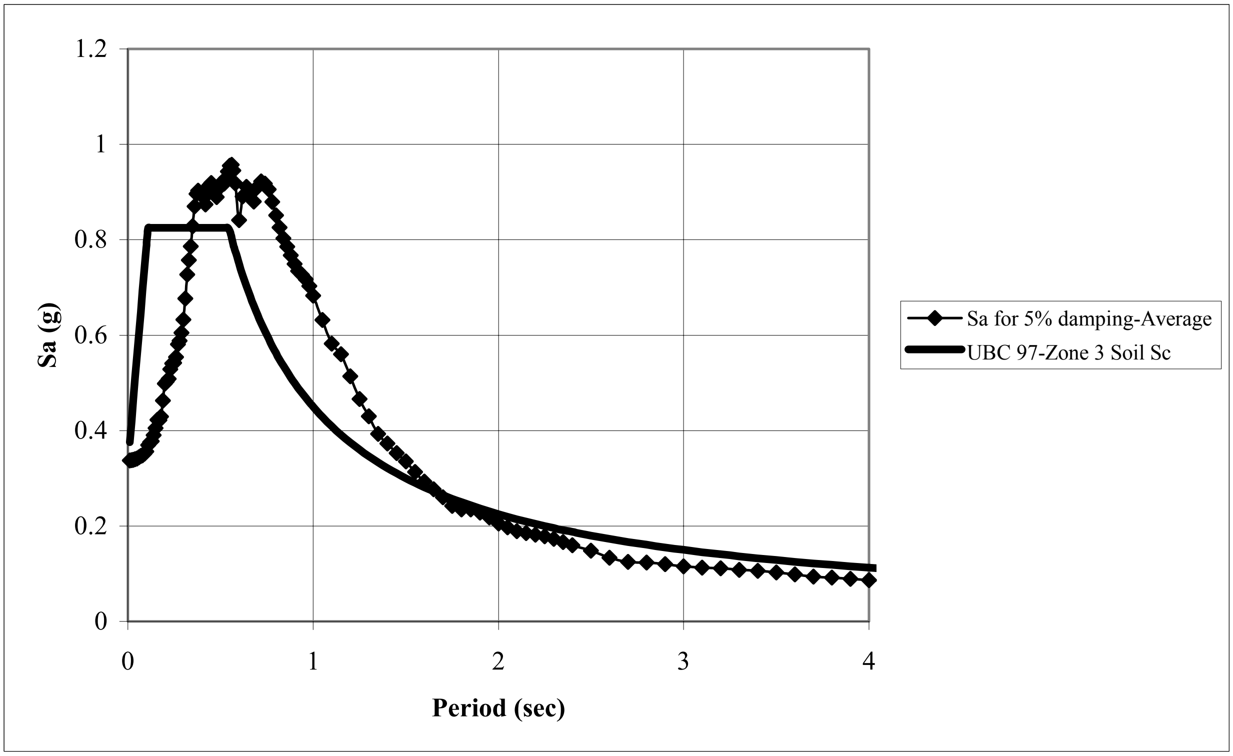


(a) Artificial ground motions

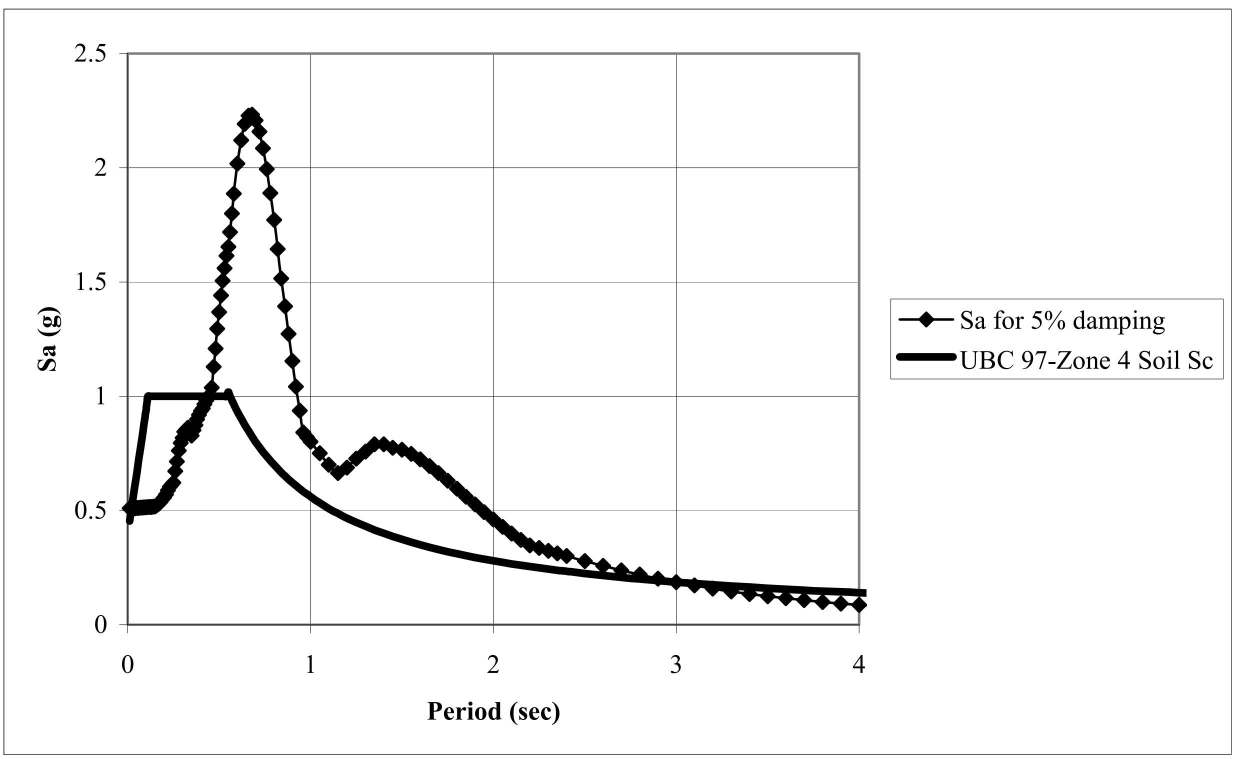


(b) El Salvador earthquake

Figure 5.22: Response spectrum at surface and of the Viaducto site from analyses and UBC 97 design spectrum.



(a) Artificial ground motions



(b) El Salvador earthquake

Figure 5.23: Response spectrum at surface of the Civil site from analyses and UBC 97 design spectrum.

5.6.2 *Results for Group B*

The ground response analysis results for the six sites in Group B are presented in this section. The sites in this group have shear wave velocity information but no nearby geotechnical boring logs. All sites in Group B classified as NEHRP class S_d. Table 5.8 shows the fundamental period of the soil deposit and the peak acceleration at the surface for the linear and non linear cases obtained with the artificial ground motions. The quantities listed in Table 5.8 are the arithmetic average of the four individual results for the artificial ground motions. The results obtained from the El Salvador earthquake for Group B sites are listed in Table 5.9. More details of these analyses can be found in Perez (2005).

It can be observed from these tables that for this group the seismic accelerations prescribed at the surface by the UBC-97 are comparable to the values obtained from the site specific analyses. The exception is the Highway 341 site, which as mentioned before is located within the Añasco river valley and is consists of a thick alluvial deposit. The greater amplifications computed for this site are as expected given the local site conditions that included a thick deposit of low shear wave velocity soils with a longer site period closer to the periods of the input ground motions. Large amplifications were also computed when using the El Salvador earthquake, as shown in Table 5.9.

Figures 5.24 through 5.29 show the ground response spectrum for a 5% damping ratio at the surface of each site obtained with the acceleration time history computed at the surface. The average ground response spectrum curves for the artificial ground motions are presented and compared with the UBC-97 design spectrum for seismic Zone 3 for the corresponding NEHRP soil profile classification in Figures 5.24(a) to 5.29(a). Figures 5.24(b) to 5.29(b) display similar results but for the 1986 El Salvador earthquake. In this case results are compared with the UBC-97 design spectrum for Zone 4.

Table 5.8: Summary of average results for Group B subjected to artificial ground motions.

Site ID	$\bar{V}_s$ [a] m/s	UBC-97	T_s [b] (linear) Sec	T_s [b] (non linear) sec	UBC-97 [c] Acc. g	Max. Acc. [d] (non linear) g
341HWY	203	Sd	0.62	0.72	0.36	0.57
Maní Park	275	Sd	0.31	0.39	0.36	0.32
Seco Park	244	Sd	0.44	0.66	0.36	0.27
Isidoro García	211	Sd	0.44	0.63	0.36	0.28
Ramírez de Arrellano	244	Sd	0.36	0.52	0.36	0.36
Sultanita	272	Sd	0.78	1.34	0.36	0.28

a. Represents an average wave velocity in upper 30m (100ft) as defined in UBC-97.

b. Soil periods (Ts) are average values for the four artificial ground motions.

c. UBC-97 ground acceleration for seismic zone 3 (seismic coefficient Ca).

d. The maximum accelerations (Max. Acc.) reported are the average values at the surface of the soil deposit.

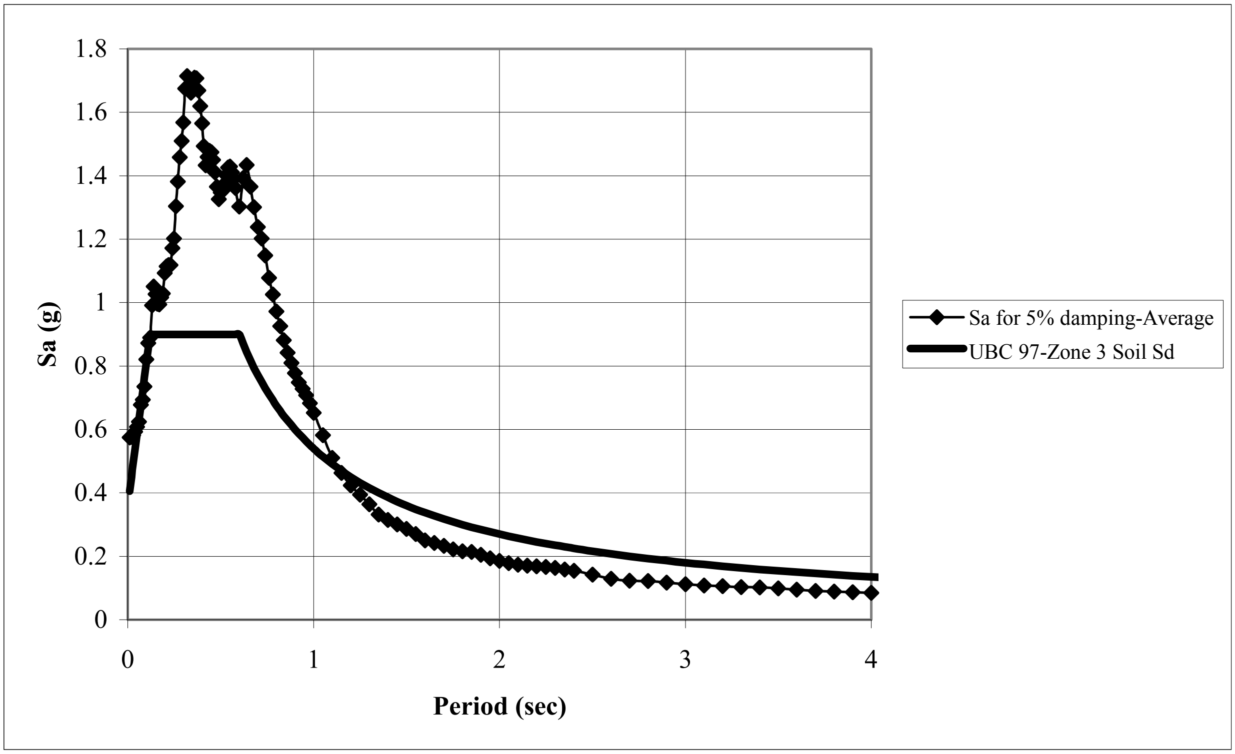
Table 5.9: Summary of results for Group B sites subjected to the El Salvador earthquake record.

Site ID	$\bar{V}_s$ [a] m/s	UBC-97	T_s [b] (linear) sec.	T_s [b] (non linear) sec.	UBC-97 [c] Acc. g	Max. Acc. (non linear) g
341HWY	203	Sd	0.62	0.86	0.44	0.62
Maní Park	275	Sd	0.31	0.43	0.44	0.44
Seco Park	244	Sd	0.44	0.77	0.44	0.34
Isidoro García	211	Sd	0.44	0.76	0.44	0.40
Ramírez de Arrellano	244	Sd	0.36	0.63	0.44	0.34
Sultanita	272	Sd	0.78	1.91	0.44	0.45

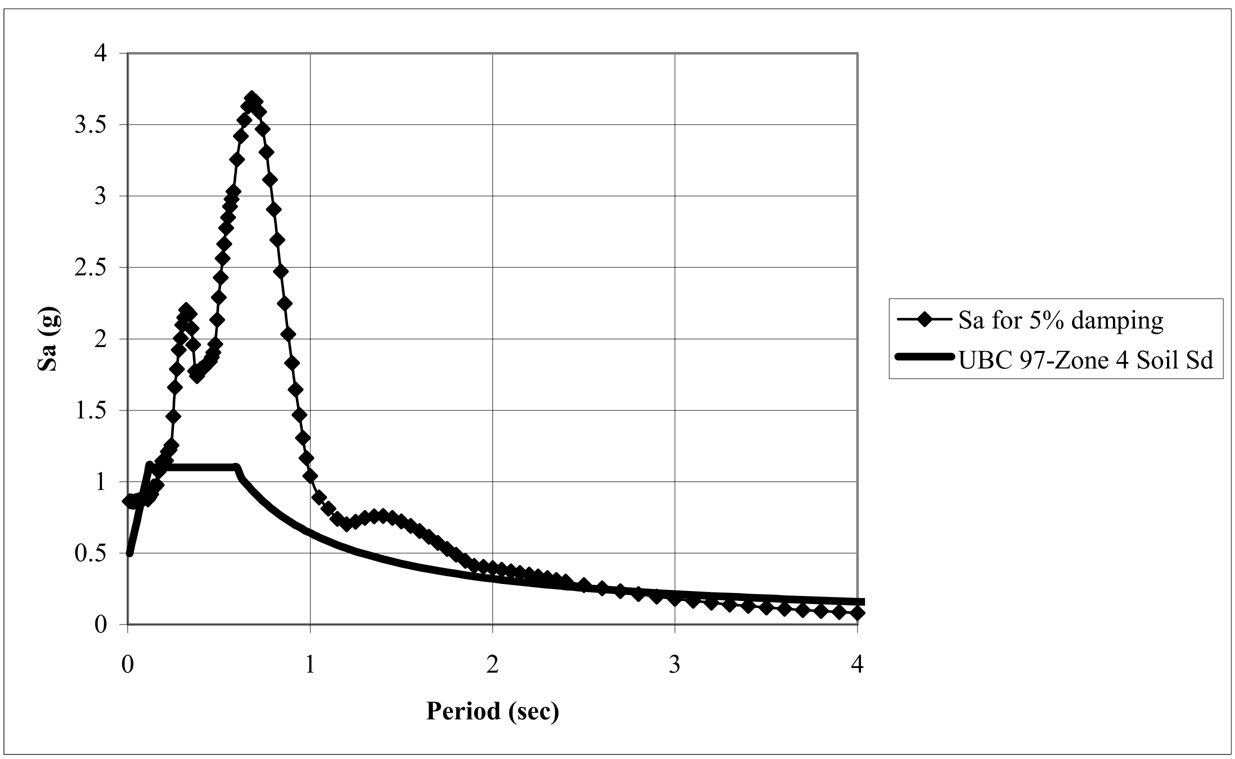
a. Represents an average wave velocity in upper 30m (100ft) as defined in UBC-97.

b. Soil periods (Ts) are average values for the four artificial ground motions.

c. UBC-97 ground acceleration for seismic zone 4 and near source factor Na = 1.0 (seismic coefficient Ca).

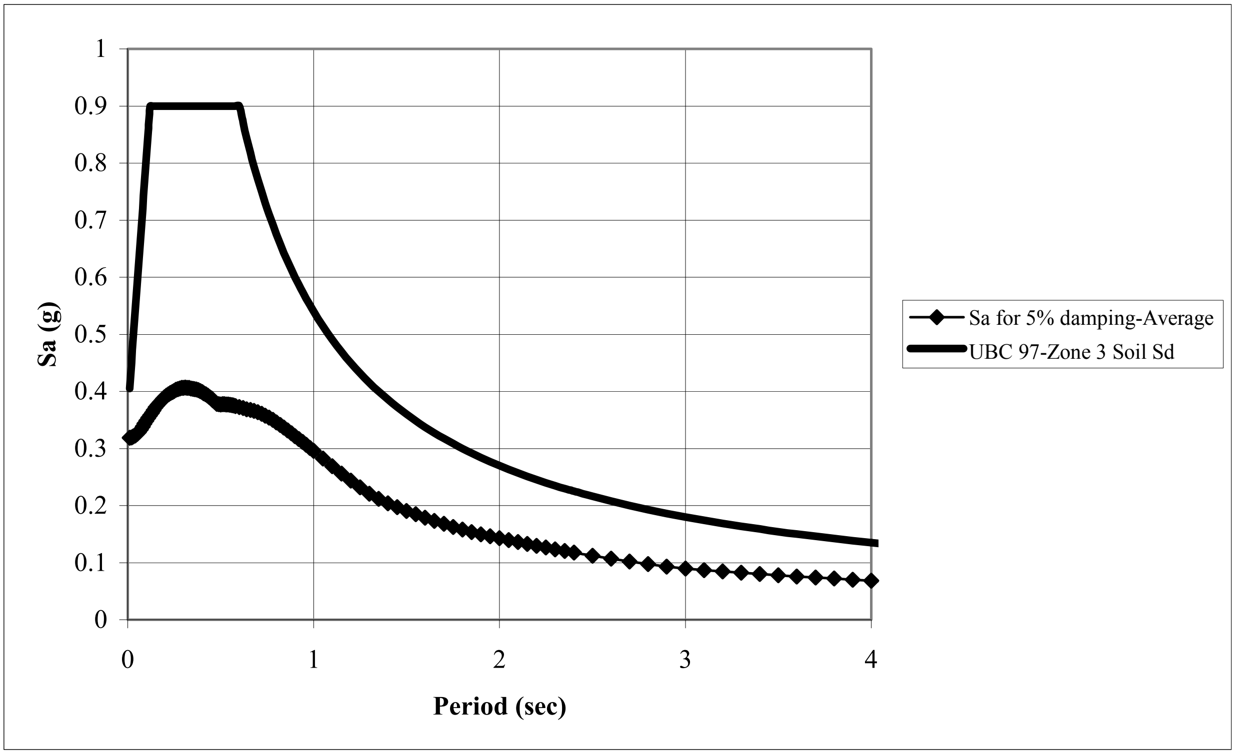


(a) Artificial ground motions

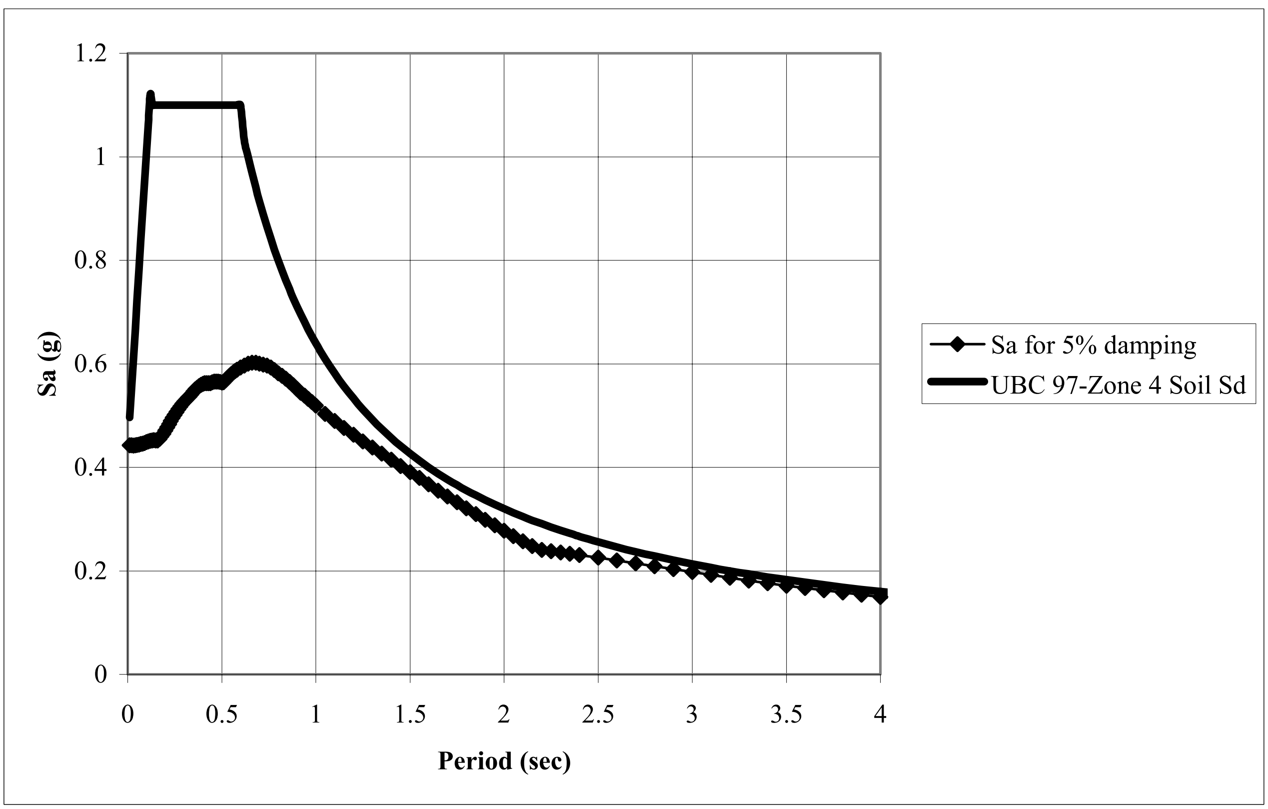


(b) El Salvador earthquake

Figure 5.24: Response spectrum at surface of the 341HWY site from analyses and UBC 97 design spectrum.

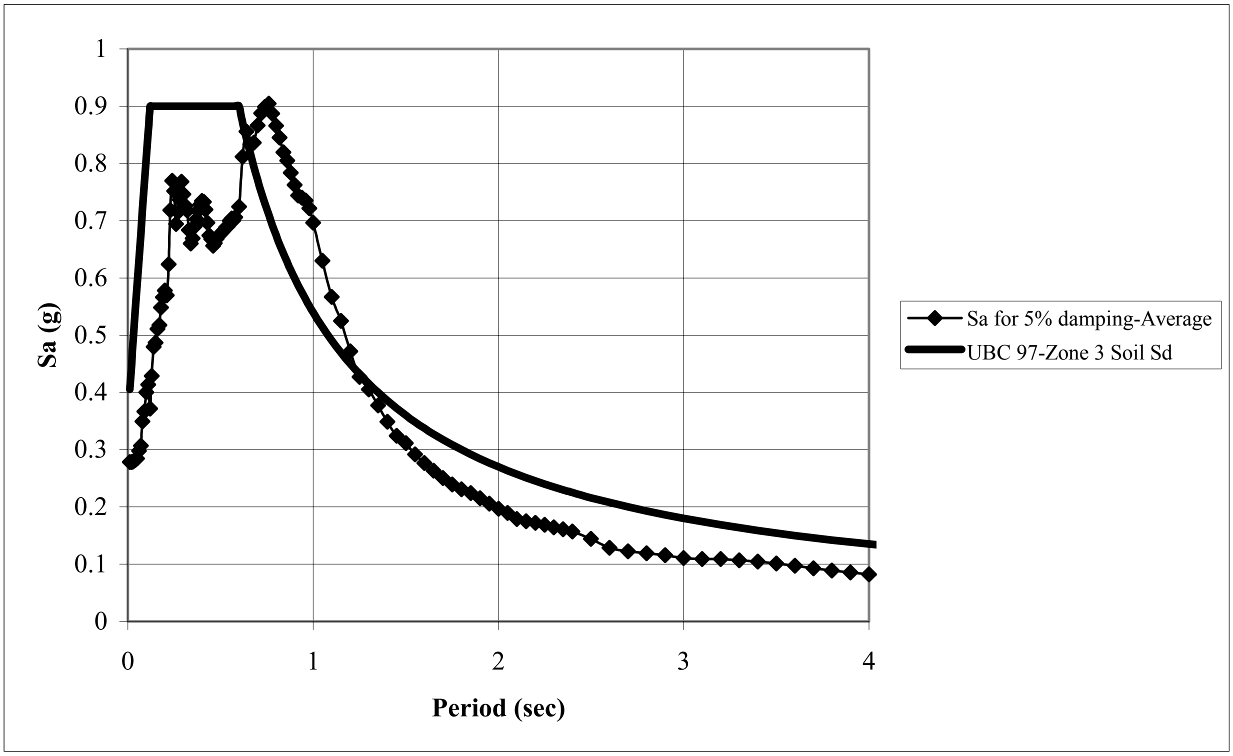


(a) Artificial ground motions

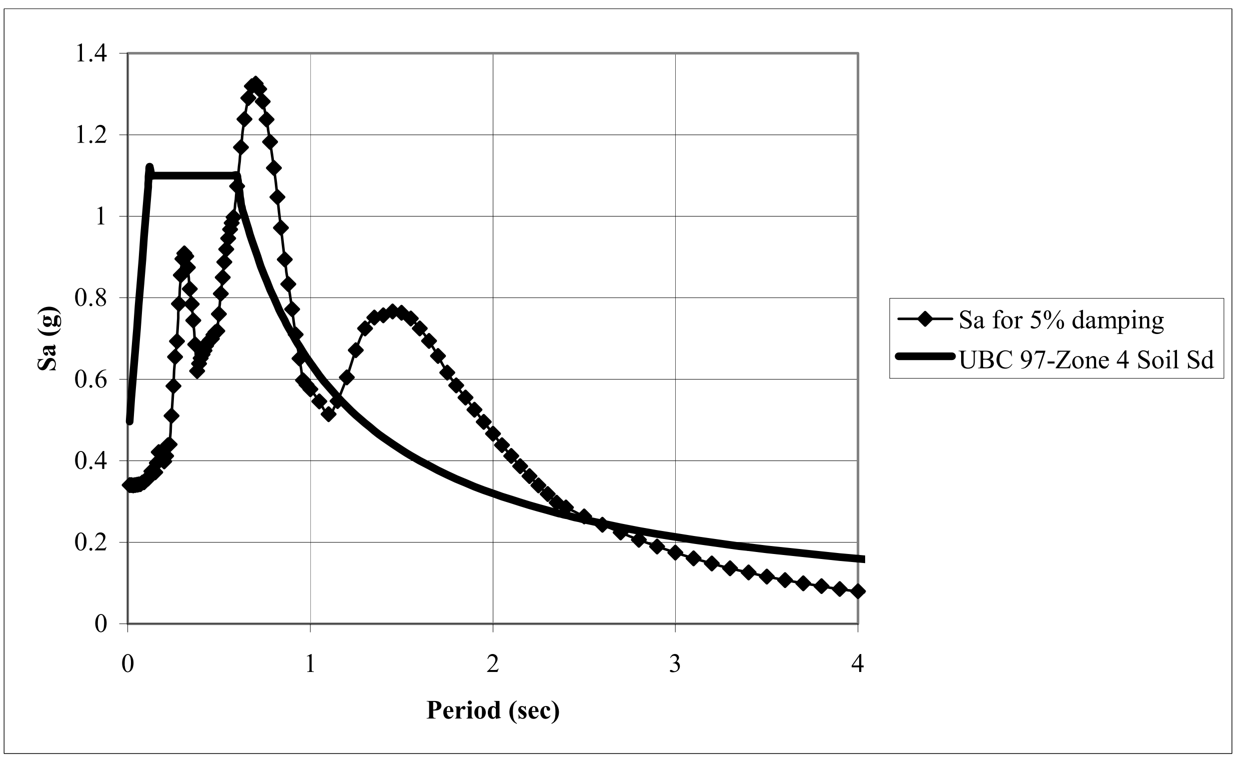


(b) El Salvador earthquake

Figure 5.25: Response spectrum at surface of the Maní Park site from analyses and UBC 97 design spectrum.

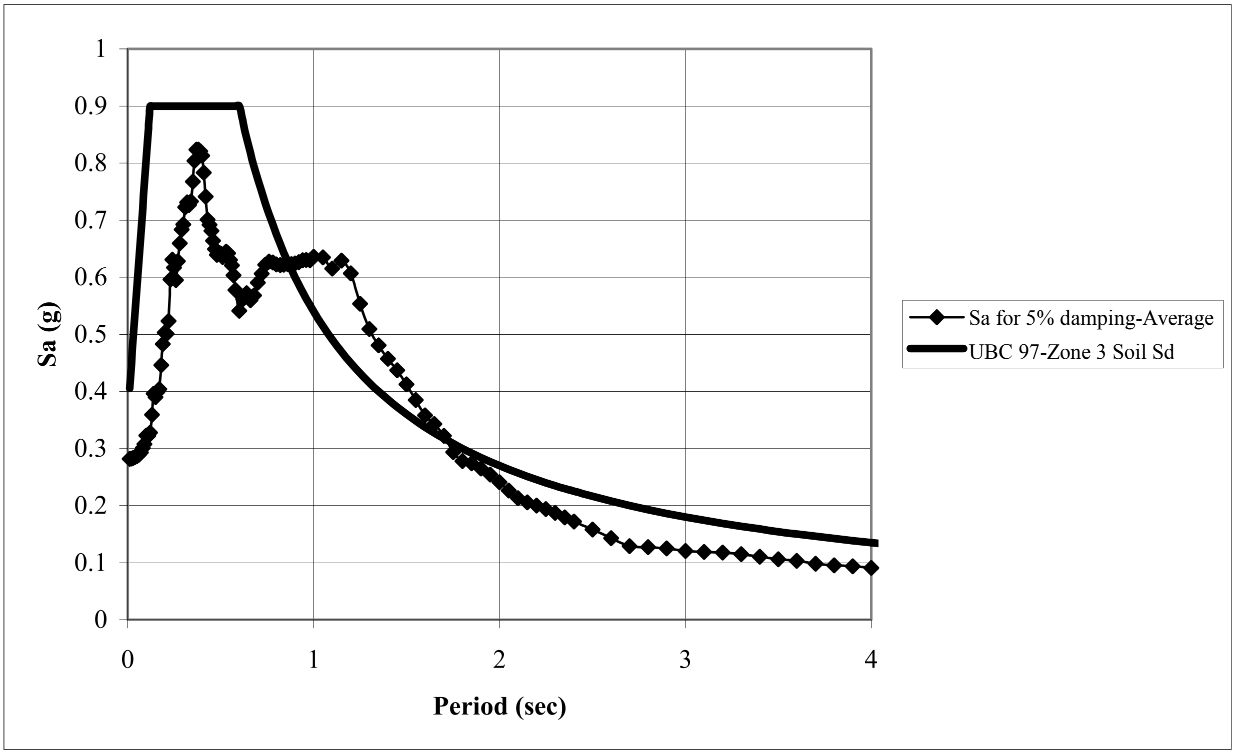


(a) Artificial ground motions

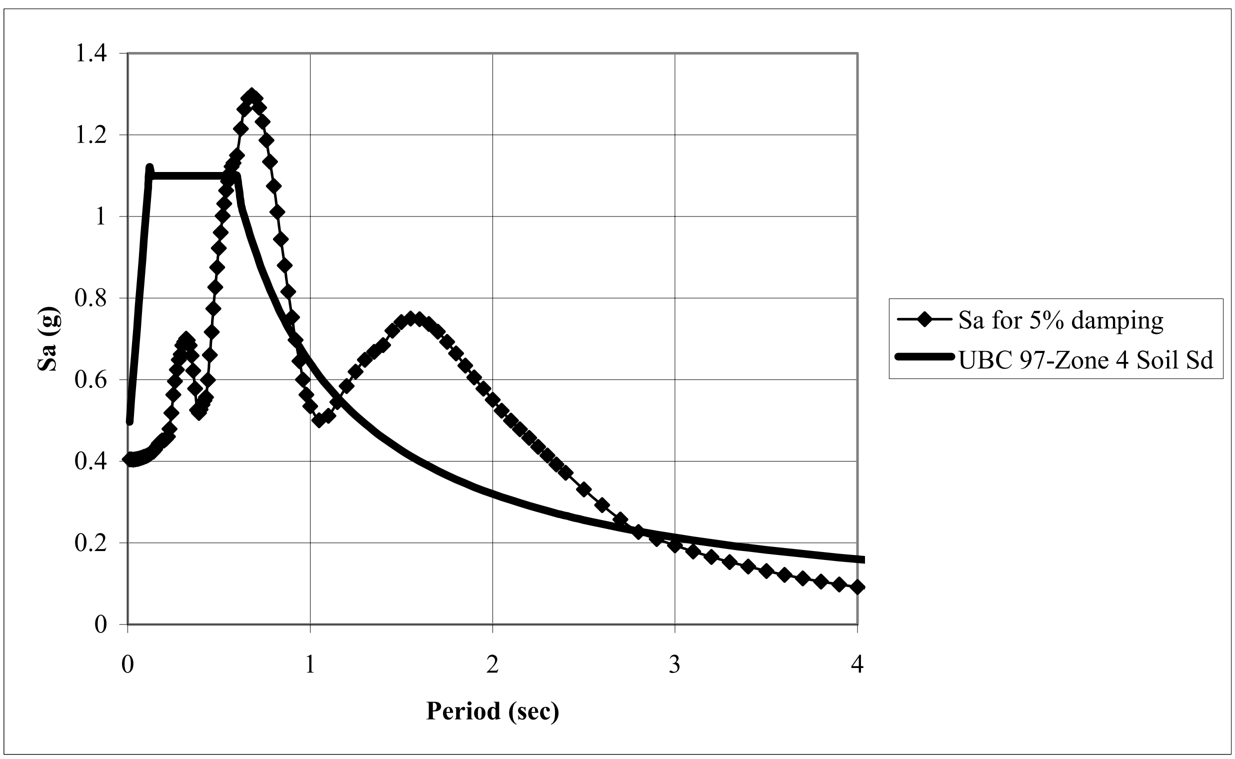


(b) El Salvador earthquake

Figure 5.26: Response spectrum at surface of the Seco Park site from analyses and UBC 97 design spectrum.

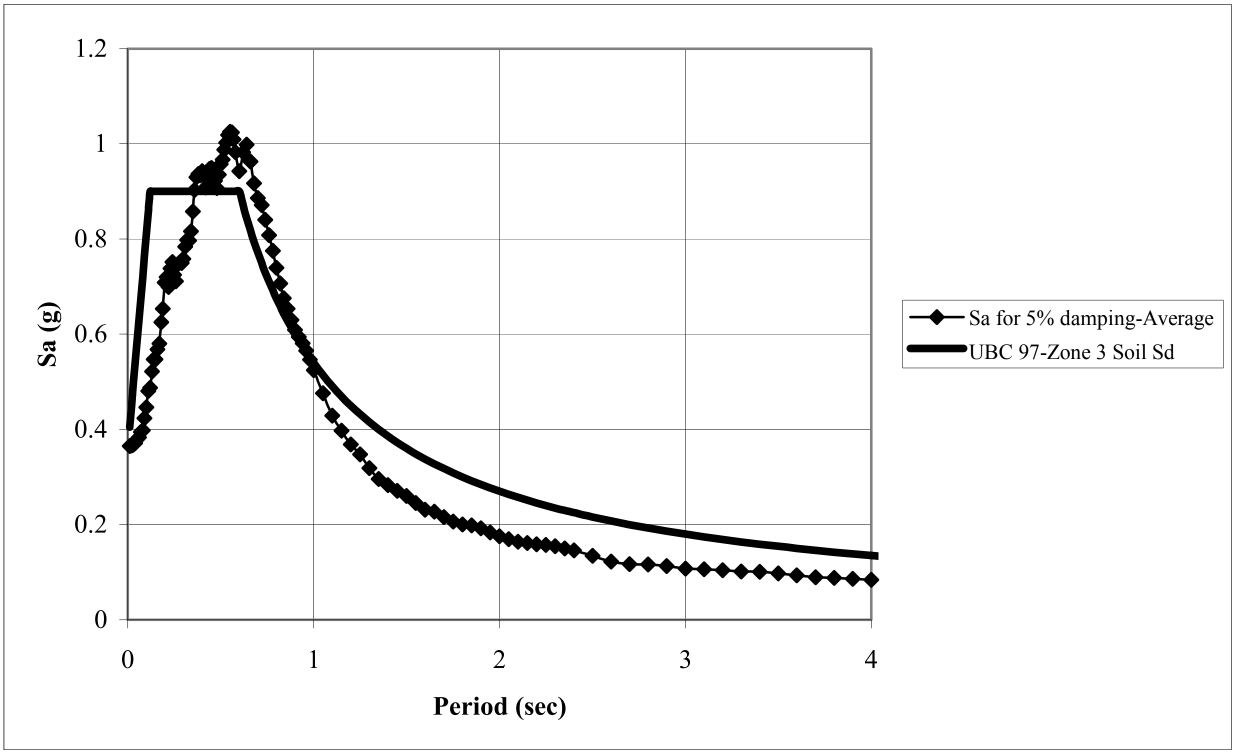


(a) Artificial ground motions



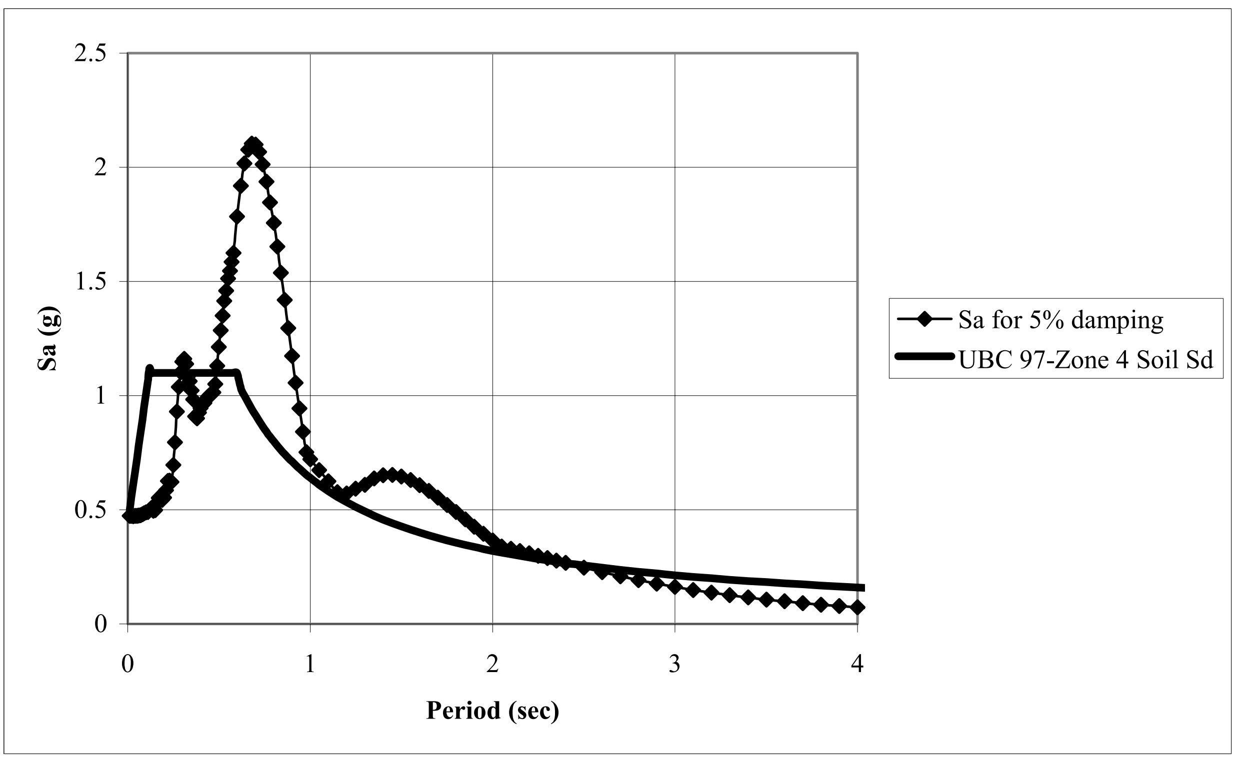
(b) El Salvador earthquake

Figure 5.27: Response spectrum at surface of the Isidoro García site from analyses and UBC 97 design spectrum.



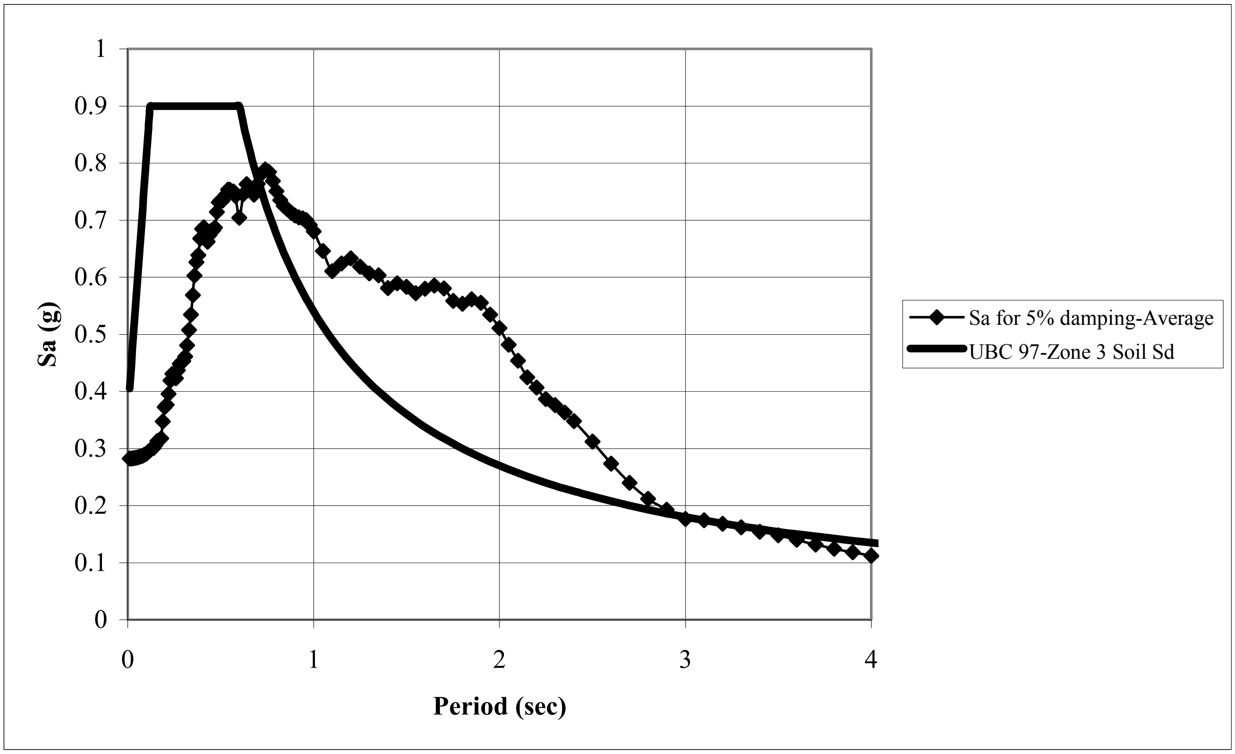
\

(a) Artificial ground motions

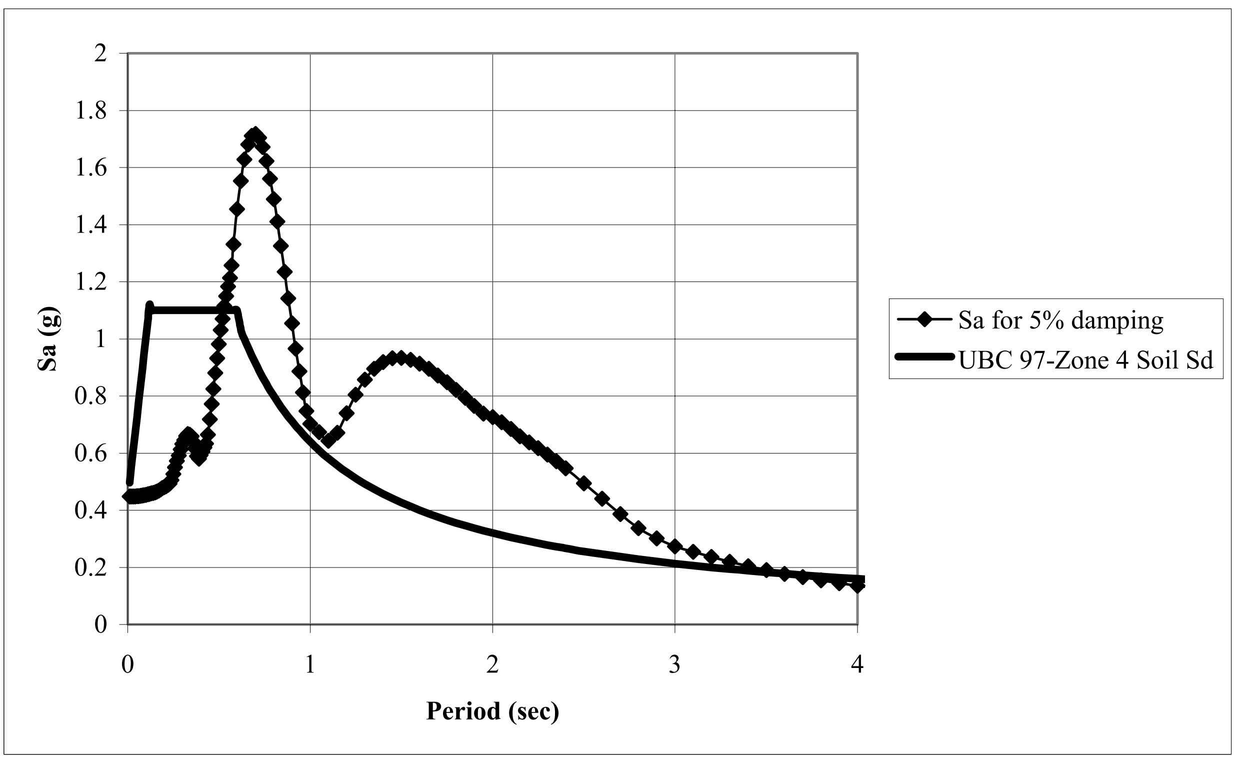


(b) El Salvador earthquake

Figure 5.28: Response spectrum at surface of the Ramírez de Arellano site from analyses and UBC 97 design spectrum.



(a) Artificial ground motions



(b) El Salvador earthquake

Figure 5.29: Response spectrum at surface of the Sultanita site from analyses and UBC 97 design spectrum.

5.6.3 *Results for Sites of Group C*

This section presents the results for the four sites assigned to Group C. Group C sites correspond to sites where only geotechnical information from boring logs was available and the shear wave velocity profiles had to be estimated using correlations with SPT N values or CPT data (if available). The Group C included one site with NEHRP class S_c (El Castillo), one S_d (El Bosque), and two S_e (the India Brewery and the Marina). Tables 5.10 and 5.11 summarize the results in terms of soil fundamental periods and peak accelerations at the surface obtained with the artificial ground motions and from El Salvador earthquake, respectively. These sites were quite thick and combined with the estimated very low average shear wave velocities resulted in long site periods. Therefore high amplifications were computed for these sites, particularly compared to sites from previous groups. Further site characterization is recommended at these sites to confirm these findings More details of these ground motion analyses can be found in Perez (2005).

Figures 5.30 through 5.33 show for each of the four sites of Group C the ground response spectra at the surface for the artificial ground motions and for the 1986 El Salvador earthquake record. The response spectra were computed with the acceleration time histories from the equivalent linear analyses performed. The ground response spectra, from the four input artificial ground motions, are presented as an average in Figures 5.30(a) to 5.33(a). The ground response spectra for the EL Salvador Earthquake for the four sites are shown in Figures 5.30(b) through 5.33(b).

Table 5.10: Summary of average results for Group C sites subjected to artificial ground motions.

Site ID	$\bar{V}_s$ [a] m/s	UBC-97	T_s [b] (linear) sec	T_s [b] (non linear) sec	UBC-97[c] Acc. g	Max. Acc.[d] (non linear) G
El Bosque	242	Sd	0.47	0.63	0.36	0.46
El Castillo	423	Sc	0.27	0.45	0.33	0.42
India	145	Se	0.39	0.59	0.36	0.35
Marina	173	Se	0.53	0.76	0.36	0.31

a. Represents an average wave velocity in upper 30m (100ft) as defined in UBC-97.

b. Soil periods (Ts) are average values for the four artificial ground motions.

c. UBC-97 ground acceleration for seismic zone 3 (seismic coefficient Ca).

d. The maximum accelerations (Max. Acc.) reported are the average values at the surface of the soil deposit.

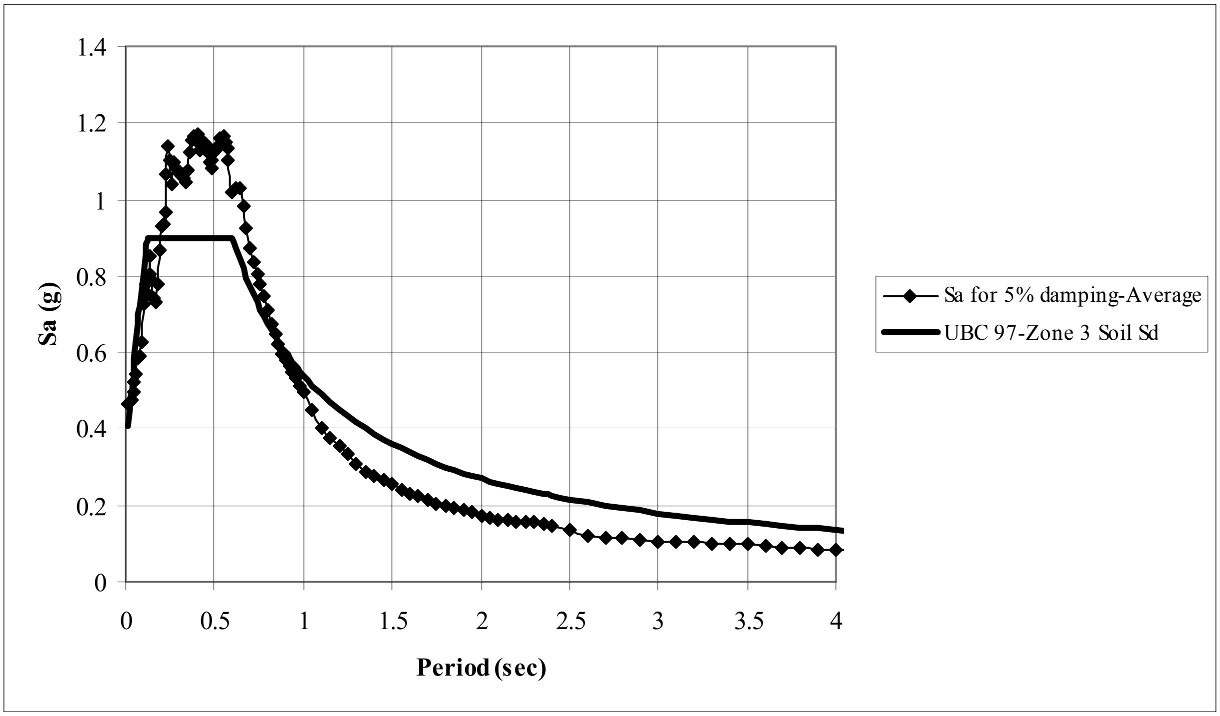
Table 5.11: Summary of results for Group C sites subjected to the El Salvador earthquake record.

Site ID	$\bar{V}_s$ [a] m/s	UBC-97	T_s [b] (linear) sec.	T_s [b] (non linear) sec.	UBC-97[c] Acc. g	Max. Acc. (non linear) g
El Bosque	242	Sd	0.47	0.72	0.44	0.51
El Castillo	423	Sc	0.27	0.58	0.40	0.58
India	145	Se	0.39	0.76	0.36	0.39
Marina	173	Se	0.53	0.83	0.36	0.37

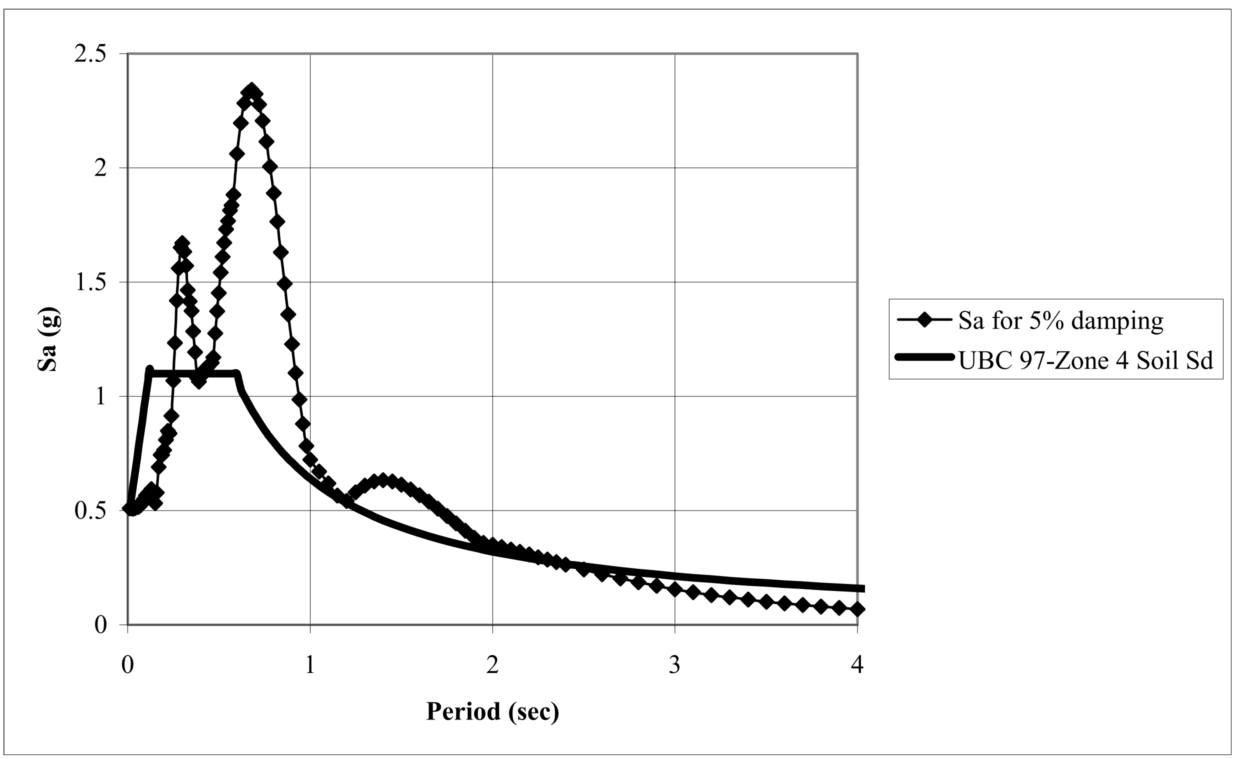
a. Represents an average wave velocity in upper 30m (100ft) as defined in UBC-97.

b. Soil periods (Ts) are average values for the four artificial ground motions.

c. UBC-97 ground acceleration for seismic zone 4 and near source factor Na = 1.0 (seismic coefficient Ca).

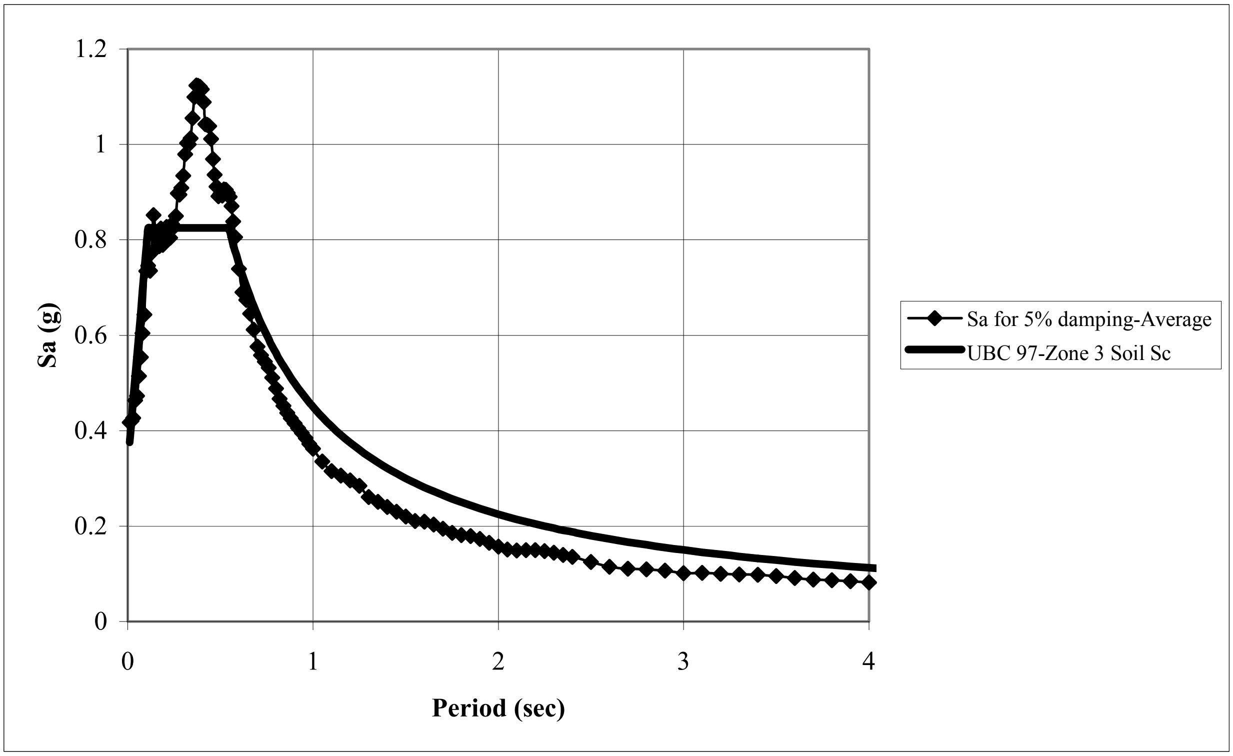


(a) Artificial ground motions

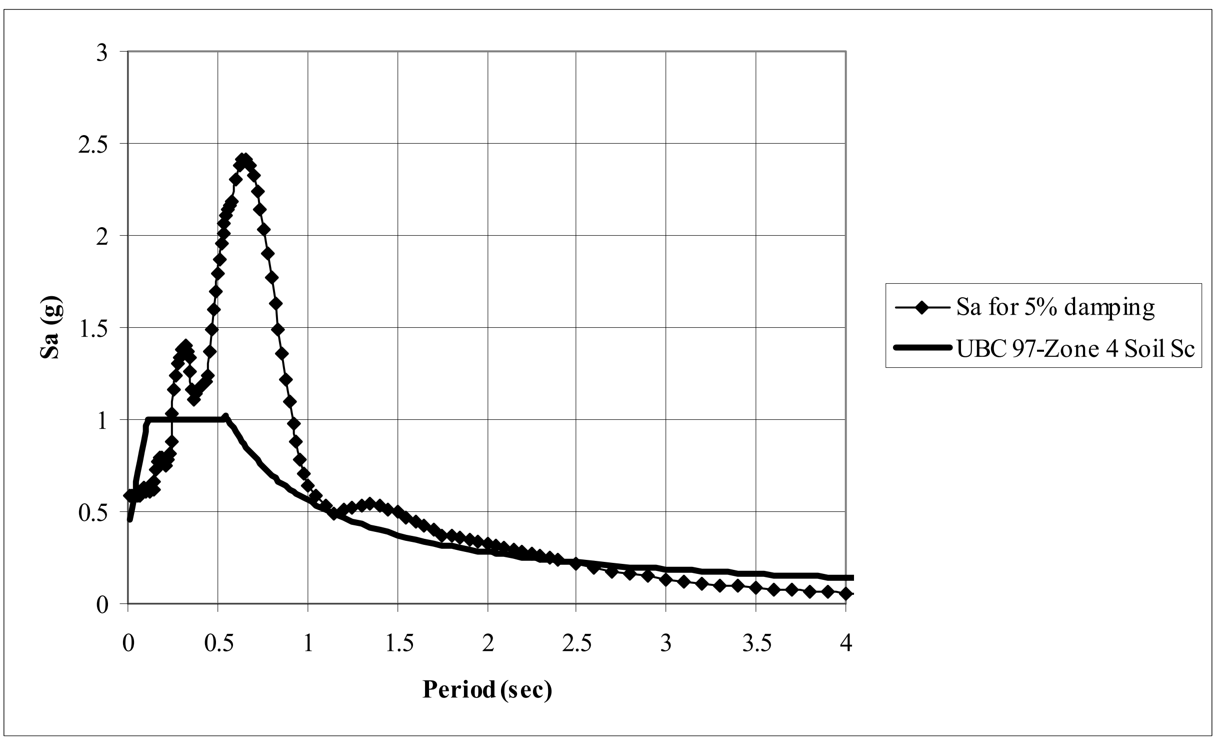


(b) El Salvador earthquake

Figure 5.30: Response spectrum at surface of the El Bosque site from analyses and UBC 97 design spectrum.

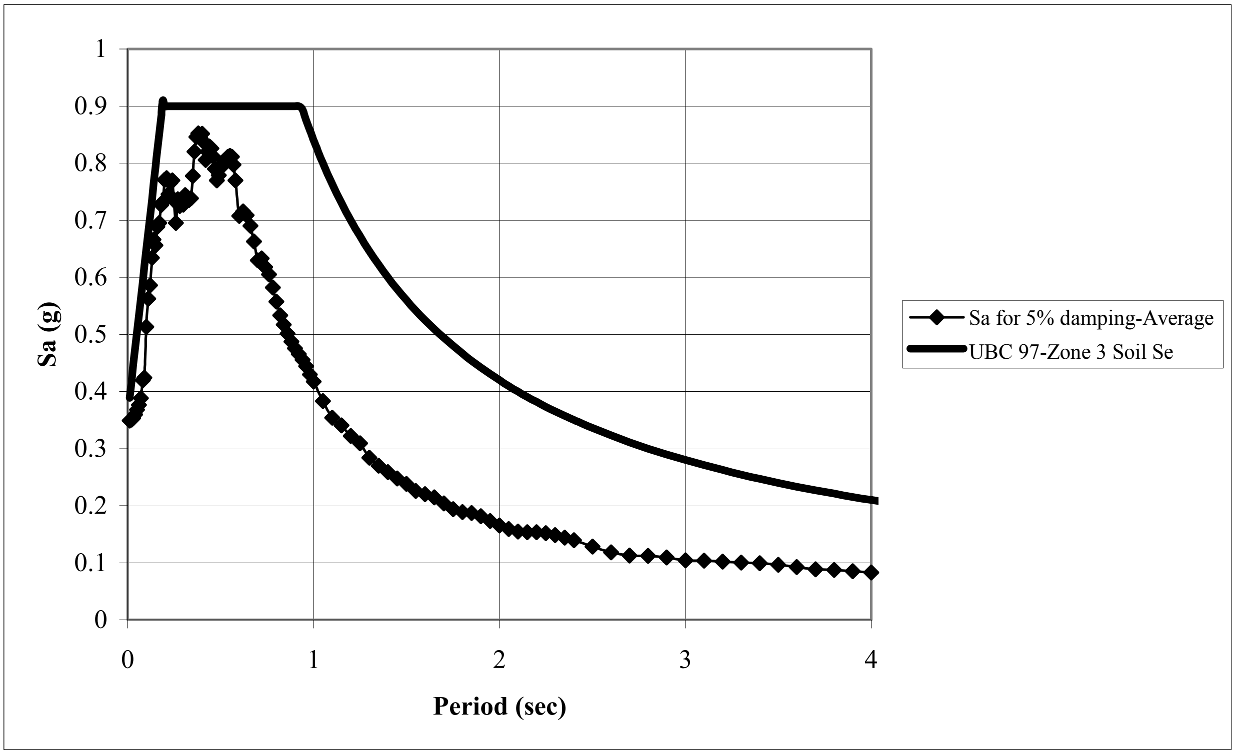


(a) Artificial ground motions

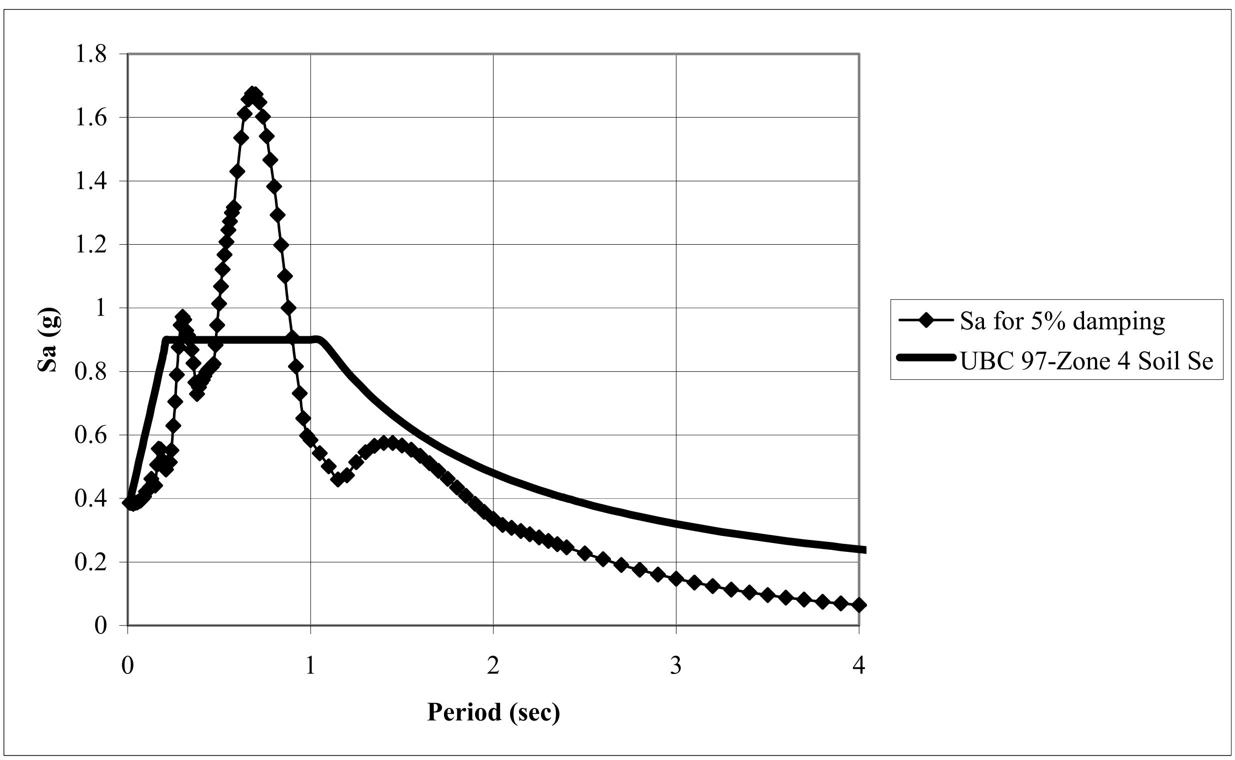


(b) El Salvador earthquake

Figure 5.31: Response spectrum at surface for the El Castillo site from analyses and UBC 97 design spectrum.

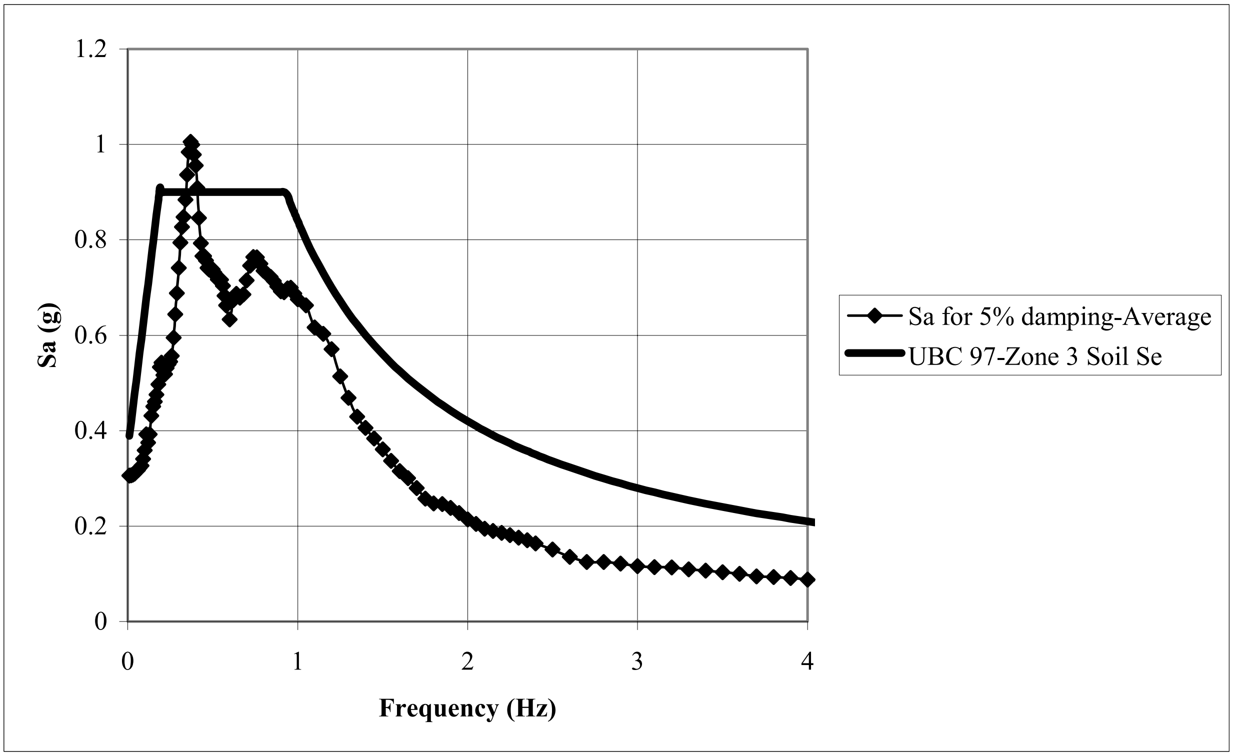


(a) Artificial ground motions

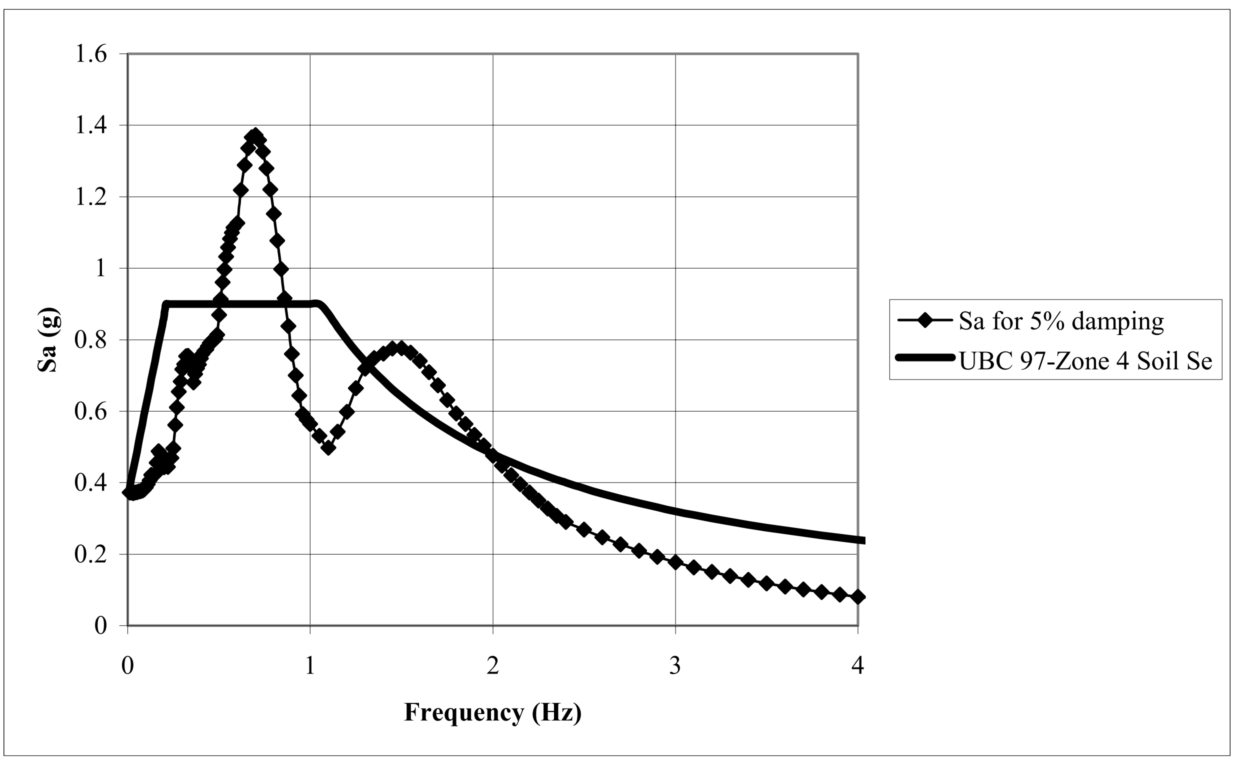


(b) El Salvador earthquake

Figure 5.32: Response spectrum at surface of the India site from analyses and UBC 97 design spectrum.



(a) Artificial ground motions

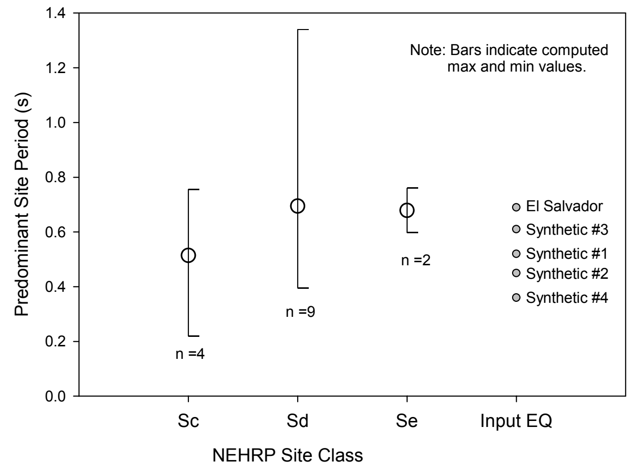


(b) El Salvador earthquake

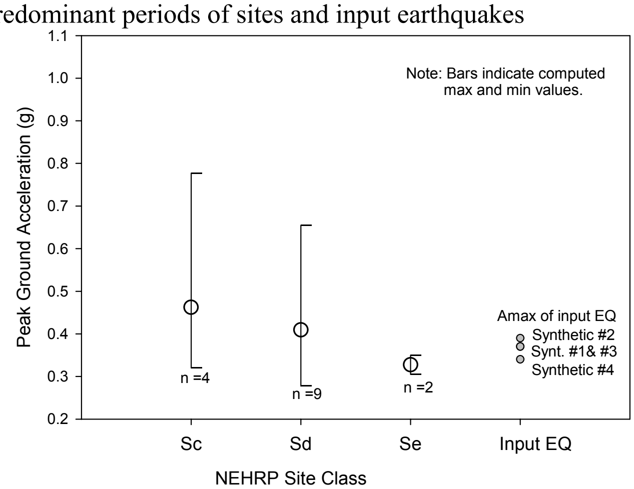
Figure 5.33: Response spectrum at surface of the Marina site from analyses and UBC 97 design spectrum.

5.7 *Summary of Ground Response Analyses*

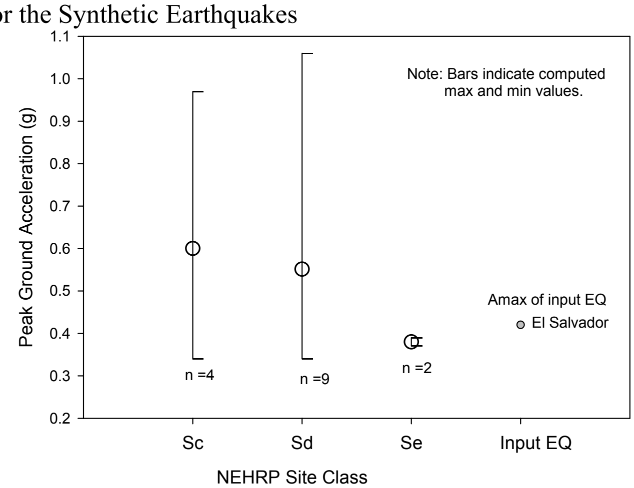
Ground response analyses were carried out for fifteen sites in Mayagüez. The sites were divided into three groups types (A, B, and C) depending on the amount of information available for each site. Group A consisted of sites that had the best quality of data (i.e., had both shear wave velocity and geotechnical borehole data). Group B sites had shear wave velocity data but no geotechnical borehole information, hence limiting somewhat our ability to define the soil types in each profile. Finally, Group C sites consisted of sites that only had conventional geotechnical information and no shear wave velocity data was available. Group A had 5 sites (Abonos, Class Sd; Mani, Class Sc; Biology, Class Sc; Viaducto, Class Sd; and Civil, Class Sc), Group B had 6 sites all NHERP Class Sd (Hwy 341, Mani Park, Seco Park, Isidoro Park, Ramirez de Arellano, and Sultanita), and Group C had 4 sites (El Bosque, Class Sd; El Castillo, Class Sc; La India Brewery, Class Se, and La Marina, Class Se). The interpretation of the results must take into account the group of each site as well as its NEHRP site class. Figure 5.34 shows plots summarizing the peak ground accelerations obtained at the ground surface of all the sites analyzed for the two types of input ground motions used. Figure 5.34(a) shows the site periods averages for the three NEHRP site types analyzed. For comparison purposes this figure also shows the predominant periods of the synthetic records and the El Salvador earthquake. As expected the NEHRP sites class Se had longer site periods since they consisted of thicker deposits and the soils units had lower shear wave velocity values. This figure also show the synthetic earthquakes having predominant periods closer to sites Sc, while the El Salvador earthquake has a period closer to sites in Se. Figure 5.34(b) shows the average PGA values computed when using the synthetic earthquakes as input. This figure shows larger PGA values for sites of Class Sc. This result could be related to the similarity of the input earthquake periods and the periods for the Sc sites. Figure 5.34(c) shows PGA values computed when using the El Salvador earthquake as input. For this case the larger PGA values are also computed for the Sc sites. Here the periods of the Sc sites are not as close as the input ground motion. The sites Se continue to have the lowest PGA values. In both sets of analyses the Se sites show deamplification. It is worth pointing out that 3 Sc sites are in Group A so these analyses could be considered more reliable than the analyses for the 2 Se sites which both belong to Group C. Further analyses are recommended to confirm the trends found in these analyses. The influence of bedrock depth in the modeling needs also needs to be investigated.



a) Summary of predominant periods of sites and input earthquakes



b) PGA values for the Synthetic Earthquakes

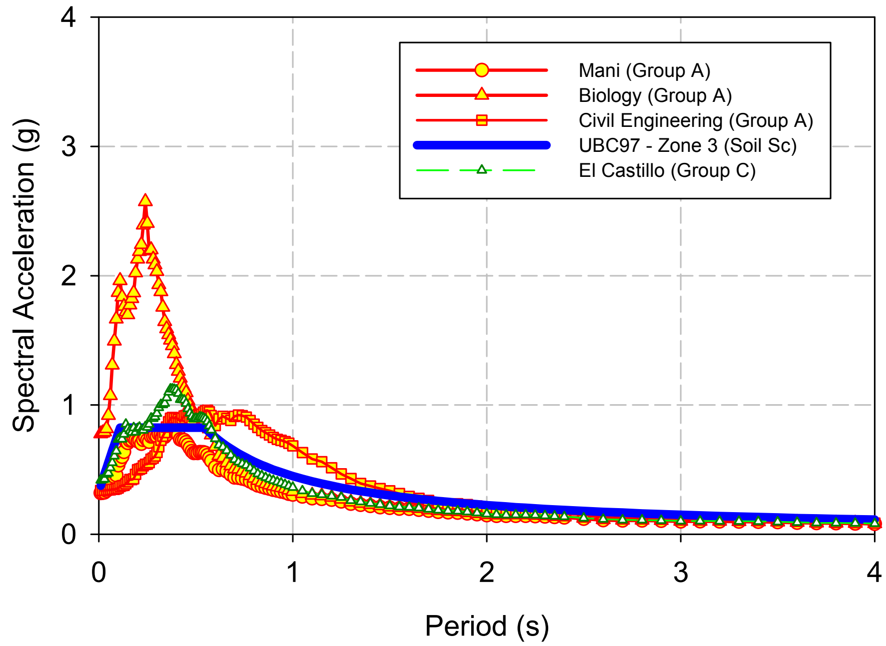


c) PGA values for the El Salvador Earthquake

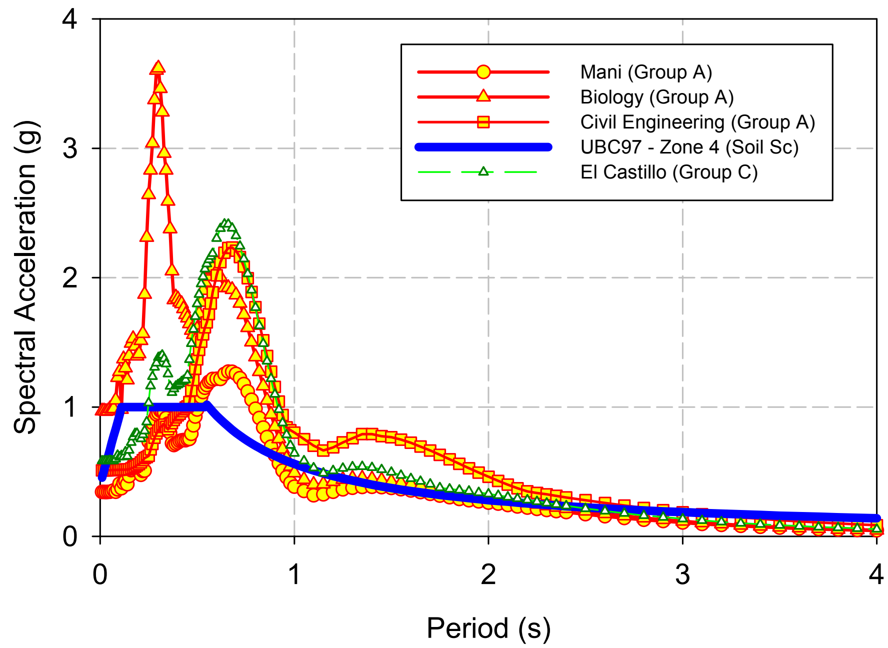
Figure 3.34 Summary of PGA values computed for Mayagüez

The peak ground accelerations recommended by UBC-97 for Zone 3 are 0.33 g, 0.36 g, and 0.36 g for NEHRP sites classes Sc, Sd, and Se, respectively. These values are smaller than predicted with the analyses using the synthetic input ground motions. The same observation can be made for the PGA values recommended by UBC-97 for Zone 4 which are the values comparable to the computations made with the El Salvador earthquake. The UBC-97 recommends for Zone 4 PGA values equal to 0.4 g , 0.44 g, and 0.36 g, for NEHRP site classes Sc, Sd, and Se, respectively.

The average ground response spectra at the ground surface of the sites in NEHRP soils Sc, Sd, and Se are summarized in Figures 5.35 through 5.37, respectively. Each of these figures shows two sets of spectra, one for the synthetic input ground motions and another corresponding to the analyses that used the El Salvador earthquake. The spectra for each site are labeled to identify the Group class of each site so the reader can consider the differences in the quality of the input information for each group type. Figure 5.35 presents the spectra for soil type Sc. In general the response spectra of the Sc sites compared reasonably well with the recommended UBC-97 spectrum for Sc soils. The results with synthetic ground motions showed better agreement than the analyses carried out with the El Salvador earthquake. The analyses obtained with the El Salvador earthquake are compared with the UBC-97 spectrum for Zone 4. The spectral accelerations computed are much higher than the code recommendations for periods about 0.7s which is the predominant period of this earthquake. The largest spectral values are observed for the sites class Sd. The highest spectral accelerations are observed for the Abonos, Hwy 341, Viaducto, and El Bosque sites. The spectra for sites Class Se compare reasonably well with the UBC-97 recommendations. Clearly further research is required in this area in order to assess the validity of the current design spectra and the local site effects in the Mayagüez area.

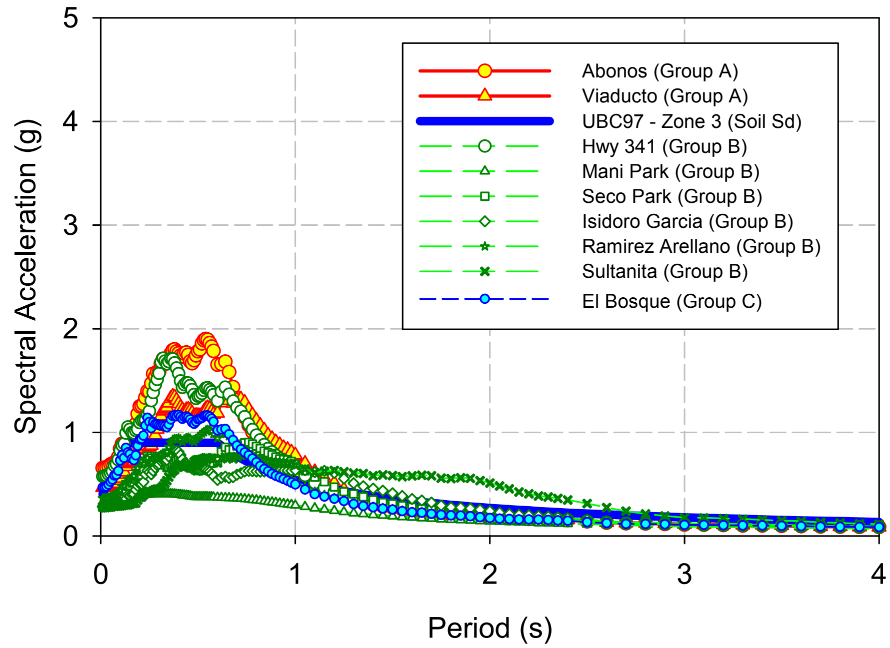


a) Summary of analyses using synthetic earthquakes as input

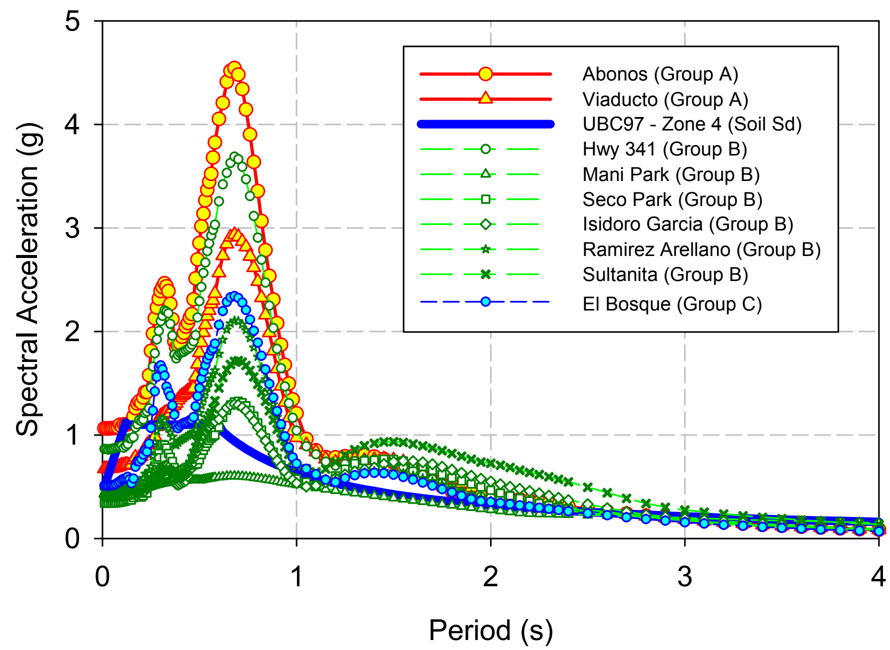


b) Summary of analyses using the El Salvador earthquake as input

Figure 3.35 Summary of ground response spectra for sites classified as Sc

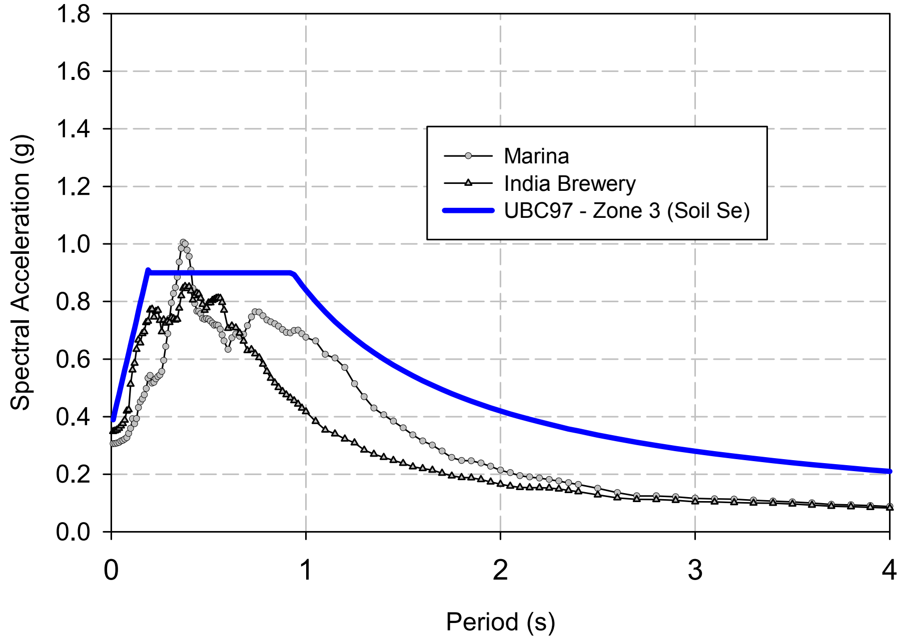


a) Summary of analyses using synthetic earthquakes as input

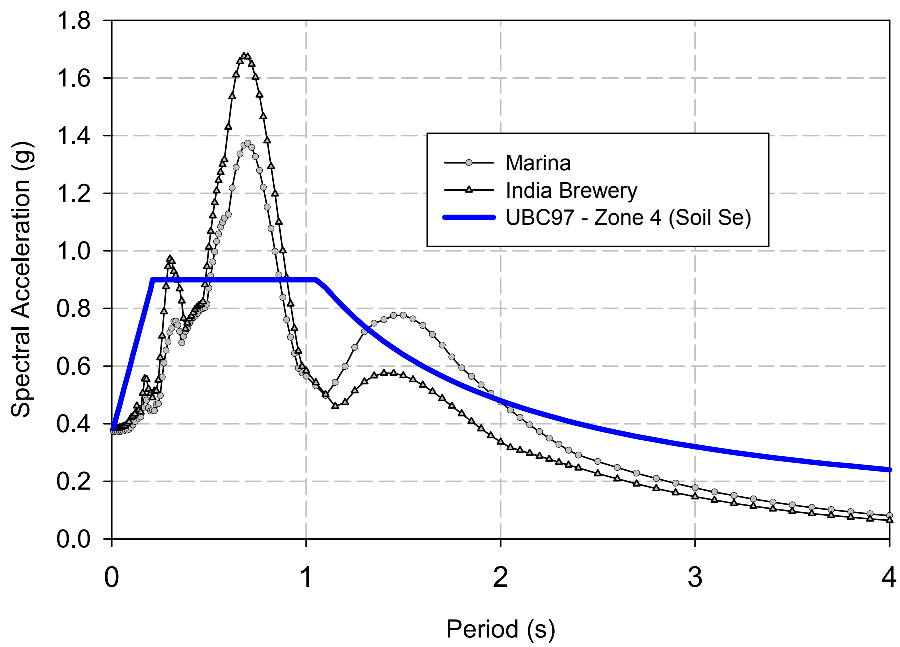


b) Summary of analyses using the El Salvador earthquake as input

Figure 3.36 Summary of ground response spectra for sites classified as Sd



a) Summary of analyses using synthetic earthquakes as input



b) Summary of analyses using the El Salvador earthquake as input

Figure 3.37 Summary of ground response spectra for sites classified as Se

CHAPTER 6 Summary and Conclusions

A detailed geotechnical model (database) of the Mayagüez city was developed using existing geotechnical data gathered from local consulting firms, research papers and reports, and government agencies and complemented with seismic refraction fieldwork. The geotechnical database consisted of a graphical interface developed in the computer program ArcMap© 9.0. The layered model includes an extensive database which allows the users to browse through and append additional information, when available, by means of an easy and effective approach. The importance of the development of this database relies in the fact that it can be used as a planning tool for structural and geotechnical engineers for design purposes and for liquefaction potential screenings. The developed database can also be used for future seismic studies that require inclusion of local site effects.

The database was complemented with geophysical testing which included Seismic Refraction and Spectral Analysis of Surface Waves (SASW) carried out as part of this study. The database also included geophysical data available from other studies.

This study also included ground motion analysis to evaluate seismic ground motions considering typical local site conditions in Mayagüez. Results from the ground response analyses were presented in Chapter 5. Analyses revealed PGA values higher than recommended by current design codes for NEHRP sites class Sc and Se. Similarly, computed ground response spectra also revealed higher spectral accelerations values than those recommended by current design codes. Additional research is strongly recommended in this area. Better site characterization is necessary, particularly related to evaluation of the depth to bedrock and the characteristics of the soil-bedrock interface (shape, diffuse or high contrast, etc), to better quantify seismic ground motions for this region. One major obstacle is the lack of seismic records in this regions which requires the use of estimated records or use of records from other parts of the world with comparable or similar seismic settings.

This study is a first step contributing with information for better seismic analyses in the Mayagüez area. This is believed to be mainly through facilitating access to comprehensive geotechnical and geophysical data for this region. However this study highlights the importance to expand the level of available data. As mentioned above, important knowledge gaps still remaining are depth to bedrock, soil period maps, bedrock/soil contact characteristics, dynamic properties, among other areas that require further research.

REFERENCES

Asencio, E., 1980, *"Western Puerto Rico Seismicity,"* USGS Open File Report 80-192.

Borja, R. I., Chao, H. Y., Montáns, F.J., and Lin C.H. (1999). "Nonlinear Ground Response At Lotung LSST Site", Journal of Goetechnical and Geoenvironmental Engineering, ASCE, Vol. 125 No. 3, pp. 187-197.

Capacete, J.L. and Herrera, A., 1972, *"The 1918 Earthquake: An Engineering Study,"* CIAA (*Colegio de Ingenieros, Arquitectos, y Agrimensores*), Vol. 22, No.1, Puerto Rico.

Colón-Dieppa, E., and Quiñonez-Martínez, F., 1985, *"A Reconnaissance of the Water Resources of the Central Guanajibo Valley, Puerto Rico,"*USGS Water Resources Investigations Report 82-4050, 47 p.

Clinton, J.F., Cua, G., Huérfano, C.V., von Hillebrandt-Andrade, C.G., and Martínez-Cruzado, J., In Press, *"The Current State of Seismic Monitoring in Puerto Rico,"* SSA Seismological Research Letters, *In Press* (Vol. 77), 11 p..

Curet, A.F., 1986, *"Geologic Map of the Mayagüez and Rosario Quadrangles, Puerto Rico,"* Map I-1657, US Geological Survey.

Dames and Moore, 1999, *"Probabilistic Seismic Hazard Analysis of Puerto Rico and Recommended Revisions to the Seismic Coefficients of the ANSI/ASCE 7-95 Standard,"* Puerto Rico Earthquake Commission, 47 p.

Environmental Systems Research Institute, Inc. 1996, "*ArcView GIS,"* 380 New York Street, Redlands, CA 92373-8100.

Environmental Systems Research Institute, Inc. 2004, "*Arc GIS Desktop,"* 380 New York Street, Redlands, CA 92373-8100.

Fernandez, A., 2004, "Seismic Refraction Tests at the UPRM Track Field and the Mayagüez Beach", Internal Report prepared for the PRSMP.

Gelabert, P.A., 1968, *"Engineering Geology of Highway Number 2 Between Aguadilla and Mayagüez, P.R.,"* Boletín de la Academia de Artes y Ciencias de Puerto Rico, Tomo IV-Num. 2, San Juan.

Imai, T. and Yoshimura, Y. (1970). "Elastic Wave Velocity and Dynamics Characteristics of the Soft Ground". Soils and Foundation, Vol. 18, No. 1, pp. 17-22.

Install Shield Software Corporation, 2002, "*DemoShield 7.5,*" 900 National Parkway, Suite 125, Schaumburg, Illinois 60173.

International Conference of Building Officials, 1997, *"1997 Uniform Building Code Volume 2: Structural Engineering Design Provisions"*.

Irizarry Padilla, J., 1999, *"Design Earthquakes and Design Spectra for Puerto Rico's Main Cities Based on World Wide Strong Motion Records,"* M.S. Thesis, Civil Engineering Dept., University of Puerto Rico at Mayaguez.

Iwasaki, T., Tokida, K., Tatsuoka, F., Watanabe, S., Yasuda, S., and Sato, H., 1982, *"Microzonation for Soil Liquefaction Potential using the Simplified Model,"* Proceedings of the 3rd International Earthquake Microzonation Conference, Seattle, Washington, pp. 1319-1330.

Kramer, S. L. (1996). Geotechnical Earthquake Engineering, Prentice Hall, Upper Saddle River, New Jersey.

Llavona, A., 2004, *"Clasificacion de Suelos (UBC-97) del Municipio de Mayagüez,"* Master of Engineering thesis, Civil Engineering Department, University of Puerto Rico – Mayagüez, .Advisor: Dr. Jose A. Martinez.

Macari, E.J., 1994, *"A Field Study in Support of the Assessment for Liquefaction and Soil Amplification in Western Puerto Rico,"* Final Document presented to the Puerto Rico Earthquake Safety Commission.

Macari, E.J., 1997, *"Earthquake Hazard Assessment of Western Puerto Rico"*, USGS NEHRP Grant 1434-HQ-97-GR-03049, Report submitted to USGS NEHRP.

Macari, E.J., Hoyos, and L.R., Divakarla, P.K., 2004, *"A Study of Earthquake Induced Liquefaction Potential In Western Puerto Rico Using GIS Technology"ASCE Geotechnical Special Publication, 10 p.*

Macari, E.J., and Hoyos, L.R. (2005), "Earthquake-induced liquefaction in western Puerto Rico using GIS technology", *Geological Society of America, Special Paper 385, 2005,* 277-287.

Martínez, J. A., Irizarry, J., and Portela, G. (2001). "Espectros de diseño para las ciudades principales de Puerto Rico basado en registros de aceleracion mundiales", Revista de Desastres Naturales, Accidentes e Infraestructura Civil, UPR-Mayaguez, Vol. 1 No. 1, pp. 21-31.

Mattson, P.H., 1960, *"Geology of the Mayagüez Area, Puerto Rico,"* Bulletin of the Geological Society of America, Vol. 71, pp. 319-362.

McCann, W. R., 1987, *"Historic Earthquakes and the Earthquake Hazard of Puerto Rico,"* Proceedings of Conference XXXVI, A Workshop on Assessment of Geologic Hazards and Risk in Puerto Rico, May 14-16, 1986, U.S. Department of the Interior Geological Survey, Open File Report, 87-008.

McCann, W.R., 1993, *"Seismic Hazard Map for Puerto Rico,"* Report to the Seismic Safety Commission of Puerto Rico.

Mercado, A., and McCann, W.R., 1998, *"Numerical Simulation of the 1918 Puerto Rico Tsunami,"* Natural Hazards 18, 57-76.

Montejo, L. A. (2004). "*Generation* and Analysis of Spectrum-Compatible Earthquakes Time-Histories using Wavelet", Master of Science thesis, University of Puerto Rico, Mayagüez Campus, Mayagüez, 203 pp.

Moya, J.C., and McCann, W.R., 1992, *"Earthquake Vulnerability Study of the Mayagüez Area, Western Puerto Rico,"* Presented at "Comisión de Seguridad Contra Terremotos" (Dr. Leandro Rodríguez, president), 43p.

Mueller, C.S., Frankel, A.D., Petersen, M.D., and Leyendecker, E.V., 2004, *"Documentation for 2003 USGS Seismic Hazard Maps for Puerto Rico and the U.S. Virgin Islands,"* U.S. Geological Survey, Golden, CO., Open File Report 03-379.

Muract, J. (2004). "El Método de Análisis Espectral de Ondas Superficiales y su Automatización Mediante Redes Neuronales", Master of Science thesis, University of Puerto Rico, Mayagüez Campus, Mayagüez, Mayagüez, 145 pp.

Odum, J., Williams, R., Stephenson, W., von Hillebrandt, C., Asencio, E., and Cameron, A., *"Near-Surface S- and P-wave Velocities of Geological Formations within Urban Areas and PRSN Stations, Puerto Rico,"* USGS Open File Report, (in preparation).

Ordónez G.A. (2003). SHAKE2000: A computer Program for the 1-D Analysis of Geotechnical Earthquake Engineering Problem.

Pacheco, J.F., and Sykes, L.R., 1992, *"Seismic Moment Catalog of Large Earthquakes, 1900 to 1989,"* Bulleting of the Seismological Society of America 82, 1306-1349.

Pérez, E., 2005 *"Ground Response Spectra at Surface for Mayagüez considering in-situ Soil Dynamic Properties,"* Master's thesis, University of Puerto Rico RUM.

Prentice, C.S., Mann, P., and Burr, G., 2000, *"Prehistoric Earthquakes Associated with a Late Quaternary Fault in the Lajas Valley, Southwestern Puerto Rico,"* Transactions of the American Geophysical Union 81, F 1182 (abstract).

Prentice, C.S., and Mann, P., 2005, *"Paleoseismic Study of the South Lajas Fault: First Documentation of an Onshore Holocene Fault in Puerto Rico,"* Active Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands, and Offshore Areas, Geological Society of America, Special Paper 385, 215-222.

Reid, H.F., and Taber, S., 1919, *"The Porto Rico Earthquakes of October – November, 1918,"* The Bulletin of the Seismological Society of America. Vol IX. p. 95-127.

Rodríguez-Martínez, J., Santiago-Rivera, L., Guzmán-Ríos, S., Gómez-Gómez, F., and Oliveras-Feliciano, M.L., 2004, "*Surface-Water, Water-Quality, and Ground-Water Assessment of the Municipio of Mayagüez, Puerto Rico, 1999-2002," USGS* Water-Resources Investigations Report 03-4317.

Rodríguez, C.E., and Capacete, J.L., 1988, *"Liquefaction Potential in Puerto Rico,"* Dimensión, Año 2, Vol. 8.

Schnabel, P. B. (1973). "Effects of Local Geology and Distance from Source on Earthquake Ground Motions". Ph.D. Thesis, University of California, Berkeley, California.

Seed, H. B., Idriss, I. M. (1970). "Soil Moduli and Damping Factors for Dynamic Response Analyses." Earthquake Engineering Research Center, Report No. EERC 70-10, University of California, Berkeley, California.

Seed, H.B., and Idriss, I.M., 1971, *"Simplified Procedure for Evaluating Liquefaction Potential,"* Journal of Soils and Foundations Division, ASCE 97(SM9), pp.1249-1272.

Seed, H.B., and Idriss, I.M., 1982, *"Ground Motions and Soil Liquefaction during Earthquakes,"* Earthquake Engineering Research Institute Monograph, Oakland, California.

Seed, H. B. and Sun, J. H. (1989). "Implication of Site Effects in the Mexico City Earthquake of September 19, 1985 for Earthquake-Resistance-Design Criteria in the San Francisco Bay Area of California." Report No. UCB/EERC-89/03, University of California, Berkeley, California.

Sosa, E., and Pando, M., 2004, *"LiquadoPR: Programa para Estimar la Susceptibilidad de Licuación Utilizando las Recomendaciones de NCEER Reporte GEO-03-001,"* Programa de Movimientos Fuertes de Puerto Rico, Universidad de Puerto Rico, Mayagüez, 50 p.

Sykes, L., McCann, W. R., and Kafka, A., 1982, *"Motion of Caribbean Plate during last Seven Million Years and Implications for Earlier Cenozoic Movements," J. Geophys. Res.* 87, 10656-10676.

Tuttle, M.P., Dyer-Williams, K., Schweig, E.S., Prentice, C., Moya J.C., and Tucker, K.B., 2003, *"Liquefaction Induced by Historic and Prehistoric Earthquakes in Western Puerto Rico,"* Seismological Research Letters.

United States Department of Agriculture Soil Conservation Service, University of Puerto Rico College of Agricultural Sciences, 1969, *"Soil Survey of Mayagüez Area of Western Puerto Rico"*.

USACE, 1995, *"Geophysical Exploration for Engineering and Environmental Investigation," Engineering* Manual EM 1110-1-1802, Washington, DC.

US Census Bureau, Census 2000 Summary File 1, July 2000. http://www.census.gov/population/estimates/puerto-rico/prmunnet.txt

USGS, 2002, "Water Resources Data for Puerto Rico and the US Virgin Islands,".

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Liam Finn, W.D., Harder, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson III, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe II, K.H., 2001, *"Liquefaction Resistance of Soils: Summary Report From The 1996 NCEER And 1998 NCEER/NSF Workshops On Evaluation Of Liquefaction Resistance Of Soils,"* Journal of Geotechnical and Geoenviromental Engineering, ASCE, Vol. 127, No. 10, 817-833.