Earthquake Vulnerability Study For The Areas of Ponce, Arecibo and Aguadilla, Puerto Rico

A Study Prepared for the
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INTRODUCTION

This report concerns the mapping of earthquake induced geologic hazards in the Ponce, Playa de Ponce, Peñuelas and Punta Cuchara, Aguadilla and Arecibo Quadrangles of Puerto Rico. This study is an annex to the Earthquake Vulnerability Study that was initiated with hazard mapping of the Metropolitan Area of San Juan. It describes the geology, geomorphology and nature of earthquake-induced geologic hazards. The tectonic setting, regional seismicity, attenuation relations, selection of the earthquake hazard level, and damage estimation methodologies have been presented in the first part of this study titled Earthquake Vulnerability Study for the Metropolitan Area of San Juan.

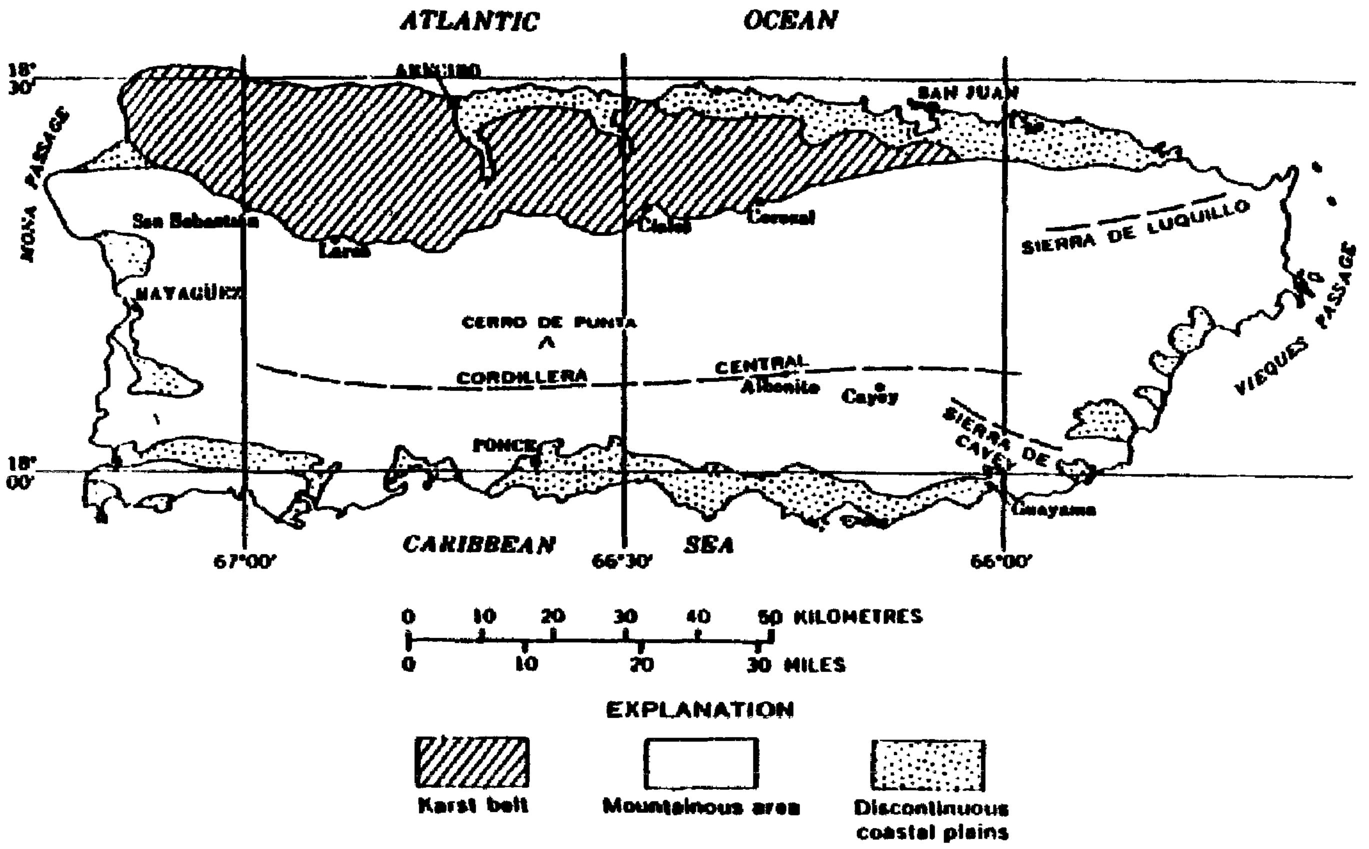
Earthquakes present a serious hazard to the island of Puerto Rico. When an earthquake occurs near a populated area, widespread destruction of life and property takes place. Puerto Rico is situated in a tectonically active zone and has experienced the effects of large earthquakes in the past. The 1918 and 1867 earthquakes had an estimated magnitude of 7.5 and were accompanied by destructive tsunamis. These events caused hundreds of deaths and millions of dollars in losses. In 1787 an earthquake with an estimated magnitude of 8-8.25 severely shocked the northern coast of Puerto Rico causing a significant amount of damage to military structures in San Juan and completely destroying Arecibo's church. Events of similar magnitude are likely to occur in the future.

Fortunately, a large earthquake has not affected the island in the past 70 years. During this period the population has tripled and urban areas have expanded proportionally. Presently a significant portion of the residential, commercial, industrial and transportation infrastructures are located in places that are vulnerable to different types of earthquake-induced geologic hazards. Thus, the potential damage created by future earthquake events is greater today than ever before.

This study examines the seismic vulnerability of the Ponce, Arecibo and Aguadilla areas by mapping the spatial distribution of geologic hazards, namely: ground shaking, liquefaction and landsliding. Each geologic hazard is mapped according to three levels of susceptibility determined by the geologic, hydrologic and geomorphic characteristics of each zone. Identification of risk situations is necessary for local disaster preparedness, land use planning, estimation of economic losses, identification of measures for reducing expected economic loss, and for the selection and implementation of mitigation strategies.

GEOMORPHOLOGY AND GEOLOGY

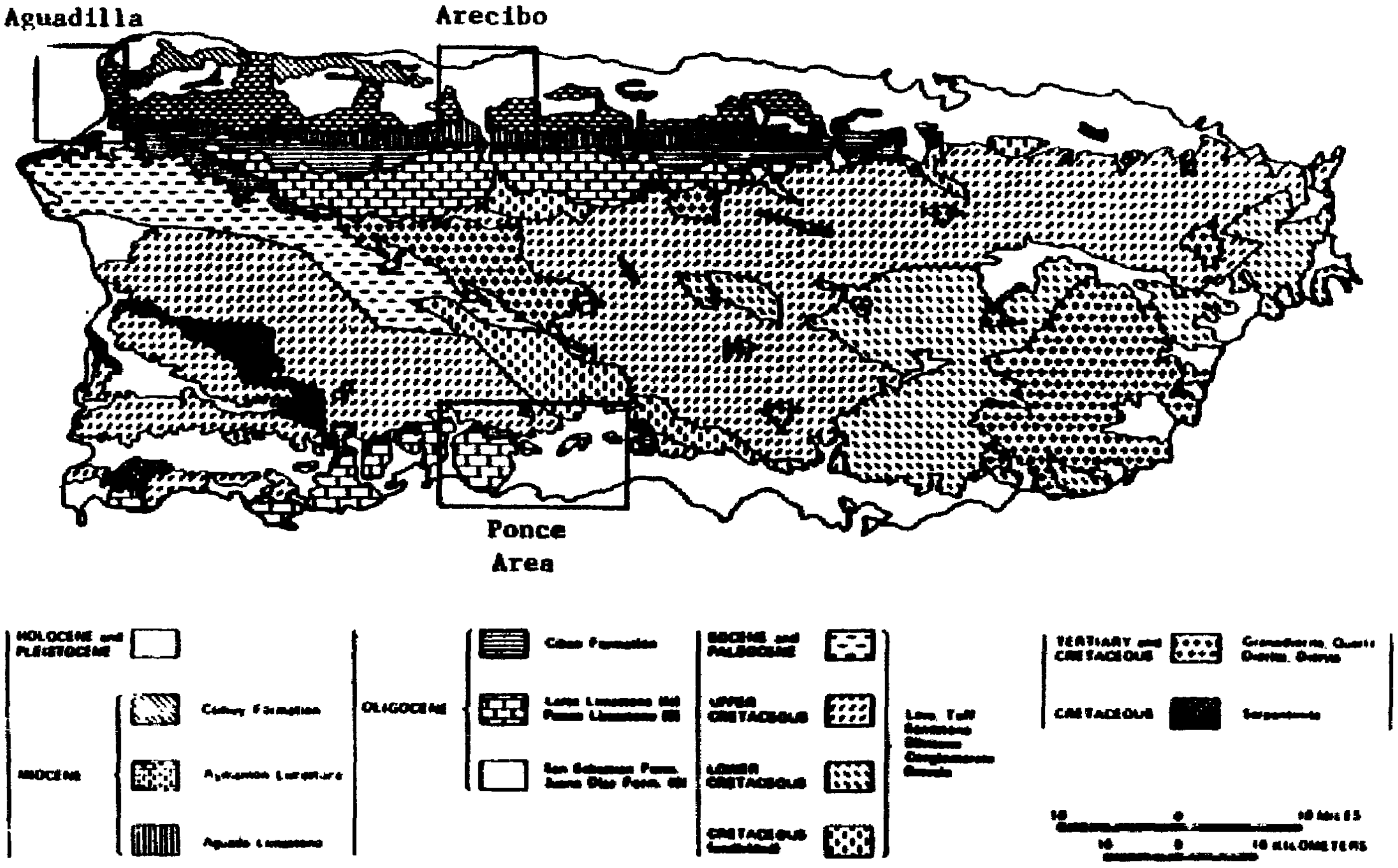
Three physiographic regions are present within the study areas: the Interior Volcanic Upland Province, the Northern Karst Province and the Coastal Plains Province (figure 1). These provinces are characterized by a unique combination of relief, landform and geology. The interior upland shows the effects of fluvial erosion over a complex sequence of volcanic and sedimentary deposits of Cretaceous and Early Terciary age. The Cretaceous rocks were formed during a period when volcanism and sedimentation were dominant geological processes. The lower Cretaceous rocks consist primarily of lava, lava breccia, tuff and tuffaceous breccia with some thin bedded sandstone, siltstone, and limestone (figure 2) When exposed, they are generally thickly weathered. Upper Cretaceous rocks consist of tuffaceous sandstone, siltstone, breccia, conglomerate, lava, tuff, and some pure and impure limestone lenses. When exposed, they too are deeply weathered (Briggs and Akers, 1965; Briggs, 1964). Convergence between the Caribbean and the North American plate at the end of the Mesozoic gave rise to the "Caribbean Orogeny" (Malfait et al., 1972). At the end of orogeny (middle Eocene), most Cretaceous and Early Terciary rocks had been faulted, folded and intruded. Early Terciary rocks were formed during a mountain building period. Both intrusive and extrusive igneous activity were the dominant geologic processes. Intrusive rocks emplaced during the orogeny are mainly granodiorite, quartz-diorite and some minor quartz



Map from Puerto Rico showing principal physiographic divisions

From Monroe (1976)

Fig. 1



Study area location and simplified geologic map of Puerto Rico

Fig. 2

From Beinroth (1969)

porphyry, gabbro, and amphibolite. Associated with the intrusives are zones of hydrothermal alteration and contact metamorphism (Hildebrand, 1961).

Paleocene and Eocene deposits consist of siltstone, sandstone, conglomerate, lava, and tuff. They are locally deeply weathered.

In the study area, the northern Karst province consists of the Cibao, Aguada, Aymamon and Camuy formations (Monroe, 1973, 1976, 1977, 1980, Pease and Monroe 1977). The San Sebastian formation lies unconformably at the base of the mid-Terciary sequence over Cretaceous volcanics and sedimentaries. The formation is heterogeneous and contains clayey sand, lenses of sandy clay, pebbles, and cobbles. The thickness is variable, but can reach 155 meters.

The Cibao formation consists of an argillaceous marl, chalky limestone, and thin beds of sand and clay. An outcropping member in the Arecibo Quadrangle is the Montebello Limestone. It consists of fine to very fine grained nearly pure limestone, most commonly thick bedded or massive and locally highly fossiliferous. The Aguada formation consists of alternating beds of indurated fine to medium grained calcarenite and clayey to chalky limestone. Its thickness ranges from 90 to 150 meters. It has a wide variety of Karst features but the most distinctive are deep solutional dolines.

Comformably overlying the Aguada is the Aymamon Limestone formation, consisting of massive to thickly bedded, very pure fossiliferous limestone generally indurated into finely crystalline limestone. Its thickness varies from 110 meters at Aguadilla to 190-205 meters at Arecibo (Monroe, 1980, 1973). Sinkhole formation is a potential hazard in the Aymamon and Aguada Limestone formations.

The Camuy limestone formation consists of medium to fine grained somewhat clayey chalk, and marl; commonly thickly bedded with rare beds of quartz sandstone. Its thickness is approximately 170 meters. It forms a discontinuous belt from Rio de la Plata west to Isabela, and rests unconformably upon the Aymamon Limestone (Monroe, 1976).

In the Ponce study area, middle Terciary rocks consist of the Juana Diaz Formation of Oligocene and Miocene age and the Ponce Limestone of Miocene age. The Juana Diaz consists of lenticular and intertonguing beds of sand, gravel, mudstone, clay and limestone. The Juana Diaz Formation is overlain unconformably by the Ponce Limestone, which consists of very hard fossiliferous calcarenite (Monroe, 1976).

The Coastal Plain Province essentially consists of Quaternary surficial deposits. They include flood plain alluvium, swamp, lagoon, terrace and alluvial fan deposits. These are mainly sand, clay, sandy clay, gravel and silt. At the Arecibo study area, deposits are mostly flood plain related. Even Cienaga Tiburones (a former lagoon) has been filled with alluvium (Monroe, 1976). At the Rio Culebrinas floodplain in the Aguadilla study area, Monroe (1969) estimates a thickness of 10 meters in the alluvium, while for the same area of the Rio

Culebrinas floodplain, Gomez (1987) estimates that the depth of the alluvial aquifer is probably similar to that of the Rio Añasco valley, which is more than ten times thicker.

The Southern Coastal Plains consist of a series of large alluvial fans composed of poorly sorted clastic debris transported from the mountains to the south. Gravel and cobbles are very common and become concentrated in the shorelines when the finer material is washed away by waves and currents (Monroe, 1980). Most of the streams entering the Coastal Plain spread out into alluvial fans.

Beach deposits consist dominantly of medium to fine grained sand composed of particles of quartz, feldspar, shell fragments and calcium carbonate. Their thickness is variable, but may reach approximately up to 6 meters. Dune deposits are generally fine grained sand composed of materials similar to those on the beach. Their thickness may reach 15 meters. Extensive abandoned beach ridges that extend more than 1 mile inland are present to the south and south east of the town of Ponce.

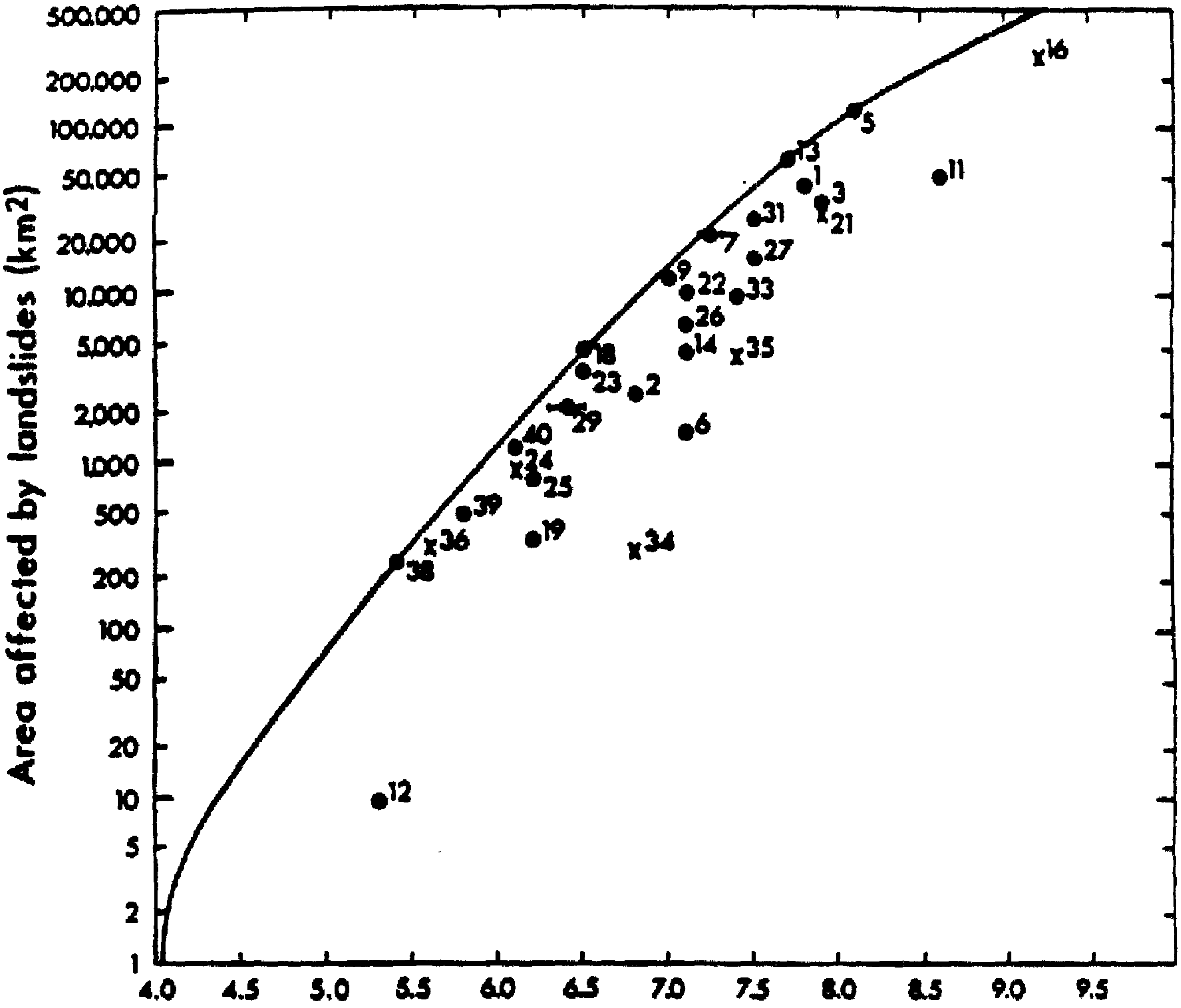
Beach rock is commonly present in the intertidal zone due to sand cementation in the Arecibo and Aguadilla study areas. Eolianites are present in the Arecibo study area. They are cemented dunes and consist of cemented sand, friable to well indurated, calcite cemented, crossbedded, calcareous, eolian sandstone composed of fine to course grains of shell fragments and quartz. The maximum thickness ranges from 20 to 25 meters.

Landslides

Landslides result from the movement of soil and rocks down the slopes. They can occur in practically all types of geologic materials and generally result from a complex combination of different causes. Their movement mechanism includes falls, slides, flows, topples, lateral spreads and complex combinations of the above. Their size varies from small blocks, less than 1 meter, to large complex slide-flow, covering an area exceeding hundreds of thousands square meters.

Landslides occur when the shear stresses exceed the shear resistance of the geologic materials. Shear stresses produced by ground motion are normally increased during strong earthquakes causing failure in slopes. These commonly occur in steep marginally stable slopes where the downslope component of the force of gravity is high. In addition, earthquakes can trigger landslides not only by increasing the shear stresses but by decreasing the shear resistance. When slopes are subjected to repeated loadings, irregular pulses weaken and eventually loosen the rock.

Keefer (1984) studied the relationship between earthquake magnitude and the extension of the areas affected by landslides. In addition, he examined the epicentral distance and Modified Mercalli Intensity at which different landslides occur. The size of the areas affected by landslides shows a strong positive correlation with earthquake magnitude (figure 3).

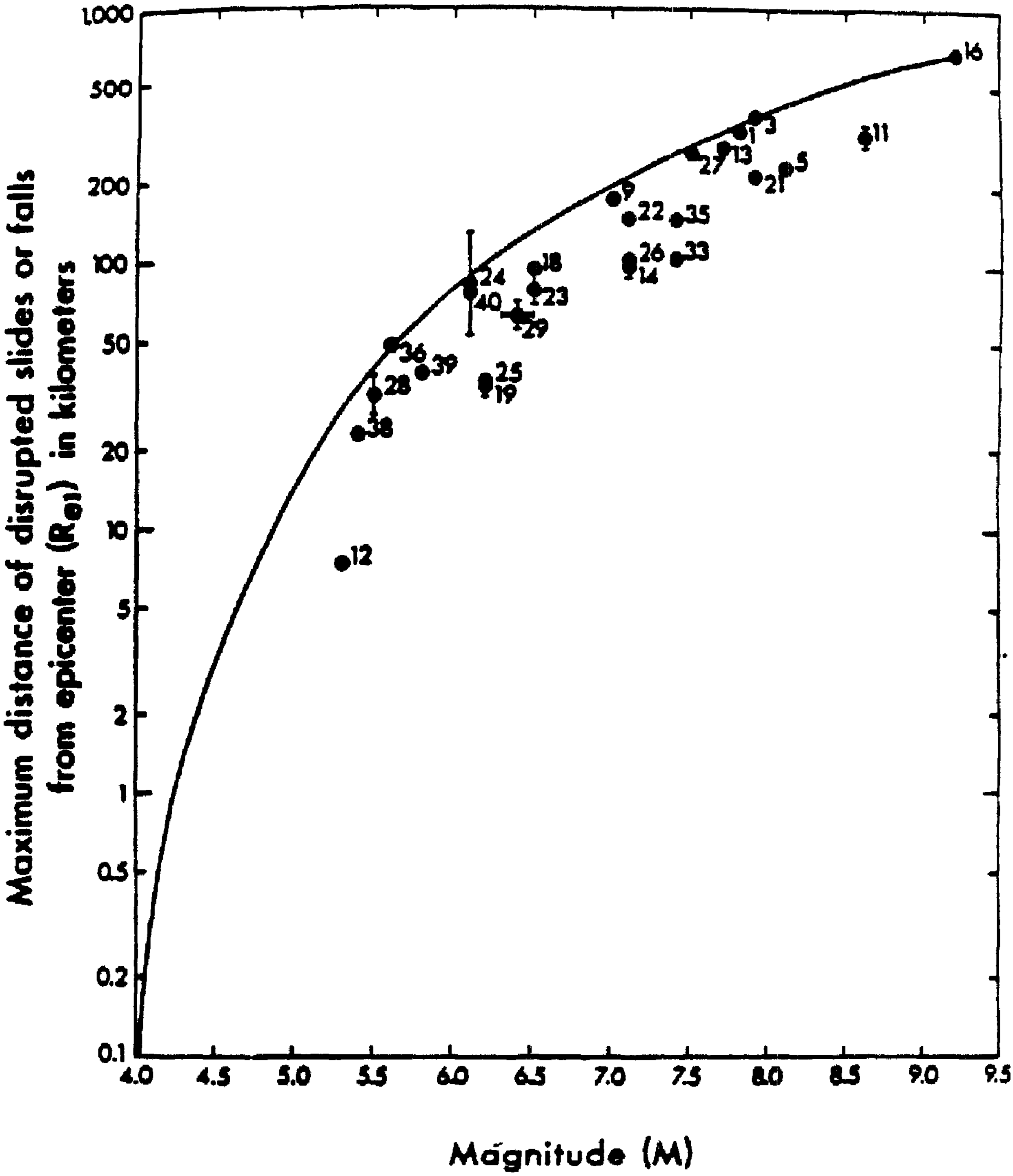


Area affected by landslides in earthquakes of different magnitudes

Fig. 3 From Keefer (1984)

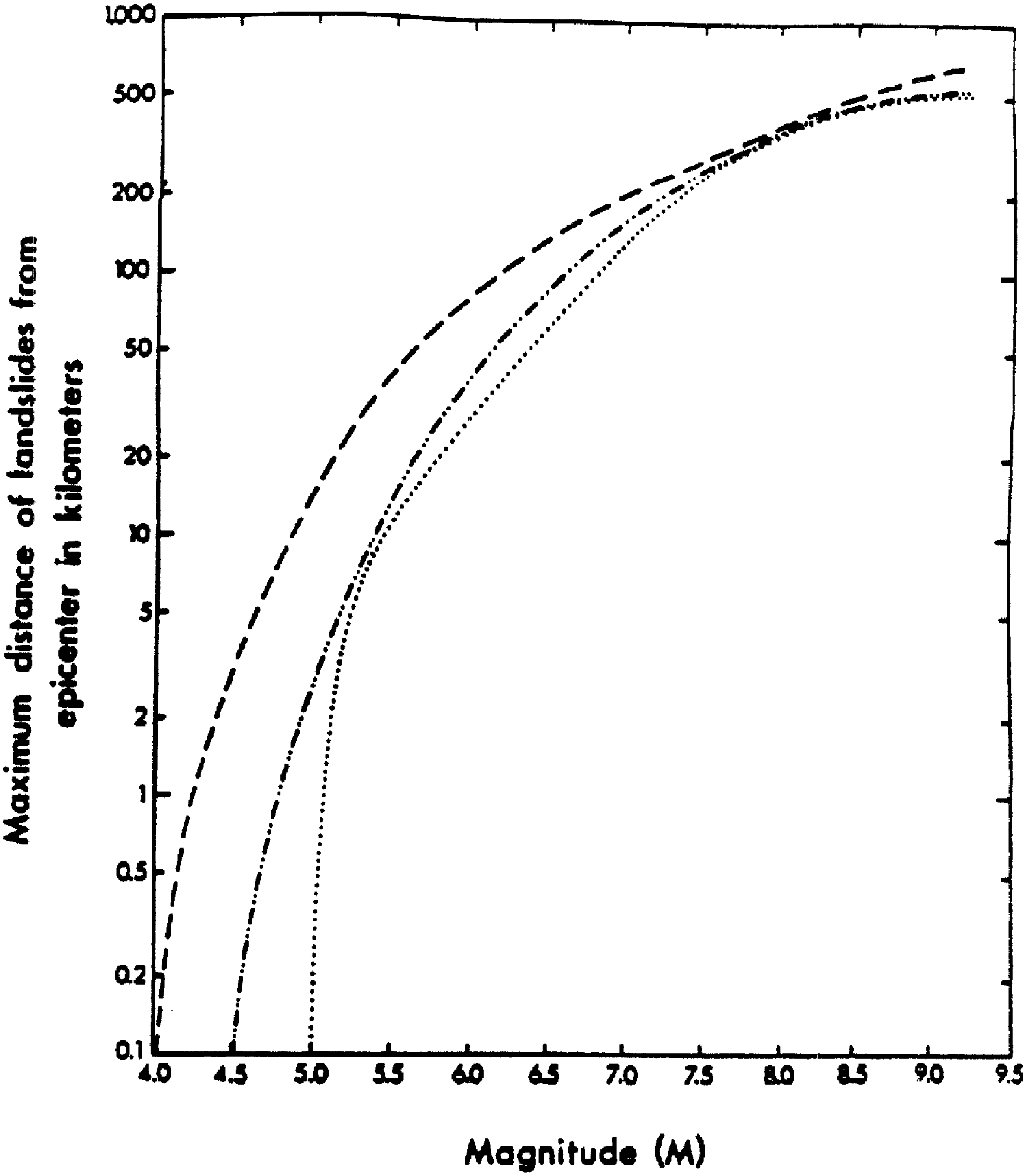
The graph shows that an earthquake of magnitude (M) 7.5 can cause landslides in an area of approximately 40,000 sq. km.
When this area is centered over the offshore fault zones south of Ponce, at the Mona Canyon and the Puerto Rico Trench, it shows that the areas of Ponce, Aguadilla and Arecibo are very likely to experience slope failures. Generally any event greater than magnitude (M) 4 is capable of causing landslides.

The variation of maximum epicentral distance at which disrupted slides, falls and landslides occur (figure 4 and 5) indicates that the selected hazard level earthquake is capable of causing landslides at a distance of 200 km. from the epicenter, showing that any of the active offshore faults is capable of causing landslides in any part of Puerto Rico. Examination of the upper bound relations (figure 5) suggests that disrupted slides and falls can be triggered by shaking weaker than coherent slides, and that coherent slides can be triggered by shaking weaker than lateral spreads or flows (Keefer 1984). Thus, there are threshold magnitudes at which different ground failures can occur.
The intensities that will be experienced in the area of Ponce, Aguadilla and Arecibo during the selected hazard level event exceed the minimum intensity required to produce all types of ground failure.



Maximum distance from epicenter to disrupted slides or falls in earthquakes of different magnitudes

Fig. 4 From Keefer (1984)



Upper bounds showing maximum distances from epicenters at which landslides of different types are likely to occur. Dashed line is bound for disrupted slides and falls, dashed double dot line is bound for coherent slides, and dotted line is bound for lateral spreads and flows.

Fig. 5

From Keefer (1984)

The selected hazard level will produce a Modified Mercalli Intensity of VIII to at least IX (deep alluvium), a value up to two intensities above the predominant minimum seismic shaking intensities required to trigger disrupted slides and falls (MMI VI), and coherent slides, lateral spreads, and flows (MMI VII). Thus, ground motion in the study quadrangles, given the areal epicentral and intensity characteristics of the selected hazard level, is strong enough to cause all types of mass movements.

The mapping of areas susceptible to landsliding takes into consideration slope inclination as a primary factor affecting slope stability. In general, steep slope areas are chief sites of instability, mainly through their control of the downslope component of the weight of slope material. Many factors contribute to the increased shear stress, the most important are the removal of lateral support, surcharge, removal of underlying support, lateral pressure, and obviously the transitory earth stresses caused by ground motion.

However, the degree of stability is greatly affected by the shear strength of the materials underlying the slope. This depends on their initial state as determined by composition, texture, gross structure and slope geometry. The last two include discontinuities such as faults, bedding planes, foliation, cleavage, joints, slickensides, brecciated zones, massive beds over weak or plastic materials, strata inclined toward free face, alternation of beds with different permeabilities, and slope orientation. In addition, shear strength is reduced due to weathering and other physicochemical reactions, as well as changes in the intergranular forces due to water content and pressure in pore and fractures.

Degree of susceptibility to landslides is mapped according to three categories, high, moderate to high, and low. Zones of high susceptibility in the study areas include those where geologic formations are characterized by a high landslide incidence due to steep slopes in potentially unstable materials, as well as the presence of weak geologic strata below more resistant ones.

In the Aguadilla Quadrangle these conditions are present in the Terciary age Cibao, Aguada and San Sebastian formations, especially in the areas altered by human activities. These show a high incidence of landslides extending along a considerable portion of their outcrop from Aguadilla to the southwestern portion of the Metropolitan area of San Juan. The geologic contact along steep scarpments, where the Aguada formation rests on clay and sandy clay of the Cibao formation, is potentially unstable. When the clay becomes saturated with water it tends to flow and to sluff off downhill removing support from beneath the limestone, which then fractures and slides down the lubricated slope (Monroe 1964).

In similar humid tropical geomorphic environments, earthquakes have triggered rotational slumps involving failure of incompetent, plastic strata below limestone (Simmonet, 1967).

Small outcrops of the San Sebastian formation are present in the Aguadilla Quadrangle. Large landslides occur along this formation especially where the thick clayey beds of the San Sebastian formation are exposed beneath the Lares limestone along a scarpment that extends from Aguadilla to Bayamon.

Areas mapped with moderate to high landslide susceptibility in the Aguadilla Quadrangle include the limestone cliffs where the northwestern plateau abruptly descends close to the beach, as well as portions of the Cibao and Aguada Formations. During the October 11, 1918 earthquake, Reid and Taber (1919) reported that more than 6,000 meters of limestone blocks tumbled down from high coastal cliffs close to Punta Agujereada in Aguadilla, and that smaller rock slides occurred especially along mountain roads in the western part of the Island.

In the Arecibo Quadrangle, zones mapped with moderate to high landslide susceptibility include the oversteepened valley sides of the Rio Grande de Arecibo and that of one its tributaries, the Tanama river system. In these areas, lateral support has been removed by downcutting and stream lateral erosion. Along the valley sides of the southern portion of the quadrangle, the weaker Cibao formation is exposed beneath more competent Aguada limestone.

In the Ponce area zones mapped as moderate to high susceptibility are more susceptible toward the north where slopes are steeper than 25 degrees. These zones include the southern section of the

Cordillera Central where Cretaceous and Early Terciary rocks have been extensively folded and faulted. They are covered by relatively thin inceptisols of the Callabo and Caguabo-Mucara-Quebrada association (depth to bedrock < 3 ft. except Quebrada where depth to bedrock is approx. 5 ft.). A generally lower susceptibility is associated with the Ponce and Juana Diaz limestone formations, but locally they will have a high susceptibility where weaker beds outcrop beneath harder, more competent, strata.
Outcrops of the Juana Díaz and Ponce limestone formations are dominated by mollisols of the Aguilita-Tuque association. A layer of colluvial material, commonly reaching more than 1 meter in thickness, is present in many slopes of the limestone hills. When dry, most of these slope materials are stable.

On the other hand, protracted periods of rain can completely saturate the soils, increasing the pore water pressure, reducing the shear strength, and increasing the shear stress with the weight of the water. The effects of extreme rainfall in the Ponce area were suffered in October, 1985, when hundreds of debris flows and slides occurred throughout the region. The most devastating of these was the Barrio Mameyes landslide disaster, where approximately 100 people died.

It is mind-boggling to think what can happen if the selected hazard level earthquake occurs after a long protracted period of rain. The possibility is real and should not be discarded, but seriously considered in the earthquake hazard mitigation plans of the region. In tropical environments similar to those mapped as moderate susceptibility, the percentage of the surface area that as failed during an earthquake of similar magnitude as the probable earthquake ranges from 25 to 40 percent (Simonett, 1967; Pain, 1972). Thus, under these conditions slope materials are expected to move into the bottom valley and choke them with large masses of debris capable of temporarily damming streams. The sudden breaking of the dams by overtopping poses a serious flood hazard to downstream areas.

Areas with low susceptibility to landslides include nearly flat slope zones and very stable rock outcrops. Most of these areas are within the B-1 mapping zone where the ground motion amplification potential is not significant.

Liquefaction

Earthquake generated liquefaction may be defined as the process whereby water-saturated sediments are transformed into a fluid state as a result of build up of hydrostatic pressure between the sediment grains (Schmidt, 1986). When cohesionless water-saturated materials are subjected to earthquake vibrations, the tendency to compact is accompanied by an increase in pore water pressure in the soil due to load transfer from soil particles to pore water. Drainage can occur, but if restricted, pore water pressure can rise to an amount equal to the weight of the column of soil above the soil layer. Under this condition the soil may suffer great deformation and behave like a fluid, rather than like a soil, for a short period of time. Any structures, fills, and embankments located on liquefying soil will undergo deformations.

These can be caused by flow failures, lateral spreads, and by the loss of bearing strength. Flow failures occur when loose, granular sediment, near or at the ground surface, is liquefied and slope conditions permit unrestricted flow displacement which normally transports large blocks of cohesive sediment on top of the flowing mass. This is the most damaging type of slide caused by liquefaction, due to the long distances (more than a kilometer) that the mass can move. Liquefaction-induced flow failures on moderate to steep slopes are very unlikely to occur in the areas of Aguadilla, Ponce and Arecibo. The general absence of loose granular deposits or loose non-cohesive residual materials in the hillslopes is the result of the nature of the geologic materials and the intense tropical weathering that produces much more cohesive residuum. Lateral spreading landslides result when layers of loose to moderately dense material become liquefied at shallow depth and movement is restricted to distances of a few tens of meters or less (Schimdt, 1986). These commonly occur in gentle slope areas and form slow moving masses that spread laterally.

In addition, ground settlement and sand boils can occur. The settlement of sand is principally caused by the horizontal shear component of motion. Lee and Albasia (1974) found that vertical settlements from drainage effects may be as much as 3% of the height of the affected soil layer. If sands are saturated, ground subsidence might be expected from soil compaction and water drainage at stresses less than required to induce complete liquefaction. The volumetric settlements from pore water pressure that are lower than that causing liquefaction are generally less than 1%.

Geologic conditions favoring liquefaction are:

1. a potentially liquefiable bed or lense of porous, well-sorted sand.
2. water saturation of intergranular pore spaces in the bed or lense.
3. confinement of pore water by impermeable layers above and below the liquefiable bed.
4. proximity of the liquefiable bed to the surface (50 feet or less).

Liquefaction occurs mainly where sands and silts have been deposited during the last 10,000 years, and where ground water is within 10 meters of the surface. Generally, the younger and looser the sediment and the higher the water table, the more susceptible the soil is to liquefaction.

In Puerto Rico, liquefaction was observed in the lowlands of Rincón during the October 1, 1918 earthquake. Water, bringing up sand, issued from cracks. The same phenomenon was observed in Añasco, but here the water brought up black sand. Liquefaction was reported in sandy, saturated alluvial materials in areas where the earthquake intensity (Rossi-Forel) was greater than VII (Reid and Taber, 1918). Massive water drainage from alluvial soils increased stream discharge for days after the earthquake.

This phenomenon can be attributed to reconsolidation of the liquefied layer, which causes pore water to move into overlying deposits.

Three major factors are conducive to liquefaction: ground shaking, a shallow water table, and sandy materials. In terms of ground shaking, the selected hazard level of MMI VIII is capable of generating cyclic stresses strong enough to cause liquefaction in the study area. The predominant minimum intensity reported is MMI V (Keefer, 1984). Thus, the study area will experience an MMI of 1 to 2 above the predominant minimum liquefaction threshold. Shallow water tables and sand deposits coincide in river channels, dunes, beach deposits, deltas, silica sand deposits, flood plains, and other topographic lowlands. In these areas the water table is

TABLE 1

Estimated Susceptibility of Sedimentary deposits to Liquefaction During Strong Seismic 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

(continued)

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		-	-

usually less than two meters deep and rarely exceeds five meters. Areas susceptible to liquefaction are mapped according to geomorphic setting, landforms, types and age of geologic deposits, and water table depth (table 1). These factors are used to estimate areas of high, moderate, and low susceptibility. In large scale mapping, or when site specific liquefaction susceptibility must be known, more refined methods based on boring logs and standard penetration tests (techniques developed by Seed and Idriss, 1971, and Seed, 1979) may be used to determine liquefaction potential.

Included in areas of moderate to high susceptibility are Holocene beach deposits. These are dominantly medium to fine grained sand mostly composed of particles of quartz, feldspar, shell fragments and calcium carbonate. Thickness generally ranges from one to five meters. These deposits are located in areas where the ground water table is near the surface due to its location next to the shoreline.

In the Arecibo, Peñuelas and Punta Cuchara, and Aguadilla Quadrangles, zones mapped as A-3 mostly consist of beach deposits and dune sand of Holocene age. In the Playa de Ponce Quadrangle to the east of the Ponce Port area a relatively short stretch of coast has undergone the most rapid advance of any Puerto Rican shore (Kaye C.A., 1959). A series of well marked beach ridges extend inland about a mile from the shore. These are low beach ridges less than 2 meters in height. Kaye calculated a rate of

coastal advance of 5 feet per year between 1936 and 1951. The deposits are made of very loose medium and fine grained sand and should be considered as areas of high susceptibility to liquefaction.
Zones of low susceptibility are older Pleistocene silica sand deposits in the Arecibo and Aguadilla Quadrangles. They are generally one to four meters thick, and the water tables are commonly deeper than in younger deposits.

The liquefaction potential during an earthquake is not exclusive of beach, dune sand and abandoned beach ridges deposits.
A very high potential is locally present in river channels, deltas, uncompacted fills, and lagoonal and flood plain deposits less than 500 years old. Due to map scale limitations, these areas are not mapped independently. Swamp and lagoonal deposits (hydraquents) in the Ponce and Aguadilla areas were mapped as zones with high liquefaction potential when associated with recent Holocene age sand deposits.

Flood plain deposits are vulnerable where the alluvium is composed of cohesionless materials such as silt, silty sand, or fine grained sand. Most of the alluvium in the study area is composed of clay, sandy clay, and sand. Liquefaction-induced flow failure and lateral spreading toward river channels are likely to occur where saturated sand lenses are present. Lateral spreading of flood plain deposits toward river channels destroyed more than 200 bridges during the 1964 Alaska earthquake. They are particulary destructive to pipelines and water mains, a factor which impeded the effort to fight the fire that ignited during the San Francisco earthquake (Hays, 1981). During the 1918 earthquake, the Aguadilla water supply pipe over Río Culebrinas was ruptured by compression when the concrete piers supporting the pipe moved more than 2 meters towards each other across the stream (Reid and Taber, 1918).