Western Puerto Rico, since intermediate depth earthquakes are found beneath the area. That zone, which which extends to the eastern Dominican Republic, has produced seismic events of magnitude 7.0 in the past. Similar tectonic environments, such as the Lesser Antilles, have produced events as large as 7.5. Because of their distance from western Puerto Rico, intermediate depth events in the Dominican Republic as small as 6.0 may be felt in the Mayagüez Area with only moderate intensity. Events as small as 5.0 have been felt (II-III MM) in the Mayagüez Alluvial Plain, but not in the mountainous area to the west.

Maximum Magnitude of Seismic Sources- Some of the shallow seismic zones with seismic potential and an estimate of the maximum magnitude that each might generate are shown in figure 5 (McCann and Sykes, 1984). The shallow zones in rough order of importance are:

1. The Mona Canyon; Capable of generating shocks of 7.5-8.0 . In 1918 generated an event of 7.5.

2. The Puerto Rico Trench; Capable of generating a maximum event of M ~ 8.0. In 1943 it produced an event of 7.75.

3. Western Puerto Rico seismic zone; capable of generating earthquakes as large as 6.5.

4. The Muertos Trough; Capable of generating a events of 7.5-8.0.

5. The Anegada Trough; Capable of generating a shocks of 7.5-8.0 . In 1867 generated an event of about 7.5 .

The first three sources are considered the most important for western Puerto Rico. The fourth source would produce accelerations similar to those generated by source 2 so it will not be addressed as a separate case here. The threat from intermediate depth earthquakes is possibly as important as shallow sources. Effects of a major intermediate depth earthquake could be similar to those of a major earthquake in the Puerto Rico Trench (source 2) so that case will not be treated independently here.

EVALUATION OF EARTHQUAKE HAZARD

Selection of Earthquake Hazard Level- The historical data indicate that the island of Puerto Rico experiences on the average an earthquake with a Mercalli Modified intensity of VII once every 50 years and intensity VIII once every 100 years (Der Kiureghian and Ang, 1975; and Molinelli, 1985, Table 2).

Table 2. Return Periods of Strong Earthquake in Puerto Rico

Return period in years	MM	Estimated maximum acceleration
50	VII	.15
90	VII-VIII	.18
100	VII-VIII	.19
200	VIII	.25
450	VIII-IX	.33
500	IX	.35

(Der Kiureghian and Ang, 1975).

Following McCann and Sykes (1984), the Mona Passage has the potential to produce large earthquakes greater than 7.5 and, therefore, due to the closeness to Mayagüez and the large magnitude of potential events represents one of the major threats to the Mayagüez Area. The MM Intensity to be felt in Mayagüez with this kind of event will be between VII and VIII based on the historic information obtained by Reid and Taber (1919). Based on the historical, tectonic and seismic data available, the selected hazard level to be used in this study corresponds to an event similar to that of the 1918 Mona Canyon quake (7.5). This event corresponds to the most probable intensities to be expected in the next 50 to 100 years in Puerto Rico (Table 2).

Reid and Taber (1919a, b) modified the Rossi-Forel scale intensity so as to take into account the local construction characteristics in their description of the 1918 quake. This modification reduced the assigned intensity by more or less one intensity level below the normal Rossi-Forel scale. They calculated a Rossi-Forel intensity of VIII for the Mayagüez Region which corresponds on the Mercalli Modified scale with an intensity of VII, and correlates with an estimated peak ground acceleration of between 0.10g and 0.15g. Due to the nearness of some seismic sources (i.e. Mayagüez and Cordillera Faults located in the Puerto Rico seismic zone), it is possible that a moderate earthquake could occur in the Mayagüez area generating intensities higher than that those postulated above.

Regional Attenuation- In Puerto Rico attenuation data is limited to historic observations, mainly from the 1918 and 1867 earthquakes (Reid and Taber, 1919a). Molinelli (1985) presents a graph of regional earthquake intensity (MM) attenuation of the following earthquakes: 1946 in The Dominican Republic, 1957 in Jamaica and the data of Reid and Taber (1919a). Empirical data from other regions have been adapted to Puerto Rico (Housner, 1973). Frankel (1982) calculated a Q factor (1/attenuation) of about 400 for both P and S-waves in the Virgin Islands. While it is difficult to compare this directly to attenuation of accelerations, a Q value of 400 suggests that the regional crustal attenuation is intermediate between the highly attenuating crust of California and the crust of the Eastern U.S. Due to lack of details in seismic wave attenuation for Puerto Rico, in this work the formulas set forth by Donovan (1973) to describe the attenuation of acceleration have been employed.

Expected Accelerations in Mayagüez- No strong motion data is available for large earthquakes in or near Puerto Rico, so peak ground acceleration and attenuation has been deduced based on behavior observed in other areas (i.e., Donovan, 1973; Housner, 1973; Der Kiureghian and Ang, 1975; Marrero et al.,'1983; and Rodriguez and Capacete, 1988). A general agreement exists among these researchers concerning acceleration data for the western Puerto Rico. A general agreement exists among researchers concerning acceleration data for western Puerto Rico. Some authors have suggested maximum accelerations between 0.07g and 0.18g.

Expected accelerations have been estimated based on relationships between fault length and magnitude, and magnitude and acceleration (Slemmons, 1982; Bonilla et. al. 1984; Donovan, 1973; De Polo et. al.,1989 a, b). This information can be applied to western Puerto Rico using the most important seismic sources; Mona Canyon, Puerto Rico Trench, Mayagüez and Cordillera faults. These estimates are preliminary and their intent is to estimate maximum accelerations for Puerto Rico based on those measured in other areas according to the kind of faults and source distance. The data presented in appendix C relates distances and sizes of sources around Puerto Rico to accelerations as calculated using the formula of Donovan (1973).

GEOLOGY

Mesozoic and Cenozoic Rocks- The Mayagüez Region lies between the contact of two different geologic units; the Sierra Bermeja complex and an volcanic complex. The oldest rocks in the island belong to the Sierra Bermeja Complex (Mattson, 1960). They include mainly volcanic and metamorphic rocks and some cherts of pre-Cretaceous to Early Cretaceous age. The geology and the stratigraphic summary of the Mayagüez Region appear in the Figure 13 and Table 3.

A folded sequence of sedimentary and volcanic rocks of late Cretaceous (?) to early Tertiary age unconformably overlays this complex (Krushensky, 1978; and Krushensky and Curet, 1984). Both sequences are intruded by andesitic and basaltic hypabyssal rocks. Some hypabyssal stocks of diorite, quartz diorite, andesite and basalt intrude the old and the young complexes. These rocks have been dated as being from Late Cretaceous to Early Tertiary (Curet, 1986).

Different types of metamorphism are found in the rocks of the region: zeolitization, as well as hydrothermal and climatic alteration. Metamorphic effects observed in the volcanic-sedimentary sequence are probably related directly to the intrusive activity which affected the volcanic materials during Late Cretaceous and Early Tertiary times.

Structural deformation, mostly faulting and folding is greatest in the oldest complex. However, both older and younger units are affected by minor and major faults associated with the GSPRFZ. Major faults have almost vertical dips and show evidence of left-lateral strike-slip movement. Evidence of recent movements, if any, is erased rapidly by the intense

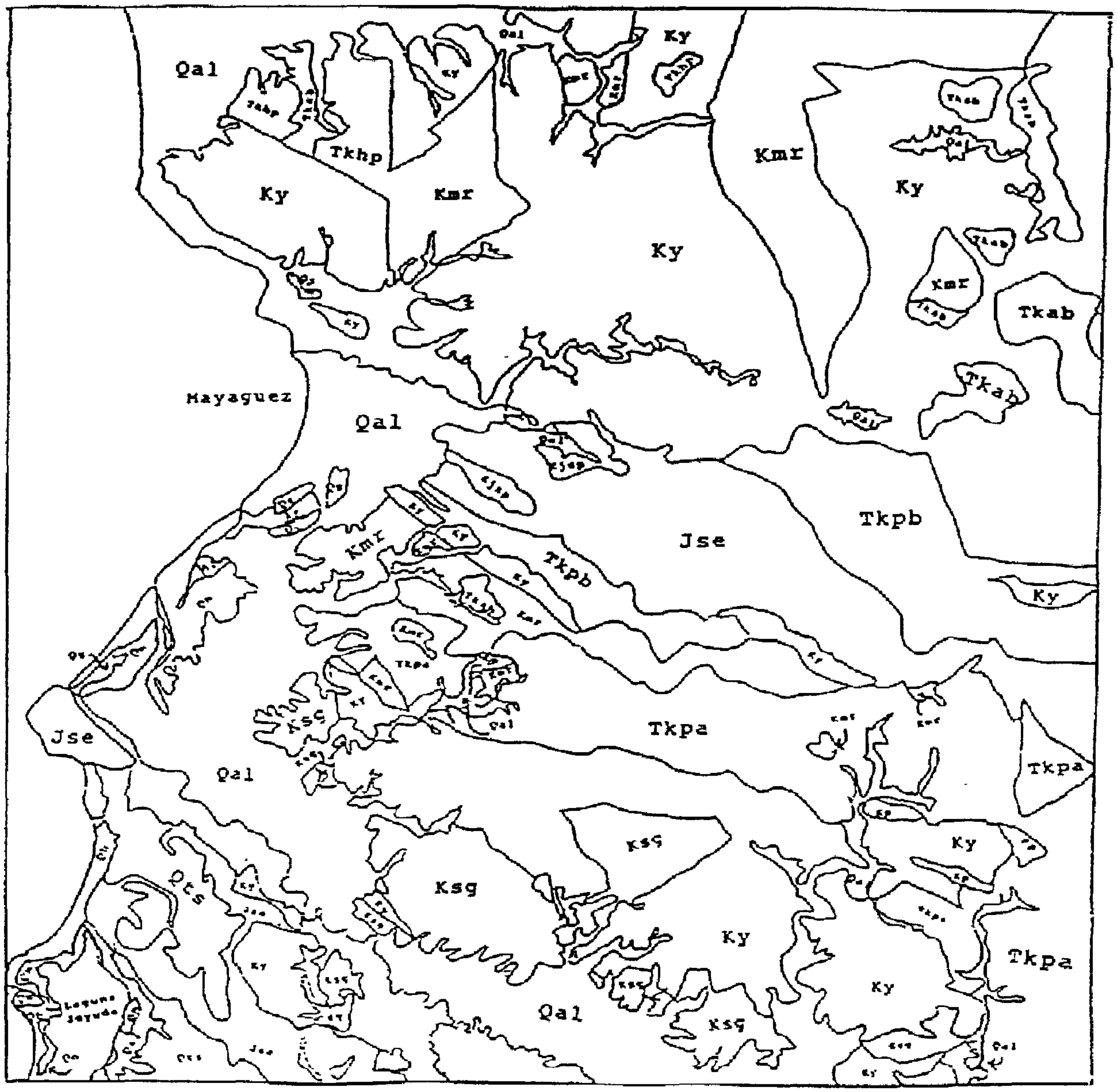

Figure 13. Geologic map of Mayagüez region showing lithologic units. See description in Tables 3a and 3b. From Curet, 1986

Table 3a. Stratigraphic Table of the Mayagüez Area (After Curet, 1986)

Age	Stratigraphy	Brief Descriptions
Holocene	**af** Artificial Fill	Sand, gravel and rock
	Qal Alluvium	Sand, silt and gravels, includes rocks falls and landslide deposits.
	Qb Beach Deposits	Sands, gravels clasts of Shells, chert, quartz and volcanic lithic clasts.
	Qs Swamp Deposits	Clay, silt, and organic matter
	Qm Mangrove Swamp Deposits	Sand silt, and organic matter
Quaternary and Tertiary	**QTs** Quartz Sand Deposits	Friable and massive sands
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)
Late and Middle Tertiary	**Klg** Lago Garzas Formations	Massive breccia,conglomerate, tuff,and limestone
	Klgm Las Marias & L. Garzas Formation	Limestone

Table 3b. Stratigraphic Table of the Mayagüez Area (After Curet,

1986)

Age	Stratigraphy	Brief Description
Maestr. and Campanian	**Kmr** Maricao Formation	Massive breccia,conglomerate sandstone and limestone
Maestr.	**Kp**Peñones Limestone	Massive Limestone
Maestr. to Turonian	**Ksg** Sabana Grande Formation	Massive breccia, conglomerate sandstone, siltstone, claystone and limestone
Maestr. to Campanian	**Ky** Yauco Formation	Calcareous volcanoclastic sandstone, siltstone, claystone, limestone, breccia, conglomerate.
Maestr. and Campanian	**Kylg** Yauco and Lago Garzas Formations interbedded	Massive volcanoclastic breccia, conglomerate, tuffs, claystone, mudstone, sandstone.
Maestr. and Campanian	**Kmsg** Maricao & S. Grande Formations Interbedded	Massive breccia, sandstone, conglomerate, siltstone, and claystone
Early Cretaceous	**Kcs** Clastic Serpentinite	Massive serpentinite, breccia and conglomerate
Early Cretaceous and Jurassic	**KJsp** Spilite	Massive basalt.
Pre.late Kimmeridgian	**Jse** Serpentinite	Massive and weathered serpentinite
	Ja Amphibolite	Crystalline, nonfoliated and slightly foliated amphibolite.

weathering and erosion common to the humid tropics (Geomatrix, 1988).

Late Tertiary and Quaternary Sediments- Quartz sand, swamp, beach, alluvium and colluvium deposited both in terrestrial and in coastal environments make up the youngest deposits in the area (Curet, 1986). Quartz sand deposits consist of massive and friable sands with 50 to 60 percent of quartz sands in a clayey matrix of kaolinite, hematite, and goethite. These deposits of Late Tertiary to Quaternary age are found in the southern portion of the study area, overlaying the serpentinite of the Bermeja Complex. Mangrove swamp deposits consist of moderately to well-sorted, fine grained sand and silt with variable amounts of organic matter. Other swamp deposits consist of clay, silt, and organic matter.

Holocene beach deposits consist of rounded, moderately to well-sorted sands, and minor gravel. Late Pleistocene and Holocene alluvium is poorly to moderately sorted, moderately to well-bedded sand, silt, and cobble or boulder gravel. While chiefly stream deposits, the units also include unsorted rock fall and landslide debris (colluvium) at the foot of steep slopes.

The thickness of the alluvium in the Guanajibo River ranges between 50 to 100 ft. (Colón, 1985), while thicknesses of more than 100 ft are common on the Añasco River plain, reaching 455 ft near the Añasco River (Díaz and Jordan, 1987).

Two borings in the old Yagüez River channel reached 120 ft without encountering a firm stratum, and sand covered lagoonal deposits were found to average 35 feet thick (Capacete and Herrera, 1972), while other sites are more than 170 ft. thick in the Mayagüez alluvial plain (McGuinness, 1946), and maybe up to 300 ft (Rodriguez and Capacete, 1988).

Geomorphological Zones- The area of study is divided into three main geomorphic zones;

the coastal deposits of Holocene age, the alluvial plain, and the mountains. Each one has specific characteristics. The coastal deposits are found along the coast of Mayagüez Bay. The bay is formed by two lengths of coast, a long southern segment and a shorter northern one. The bay lies at the northern termination of the wide insular shelf of western Puerto Rico. The alluvial plain consists mainly of the alluvial deposits of the Yagüez and Guanajibo Rivers, with some swampy areas, lagoon and mangrove deposits. Groundwater levels are found at 3-5 meters deep in the alluvial plain. The long southern coastal segment bordering the bay is where the wider coastal plain is found. The widest portion of this flatland is at the mouth of the Guanajibo River to the south and the narrowest portion is just to the north of the mouth of the Yagüez River. Finally, the central range of mountains are found along the near coastal area and rapidly rise to 350 meters above sea level. High annual rainfall and the tropical climate combine to produce high erosional rates, and thus steep slopes on the mountain sides of the study area.

EARTHQUAKE INDUCED HAZARDS TO THE MAYAGUEZ AREA

Description of Methodology- The methodology employed by Molinelli (1985, 1988) for the study of San Juan, Arecibo, Aguadilla, and Ponce, has been used to define the zones subject to different earthquake induced hazards. The methodology classifys a site according to the geologic characteristics of the materials (kind of rock or sediment and age), and the geomorphology. This methodology defines three potential hazards associated with an earthquake: ground motion amplification, liquefaction potential, and ground failure potential. Each one is described in terms of the level of susceptibility: low, moderate, and high. Finally, tsunami and flood hazards associated with an earthquake are also defined, mainly based on historic considerations and geomorphological characteristics of the zones (see Table 4). The definition of units as presented in the vulnerability map was based on aerial photo interpretations from 1936 and 1987 photographs, geological and hydrological information, historical descriptions, geotechnical borings, and geomorphological interpretations.

Ground Shaking Hazard- Ground shaking is one of the most important earthquake hazards. Earthquakes generate seismic waves (body and surface) which produce vibrations with different frequencies that can damage buildings when they resonate (Molinelli, 1985).

Body waves (P and S) travel as high frequency vibrations, while surface waves (Love and Raleigh) are characterized by lower frequencies. Most structural damage is caused by surface waves. Soil conditions such as thickness, water content, physical properties of the unconsolidated deposits and underlying rock, water saturated mud, uncompacted artificial fills (mainly over swamp and lagoonal deposits) among others, can modify the ground motions, changing the amplitudes and frequencies of the motion. Thus, from areas located at similar epicentral distance and all other factors being the same, large spatial variations in damage reflect local changes in the geologic characteristics that affect ground motion (Molinelli, 1985).

The spatial variation in damage is explained by the fact that the local geologic materials amplify to different degrees the ground motion input in a period range that coincides with the natural period of vibration for many structures. Thus, structures founded on unconsolidated materials are frequently damaged (Hays, 1980). Alluvial zones are very vulnerable to ground shaking amplification but generally less vulnerable than artificial fill placed over swamp, lagoonal, alluvium and beach deposits. Fill materials have shown shown

Table 4. Generalized earthquake induced geologic hazards zones for the Mayagüez Area.

	GROUND MOTION AMPLIFICATION	LIQUEFACTION POTENTIAL	GROUND FAILURE POTENTIAL
A-1	NOT SIGNIFICANT	LOW	VERY LOW
A-2	NOT SIGNIFICANT	LOW TO MODERATE	LOW
A-3	NOT SIGNIFICANT-TO LOW	MODERATE TO HIGH	HIGH-WHERE THE MATERIALS ARE NOT LATERALLY CONFINED AND MODERATELY SLOPING
A-3-S	HIGH	HIGH-IN SAND COVERED LAGOONAL DEPOSITS	HIGH-IN SAND COVERED LAGOONAL DEPOSITS
B-1	NOT SIGNIFICANT	NONE	VERY LOW
B 2	MODERATE TO VERY HIGH	HIGH-SPECIALLY WHERE THE MATERIALS ARE NOT LATERALLY CONFINED	HIGH-ALONG RIVER BANKS SLUMP, FLOWS AND LATERAL SPREADS
B-3	HIGH	HIGH-SPECIALLY IN THE LOOSE SANDS LAGOONAL DEPOSITS	HIGH-SLUMPS-FLOWS AND LATERAL SPREADS
C-1	NOT SIGNIFICANT	NONE	LOW
C-2	NOT SIGNIFICANT	NONE	MODERATE TO HIGH
C-3	NOT SIGNIFICANT	NONE	HIGH

to behave very poorly during earthquakes. The ground shaking damage will be determined mainly by the depth of the focus, attenuation, magnitude, and distance of the source to the study area. During an earthquake areas underlain by Quaternary sedimentary deposits such as alluvial plain and coastal deposits shake harder and longer than sites located over bedrock.

Ground motion amplification is a significant hazard in the lowlands of the Mayagüez Region because of the presence of large amounts of unconsolidated materials. These unconsolidated materials in the study area include Holocene to Recent deposits of alluvium, stream sediments, swamp deposits, water saturated mud, beach and uncompacted artificial fills. The ground water level is shallow (no more than 3 or 4 meters deep) in the alluvial plain and near the lagoonal zones. In downtown Mayagüez, specifically in the Yagüez theater zone, the area is located only about five meters above sea level, and presents a ground water level that stands within a meter of the surface (Capacete and Herrera, 1972).

Sediments in the Rio Guanajibo are between 50 and 100 feet thick. As was cited, data for the thickness of the Mayagüez alluvial plain is scarce. McGuiness (1946) documented deposits between 120 ft and 170 ft thick. For Puerto Rico, Marrero et al. (1983) (cited by; Rodriguez and Capacete, 1988) has recommended an amplification factor of 1.5 for deep soil deposits over 300 ft thick. Based on this consideration, the Añasco, the Mayagüez and the Rio Guanajibo alluvial plains (all with sites which has thickness of more than 120 ft) could be subject to moderate to high intensity ground shaking due to ground motion amplification (see description in map). These zones have been mapped as B-2 and B-3 zones (see main map and table 4 for description). B-3 zones include all the alluvial deposits of

Holocene age with thick deposits, while B-2 includes some Pleistocene terraces composed of alluvial deposits, but with materials more compacted than those of B-3 zones.

In the 1918 earthquake, extensive damage occurred in the structures located at the west end of Méndez Vigo and McKinley Streets, on the Yagüez River floodplain, and on the east end of Méndez Vigo St. where it joins the floodplain (Capacete and Herrera, 1972). This area has been defined as a B-3 zone.

Several artificial fills sites are located near the beach and on the Mayagüez plain. These areas are underlain by beach, swamp and fluvial deposits with a high ground water level that will be affected by ground shaking amplification. Some zones have been identified based on data presented by Hickenlooper, (1968), and Curet (1986). Additional data on the location of fill sites was obtained from a comparative analysis of aerial photos from; 1936, 1951, 1964, 1971, 1979 and 1987 (Figure 14). Fill areas with a high susceptibility to ground shaking lie along the north and south sides of the Rio Yagüez mouth, filled swamp areas to the south of Mayagüez and areas north of Caño Corazones, which could be an ancient mouth of the Rio Guanajibo. In the early 60's, the area between Punta Algarrobo and the Malecón was filled in to expand the port zone. New industrial facilities were built on the landfill area. This area is located in a zone with a high ground shaking amplification potential (B-3).

Zones with low ground shaking amplification potential hazard (B-1) have been mapped in some Pliocene-Pleistocene (?) terraces composed of quartz sand deposits, appearing mainly in the Sierra Sabana Alta part of the study area (Curet, 1986; Volkmann, 1984). Although the terraces consist mainly of silt and sand sediments, weathering and compaction has increased the rigidity of the deposits.

Liquefaction Hazard- Ground failure produced by soil liquefaction has been one of the most important causes of damage during some of the most destructive earthquakes in history. Differential settlement and tilting of buildings, collapse of bridges, emergence of light buried structures, and deformation of underground pipe lines are some of the damages produced by this phenomenon during and after earthquakes.

From a geotechnical point of view, the factors used to identify sites with soil liquefaction potential are: age of soil, groundwater height, grain size, density, origin, thickness, and ground accelerations and duration of the shaking (Budhu et. al., 1990). Geologically, this phenomenon occurs in recent sediments (mainly not older than Holocene) composed of loose fine- to medium-grained sands and silty sands (clay free) up to 20 meters below the ground surface, and with a relatively shallow water table (less than 10 meters below the surface).

The application of cyclic shear stresses produced by the ground-motions (induced by an earthquake) causes pore-water pressure buildup in saturated cohesionless soils (Seed, 1968). If groundwater drainage is impeded during the ground motion, because there is an increase in the pore-water pressure and a decrease in the intergranular stress, and the cyclic shearing is continued, this can cause a large amount of straining straining and even flowage; the soils, then, behave as a fluid mass (Obermeier, 1984). When the pore-water pressure becomes equal to the total mean stress, the soil looses its strength and liquefies. The duration of the ground shaking will be a very important factor in the liquefaction process. Long- duration shaking will produce the cyclic shear stress necessary to cause a 100 % excess

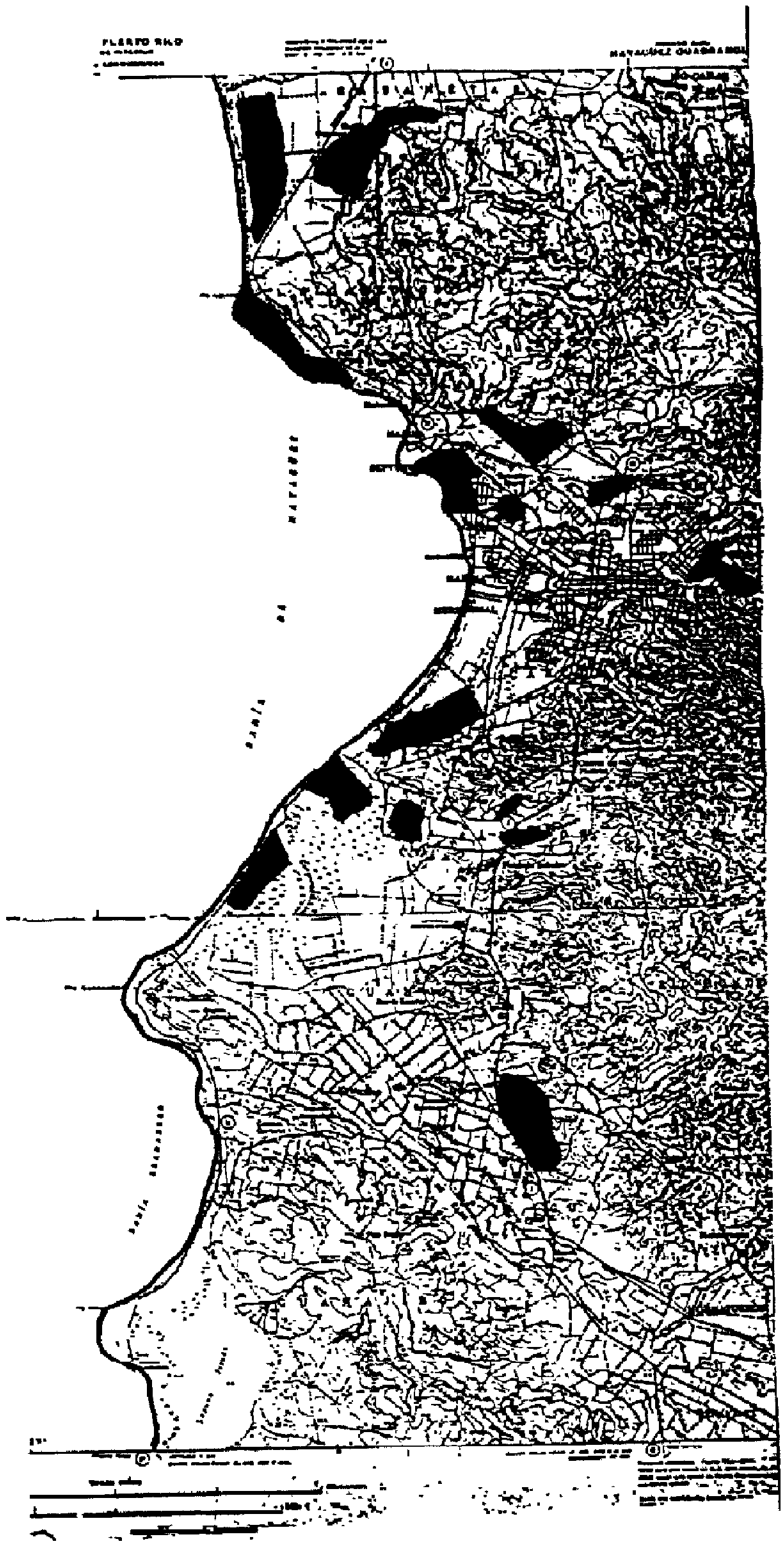

Figure 14. Artificially filled areas for urban use in the Mayagüez Quadrangle.

pore pressure ratio if the conditions required exist.

Youd and Perkins (1978) developed a table to estimate the susceptibility of sedimentary deposits to liquefaction during strong seismic shaking (Table 5). Following Youd and Perkins (1978), for a ground water level at or near the surface, the data of Tinsley et. al. (1985) indicate that most of the late Holocene sand and silt deposits in the world are highly liquefiable. Loose sand or silt (clay-free) of low densities are less resistant to liquefaction than sands and silts with high relative densities. Also, very young deposits less than 500 years in age are more susceptible to liquefaction than older (Holocene and Pleistocene age) deposits (Youd and Perkins, 1978). It is possible that liquefaction can occur on clay-rich sediments which are very young (no older than a few tens or hundred of years) and in extremely soft clay-rich soils (Obermeier, 1984). The geomorphological evidence of liquefaction is evidenced by sand blows, sand dikes, lateral spreads, ground fissures, ground settlement and differential deformation of the ground surface.

Youd and Perkins (1978) suggested that ground failure induced by liquefaction damage can vary according to the ground surface slope. Obermeier (1984) presents a table simplifying Youd's data of damage associated to the ground slope recognized during past earthquakes on sand-grained deposits. The damage caused by liquefaction will depend on the gradient where this phenomena occurs and the cyclic stress ratio produced by the shaking of the soil:

Ground Surface Slope	**Failure Mode**
< 0.5 %	Bearing Capacity
0.5 - 5.0 %	Lateral Spread
> 5.0 %	Flow landslide

According to the National Research Council (1989), the four different manifestations of liquefaction that can cause major damage to buildings and facilities are: 1. Flow slides from slopes; 2. Loss of foundation bearing capacity, leading to large settlement and/or tilting of structures; 3. Lateral spreading, that is, a movement of gradually sloping ground toward low points; 4. Ground oscillation, where ground overlaying saturated sand breaks up into jostling "plates". When the first two manifestations occur, there is great damage and loss of life. Due to the low slopes of the Mayagüez area, manifestations 2, 3, and 4 are most likely to occur during a major earthquake.

Earthquake duration and acceleration are other critical factors that affect liquefaction potential. Duration and acceleration thresholds capable of causing liquefaction have been empirically derived for different areas. These studies show that liquefaction can occur (measured in terms of Magnitude and or Intensity) during longer-duration, lower-frequency shaking of large earthquakes.

The threshold of acceleration where liquefaction was produced in past earthquakes over soft sediments has been when the ground shaking has exceeded 0.13g. This includes earthquakes as small as 5.0 M_S with a source distance less than 10 km, or with an intensity V (MM) with the same source distance (Seed and Idriss, 1971; Keefer, 1984; Obermeier, 1984; Tinsley et. al., 1985).

To data applied to Puerto Rico, Molinelli (1985) mentions that other geologic conditions favoring liquefaction are: 1) a potentially liquefiable bed or lens of porous, well sorted sand, 2) water saturation of intergranular pore spaces in the bed or lens, 3) confinement of pore water by impermeable layers above and below the liquefiable bed, and

Table 5. Estimated Susceptibility of Sedimentary deposits to Liquefaction During Strong Ground Shaking. From; Youd and Perkins, 1978.

Type of Deposit (1)	General Distribution of Cohesionless Sediments in Deposits (2)	Likelihood That Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit)			
		<500 yr (3)	Holocene (4)	Pleistocene (5)	Pre-Pleistocene (6)
(a) Continental Deposits					
River channel	Locally variable	Very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very low
Marine terraces and plains	Widespread		Low	Very low	Very low
Delta and fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine and playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low

Type of Deposit (1)	General Distribution of Cohesionless Sediments in Deposits (2)	Likelihood That Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit)			
		<500 yr (3)	Holocene (4)	Pleistocene (5)	Pre-Pleistocene (6)
(a) Continental Deposits (cont'd)					
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very low	Very low
Sebka	Locally variable	High	Moderate	Low	Very low
(b) Coastal Zone					
Delta	Widespread	Very high	High	Low	Very low
Esturine	Locally variable	High	Moderate	Low	Very low
Beach					
• High wave energy	Widespread	Moderate	Low	Very low	Very low
• Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low
(c) Artificial					
Uncompacted fill	Variable	Very high	-	-	-
Compacted fill	Variable	Low	-	-	-

Table 5. (Continuation) Estimated Susceptibility of Sedimentary deposits to Liquefaction During Strong Ground Shaking. From; Youd and Perkins, 1978.

4) proximity of the liquefiable bed to the surface (50 feet or less).

During the 1918 earthquake, soil liquefaction was located on alluvial deposits, mainly in the Añasco alluvial plain (Reid and Taber, 1919a). No descriptions exist for the Mayagüez zone, but it is possible that the evidence were not observed because in 1918 the population was very scarce and only a small area of the Mayagüez Bay was urbanized and occupied. Also, the intensive agricultural activities could have buried the evidence.

In the Mayagüez area, Arroyo (1991), assessed the liquefaction potential of one thousand borings in the study area[3]. He used the PETAL3 Program by Chen (1988) (Penetration Testing and Liquefaction) to define whhich borings present evidence of liquefaction susceptibility. The program uses the relationships proposed by Seed and Idris and others to evaluate the liquefaction potential of sandy soils with a fine percent of less than 40 % and gravelly soils.

The PETAL3 program needs the following input data to make the liquefaction computations: a) number of layers of the site studied; b) depth of each layer; c) saturated density and wet density; d) the expected depth of the ground water during the design earthquake; e) the earthquake magnitude and maximum acceleration; f) the type of in situ test performed (SPT or Cone Penetration Test CPT); and g) the SPT hammer efficiency. Boring data is presented in Appendix B.

Only 43 of the one thousand borings satisfied the criteria for use of the Seed and Idriss and others methodology. All borings are located on Holocene alluvium, beach and swamp deposits. Arroyo obtained the safety factor for these 43 borings. Values greater than

[3] Data obtained from public agencies and private companies.

or equal to one are considered safe or nonliquefiable, values less than one indicate sites of liquefaction potential (Figure 15). Almost all borings with safety factors of less than 1 have layers of loose sandy and silty-sand soils with water table level very shallow (between 1 and 5 meters deep), and the blow counts (SPT) ranging between 1 and 10. These borings are located over the alluvial plain of Mayagüez (see map).

The liquefaction potential zones found by Arroyo (1991) show an almost perfect correlation with the estimated susceptibility of sedimentary deposits to liquefaction presented by the Youd and Perkins methodology (1978) (Table 5). This was the same methodology used by Molinelli (1985 and 1988) for the liquefaction susceptibility maps in San Juan, Arecibo, Ponce and Aguadilla.

Until now the two known studies of liquefaction susceptibility based on geotechnical data (Soto et al, 1985; and Arroyo, 1991) confirm very well the application of the Youd and Perkins (1978) methodology to liquefaction assessments without data logs for purposes of general vulnerability mapping in Puerto Rico.

In the case of the area of study, the areas A-3 and A-3-S were defined as the zones most prone to liquefaction, based on Arroyo's data, the Youd and Perkins (1978) methodology, the location of recent deposits (Curet, 1986), and the mapping done by this study on the landforms of Holocene and late Pleistocene environments obtained from the interpretation of the 1936 aerial photos. These zones are located, as described before, over the beaches, mangrove, lagoonal, swamp, and alluvial zones, with a very recent date and where sand deposits appear (Figures 15, 16).

A moderate to low potential zone (A-2) is identified by the alluvial terrace and

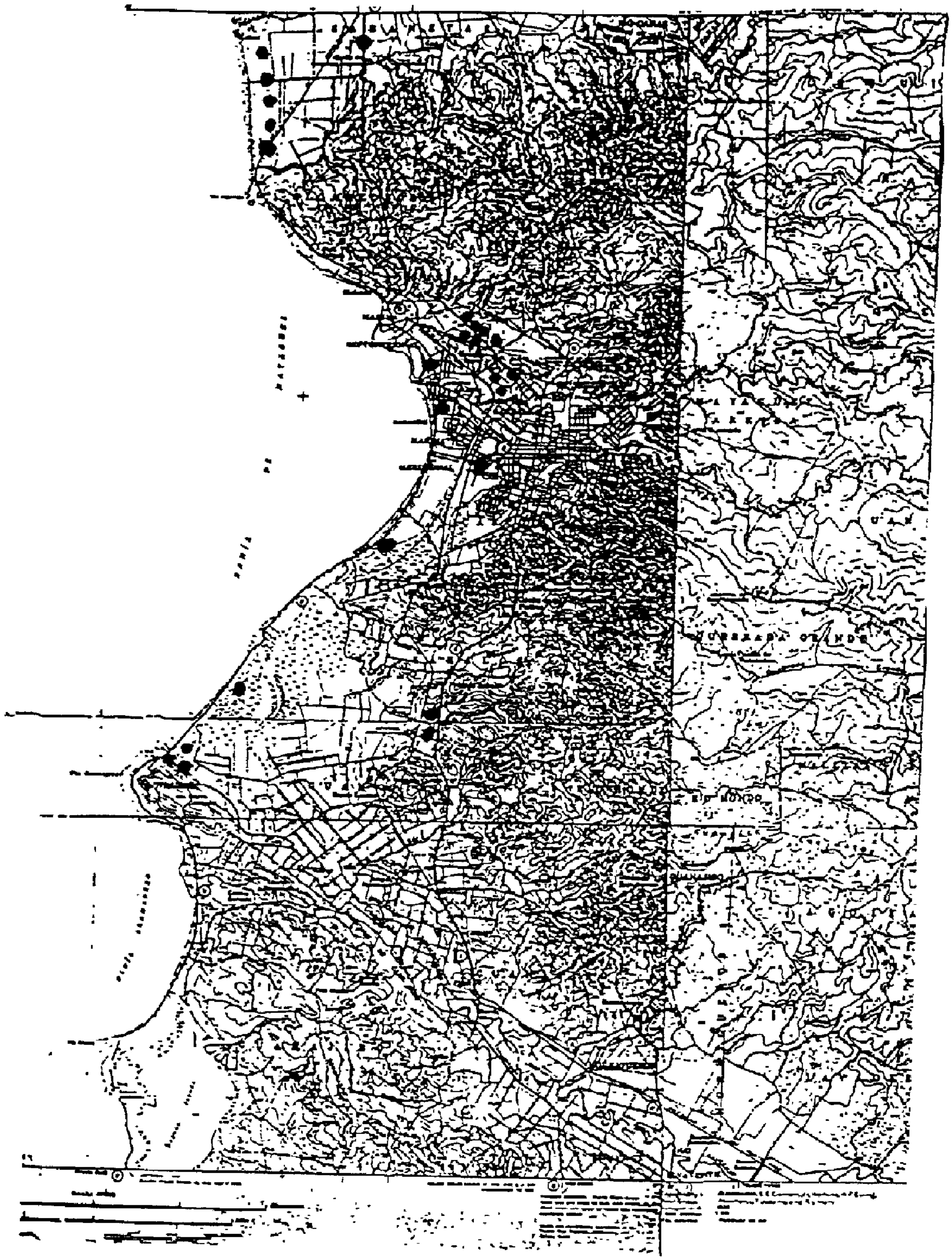

Figure 15. Sites with high liquefaction potential in the Mayagüez Quadrangle. From Arroyo, 1991.

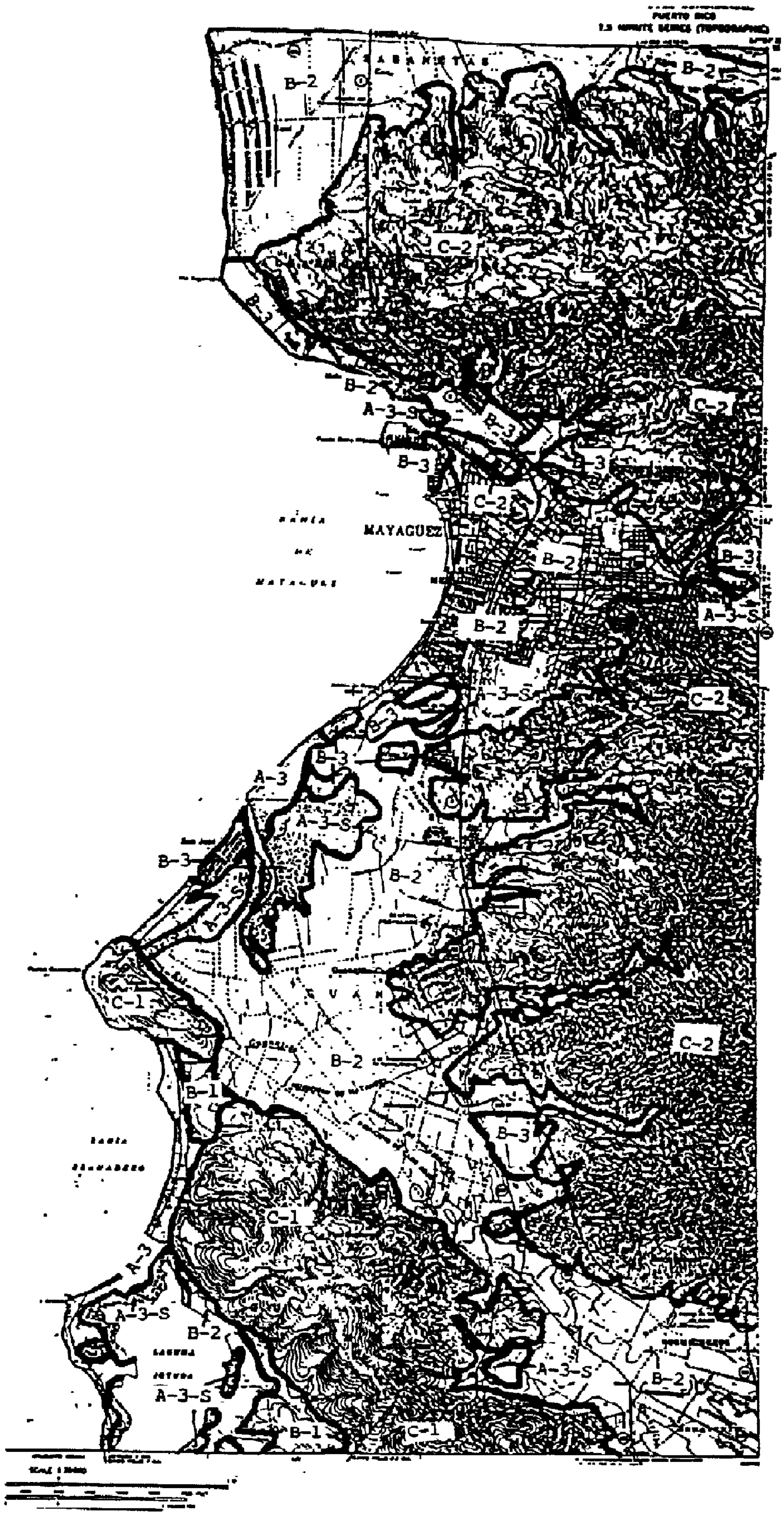

Figure 16. Units of the generalized earthquake induced geologic hazards map for the Mayagüez Area. For description see Table 4.