GROUND SHAKING

Ground shaking is caused by the sudden release of elastic strain energy stored in the rocks. This process (faulting) generates different waves that propagate from the rupture zone. Two classes of waves are generated: body and surface waves.
Body waves consist of compressional (P) and shear (S) waves. They traverse the Earth's interior with different velocities and motions. Surface waves are Love and Rayleigh waves that travel more slowly than body waves. Body waves are mainly high frequency vibrations, that are likely to make low buildings resonate. Surface waves cause mainly low frequency vibrations more efficient in making tall buildings vibrate. When buildings cannot resist earthquake vibrations generated by these waves, damage occurs (Hays, 1981). Ground shaking damages result from the interaction of ground motion with the building structure. Ground motion characteristics are mainly determined by the depth of the focus, magnitude, attenuation and local ground response.

It has long been recognized that different locations, at essentially the same epicentral distance, experience large variations in the distribution of damage due to the influence of local geologic and soil conditions on ground motion. Soil conditions such as thickness, water content, physical properties of the unconsolidated material, bedrock topography, geometry of the unconsolidated deposits, and underlying rock, among others, can modify the ground surface motions by changing the amplitude and frequency content of the motion.

Amplification of ground motion in a period range that coincides with the natural period of vibration of the structure explains the distribution of damage (Hays, 1980).

Shorter period waves oscillate in the same frequency range as lower buildings, affecting such structures close to the epicenter. Longer period waves, which oscillate in the same frequency range as taller buildings, travel farther and can affect such buildings at relatively great distances from the epicenter. This is a potentially serious hazard for the taller buildings in the Arecibo, Aguadilla and Ponce Area because tall buildings can resonate with higher period waves generated by relatively distant offshore earthquakes.

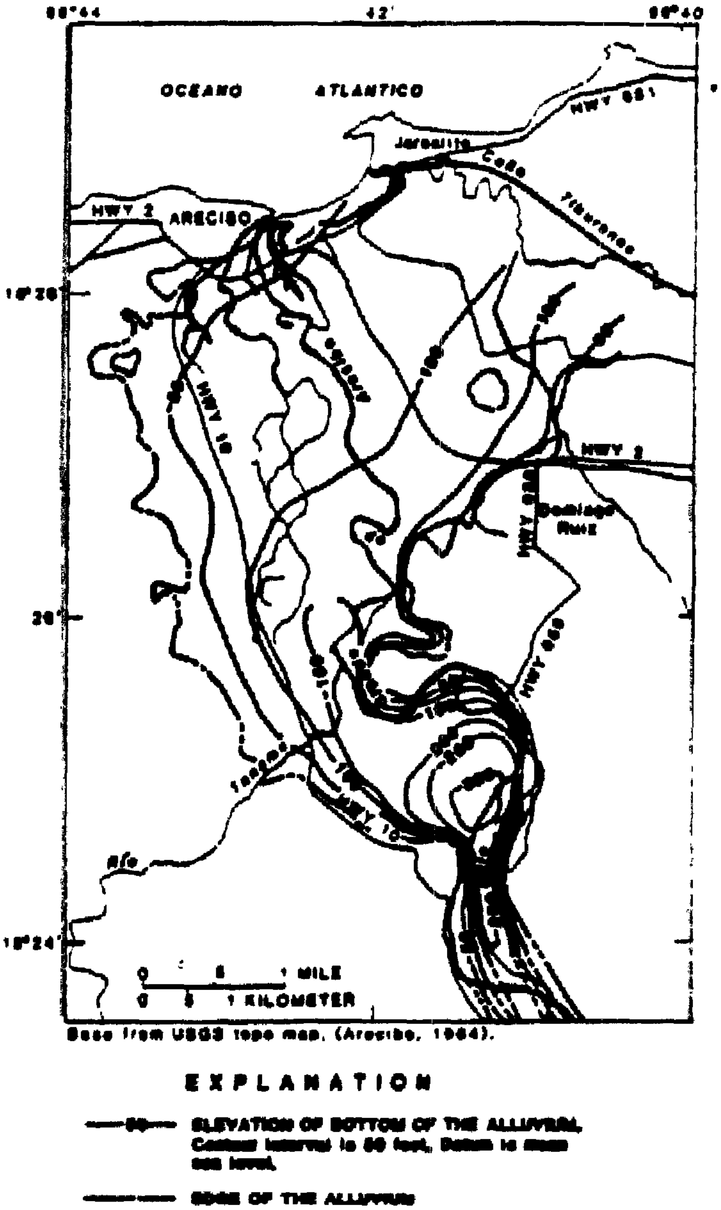
Local soil conditions modify the seismic input by generating maximum accelerations at lower periods for stiff soils where short height structures are likely to suffer more damage. In soft soils, maximum accelerations occur at higher periods where taller structures are subjected to the worst conditions.

In general, areas underlaid by thick deposits of uncompacted artificial fill, by soft, water saturated mud, or by unconsolidated stream sediments, shake longer and harder than areas underlaid by bedrock (Brown and Kockelman, 1983). During the October 11, 1918 earthquake, the La Playa sector of Ponce was more severely shaken than the higher part of the city. Humacao suffered far more than other towns in the same area because it was built upon the alluvium. The greatest damage was registered in Aguada and Anasco, both located on alluvial deposits, while Rincon, built on bedrock an closer to the epicenter than Anasco, suffered much less damage (Reid and Taber, 1919).

Three main deposits are mapped in terms of ground shaking hazard. The lowest hazard (B-1) is assigned to rock outcrops and blanket deposits. Rock outcrops include Cretaceous and Early Terciary volcanic and sedimentary rocks, middle Terciary formations such as San Sebastian, Cibao, Aymamon, Aguada, Camuy, Ponce, Juana Diaz, and eolianites. Blanket deposits are semiconsolidated materials of Pleistocene and Miocene ages characterized by being stiff, hard, and compact. Thickness reaches approximately 30 meters. Intense tropical weathering has resulted in a material that behaves much like bedrock.

All zones of moderate to high (B-2) and high (B-3) ground shaking hazard include all alluvial deposits of Holocene age and some terrace deposits of Pleistocene age. These deposits are present in the floodplains of Rio Grande de Arecibo, Culebrinas, Tallaboa, Pastillo, Portugues, Cerrillos, Inabon, Guayo, Jacaguas and Quebrada del Agua. In Arecibo the sand, clay and sandy clay beds are up to 100 meters thick where the alluvium has covered very deep solutional depressions, presently buried along the valley (figure 6). The subsurface bedrock topography is deeper toward the eastern side of the valley, and contrary to other rivers, the depth of alluvium does not augment toward the present river outlet.

Zones mapped B-3 include the deeper parts of the valley.

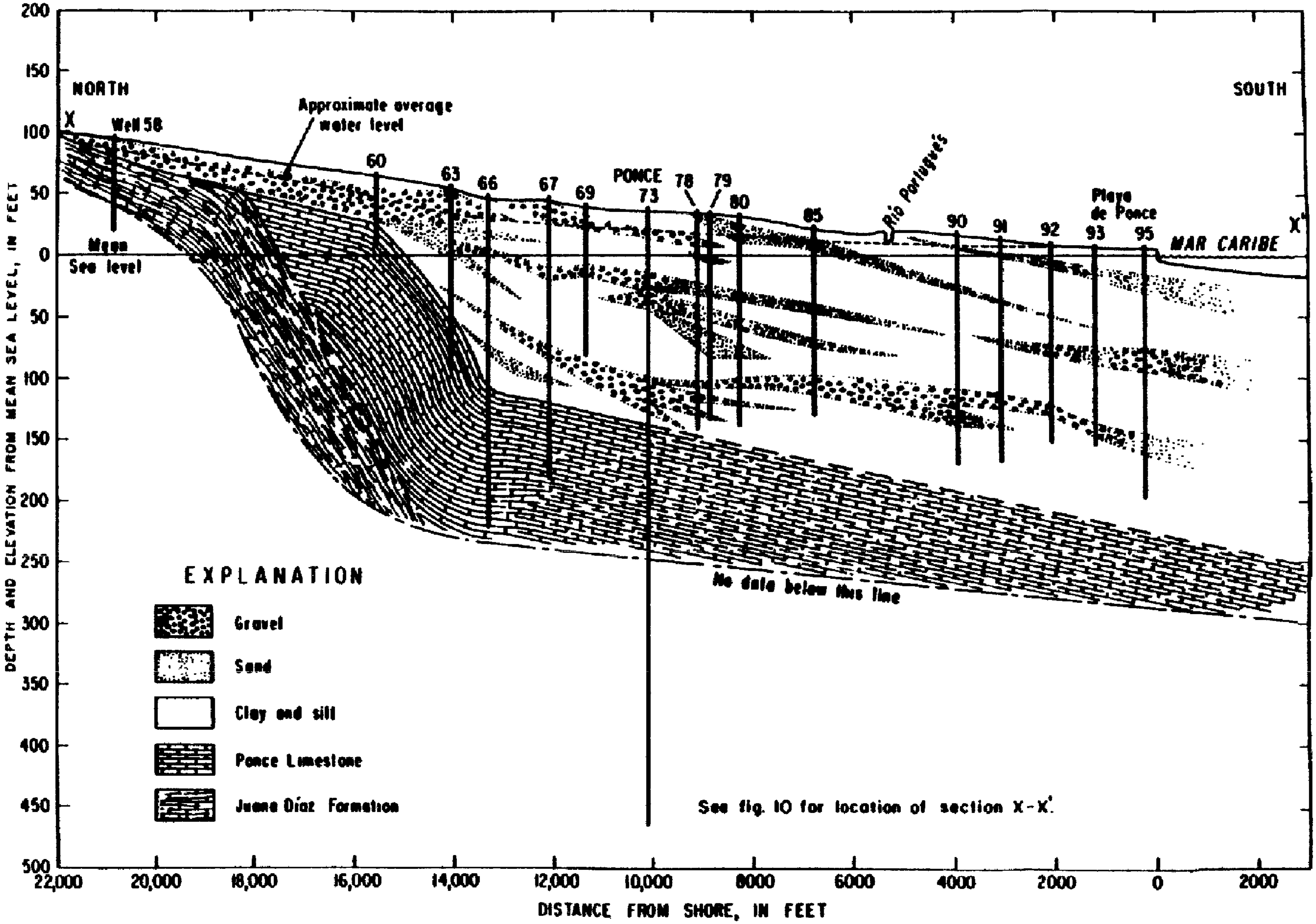


Elevation of bottom of the alluvium at the Río Grande de Arecibo Valley

Fig. 6 U.S.G.S. WRD. (1987)

In the Aguadilla study area the depth of the alluvium of the Rio Culebrinas is estimated to be approximately 10 meters (Monroe, 1967).
A much higher depth is suggested by Gomez (1987), but only on the assumption that the deposits are of similar depth to those found in the Rio Grande de Anasco valley, where the depth of the alluvium exceeds 150 meters. The area has been mapped with a moderate to high ground shaking amplification potential.

In the Ponce study area the thickness of the alluvium and its areal extent across the valley vary locally, but generally increase seaward, reaching approximately 100 meters near the coast (figure 7). At the Tallaboa river valley, high ground shaking amplification potential is present at the center and southern portions of the valley. Moderate ground shaking potential occurs mainly near the valley sides and to the north of road P.R. 2. The whole zone has been mapped B-2 since the tri-dimentional configuration of the subsurface bedrock topography is not precisely known and is likely to be very irregular.
At the Ponce area the alluvium consist of interfingering layers of clay, silt, sand and gravel, underlain by limestone and other clastic rocks.
These alluvial zones are very vulnerable to ground shaking amplification but are generally less vulnerable than artificial fills placed over swamp, lagoonal, alluvium and beach deposits.



Depth to bedrock at the Ponce study area

From Mc Clymonds (1972)

Fill materials have been shown to behave very poorly during earthquakes (Munich Re,1973). Extensive filling of coastal zones mainly at the Ponce Port area at Playa de Ponce, and to a lesser degree at Punta Morrillos in Arecibo, aggravates the degree of hazardousness during intense ground shaking.

Most of the fill material which consists of volcanic rocks, limestone rubble, sand, silt and clay, have created potentially unstable conditions. Manmade fills, consisting of materials ranging from silt to sandy gravel, have failed during earthquakes due to liquefaction of the basal zone of the fills themselves, or of natural foundation materials underlying the fills (Keefer, 1984).

In fact, flow failures carried away large sections of the port facilities at Seward, Wittier, and Valdez, Alaska during the 1964 Prince William Sound Earthquake. Ground shaking induced failures caused the sinking of Port Royal in Jamaica in 1692. Although the conditions where these events took place are not exactly the same as those present in the Ponce Port area and Punta Morrillos in Arecibo, the possibility of ground failure of portions of the artificial fill during a large earthquake cannot be discarded. The presence of relatively deep fill materials over coastal deposits and very high water tables place these areas under a combined high ground failure and ground shaking hazard.

Ground shaking damages result from the interaction of ground motion with the building structure. Ground motion characteristics are mainly determined by the depth of the focus, its magnitude, attenuation and local ground response.

BRIEF SUMMARY AND CONCLUSIONS

The geology and geomorphology of the study area are defined as a preliminary step to mapping earthquake-induced geologic hazards. Three hazards were considered in the study area: ground shaking, landslides and liquefaction. A map depicting hazard zones was prepared showing three levels of susceptibility for each hazard.

The study concludes that the most vulnerable areas to ground shaking amplification are deep alluvial deposits located at the Ponce study area and at the floodplain of the Rio Grande de Arecibo, as well as artificial fills placed over coastal deposits at the Ponce Port area, and to a lesser degree, near Punta Morrillos at Arecibo. Also exposed to a significant ground shaking amplification hazard are all zones mapped as B-Z in the Ponce, Arecibo and Aguadilla study areas.

Important lifelines such as electric energy transmission lines and substations, water mains, docks, airport facilities, vital expressways and roads are located in zones of moderate and high ground shaking amplification potential in the areas of Ponce, Aguadilla and Arecibo. The most critical situation is in the Ponce study area where most of the city is located in deep alluvial deposits.

Moderate to high liquefaction potential is present in the alluvial deposits of the Rio Grande de Arecibo, Culebrinas, Tallaboa, Pastillo, Portugues, Cerrillos, Inabon, Guayo, Jacaguas and Quebrada del Agua, as well as in saturated sand deposits near the coast in beaches, dunes and especially in abandoned beach ridges south of Ponce. Located in these zones are a large number of housing units, roads, schools, commercial buildings, industrial installations, especially those located near the Bahia de Tallaboa area, and others.

Moderate to high landslide potential is present in oversteepened valley sides along the Rio Grande de Arecibo, where lateral support has been removed by downcutting and stream lateral erosion has exposed weaker geologic strata below more resistant ones. In the Aguadilla area, slope movements are likely to occur along coastal limestone cliffs and in outcrops of weaker geologic materials.In the Ponce area, the most susceptible zones are the steep slopes of the southern section of the Cordillera Central. Here, as in other areas, landslide damage potential varies with the antecedent moisture conditions of the hillslopes. An earthquake after a protracted period of rain can severely affect lifelines, especially roads, where slope excavations, overloading, removal of lateral support, and other similar situations cause potentially unstable slope conditions.

It is recommended that earthquake mitigation strategies focus on high risk zones (mapping areas B-3, B-2, A-3, and C-3). Among the study areas considered in this report, priority should be given to the city of Ponce. Here is where the greatest risk to life and property occurs due to its location on alluvial materials that tend to amplify ground motion and to liquefy, especially in deposits located near the coast.

Before any type of important development is approved in zones mapped with a moderate to high ground shaking and liquefaction potential, detailed site specific geotechnical studies must be conducted in order to assess the specific vulnerability so that proper mitigation actions might be taken.

Tsunami hazard poses the greatest threat to the town of Aguadilla. A detailed study should be conducted to map the zones flooded during the 1918 tsunami, as well as to mathematically model the potential inland flooding of probable tsunamis in the area, and in the whole island of Puerto Rico. The Aguadilla area must be considered as one of high priority, since hundreds of people are presently living in the same shoreline areas that were flooded by the 1918 tsunami. To worsen the risk, public housing, schools and hospital facilities have been built in tsunami hazard zones, showing disregard or ignorance toward this serious hazard.

A serious effort must be done by the Commonwealth of Puerto Rico in order to provide the Puerto Rico Planning Board with the necessary maps and information regarding earthquake-induced geologic hazards maps for the whole island of Puerto Rico. This must have high priority, in order to prevent further development of housing units, hospitals, schools, and other important facilities in highly dangerous areas.

Puerto Rico must be prepared for a big earthquake. A significant portion of the residential, commercial, industrial, utility and transportation infrastructures are located in hazardous zones. Today, the potential damage that can be produced by a large earthquake event is greater than ever before. Hazard mitigation efforts must be focused on the protection of life and property. Action must be taken now, while there is time to mitigate significantly the potentially disastrous consequences of a major earthquake in Puerto Rico.

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