colluvial zones (Holocene to late Pleistocene) located in the City of Mayagüez and over the plains located along the margins of some mountains.

Reid and Taber (1919a, b), described many liquefaction characteristics in the alluvial plains, mainly ground cracks and sand blows due to the 1918 earthquake. Ground cracks parallel to the path of the neighboring streams (caused by the slumping of its banks), and cracks of different types (formed in flat lowlands where the water table stood close to the surface) were described. The ground water came up through cracks bringing up sand, which was deposited on the surface. Also, immediately after the earthquake, the ditches in the fields were flooded because of liquefaction induced ground water discharge. The water continued to flow in the ditches for several weeks.

Different zones of the Mayagüez urban area at the moment are located over flat fluvial, swamp, and lagoonal zones (Figure 16). These areas have been covered by numerous subdivisions and filled for construction purposes.

Rodriguez and Capacete (1988), using the Mona Canyon as the source of an earthquake (Figure 17), present a graphic relationship between the corrected N value SPT (number of blow counts during the standard penetration test) and the depth of the water table at which liquefaction will probably occur in the west coast of Puerto Rico during an earthquake similar to the 1918. (The data for Mayagüez do not consider the possible acceleration for an event produced in the Puerto Rico Trench north of the island).

Keefer (1984) used a world-wide database of over 40 earthquakes compiled by Kuribayashi and Tatsuoka (1975) and Kuribayashi (1977), to present a graphical

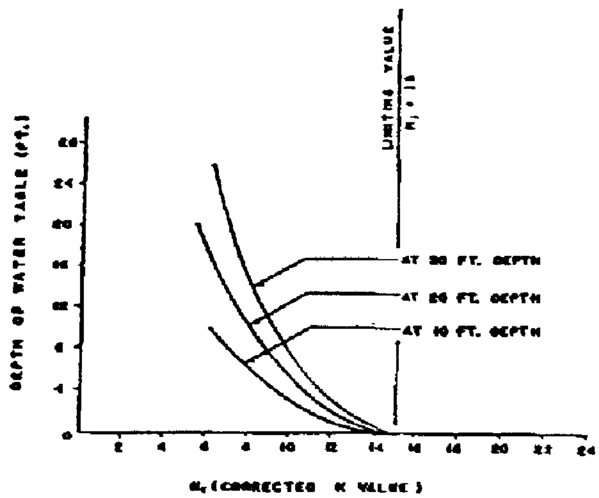

Figure 17. Curves showing corrected N values at which liquefaction will probably occur in the west coast during an earthquake similar to the 1918 earthquake. From Rodriguez and Capacete, 1988.

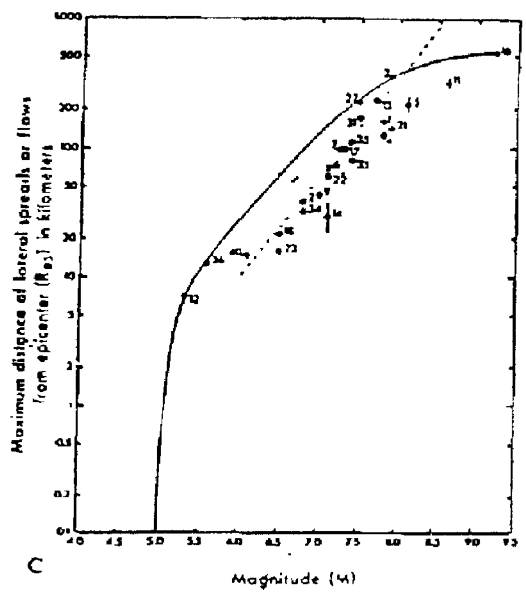

Figure 18. Maximum distance from earthquake epicenter where lateral spreads associated with liquefaction have occurred in past earthquakes. From Keefer, 1984.

representation of the maximum distance from epicenter where lateral spreads associated with liquefaction have occurred in past earthquakes (Figure 18). Also, Tinsley, et. al. (1985), based on empirical data, present how liquefaction is related to near and distant shocks (Figure 19).

Based on Keefer's relationship, liquefaction in the Mayagüez region could also be produced, with an earthquake of 7.5 M located at a distance of 100 km. This event could be generated on the southern wall of the Puerto Rico Trench.

Landslide Hazard- Earthquake induced landslides have caused tens of thousands of deaths and billions of dollars in losses during this century around the world (National Research Council, 1989). The term landslide is used in the generic sense to refer to the various types of mass movements following the Varnes (1978) classification. This includes; falls, flows, slides, topples, and complex combinations. Earthquake induced landslides present a significant hazard according to the susceptibility of the terrain. When the location of the population and buildings coincide with these areas, the risk is significantly increased.

Landslides triggered by earthquakes have been studied widely (Seed, 1968; Wilson and Keefer, 1983; Keefer, 1984; Jibson and Keefer, 1984; Wilson and Keefer, 1985). Keefer (1984) and Wilson and Keefer (1985) examined the relationship of landslides to the duration, intensity, magnitude, distance of the source, and the area affected during earthquakes. Empirical data obtained by Keefer (1984), shows that the selected hazard level of 7.5 M_S used in this study may trigger some landslides over an area up of 40,000 km2 (square kilometers) around the epicenter (Figure 20). The maximum distance of landslides produced by an event of 7.5 M_s is up to 200 km from the epicenter. An event of about magnitude 5.0 is the smallest earthquake likely to cause landslides in the epicentral zone (Wilson and Keefer, 1985), mainly rock falls and rock slides.

The occurrence of landslides generated by an earthquake will depend mainly on: type of material, geologic structure, slope angle, slope length, degree of weathering, water content, type of vegetation cover, and cyclic stress as determined by ground shaking parameters.

Puerto Rico, as in other regions of the world (Wilson and Keefer, 1985), , the number of landslides induced by an earthquake will be greatly increased if heavy or prolonged rains occur a short time before or during the earthquake. If the event occurs during a dry period less damage will occur.

To determine landslide hazard zones, a landslide inventory was prepared using 1936 and 1987 aerial photographs. The most common factors associated with instability found during the field check of the inventory were; oversteepening of slopes, degree of weathering, rock type, rock structure, morphology of the slope, and land use.

The inventory (see map) shows abundant landslides. These were identified using their morphometric characteristics as shown in air photographs as well as in the field.

Approximately 784 landslides (only landslides with a length exceeding 3 meters downslope were inventoried) were found in the study area. Landslide density in each of the geological formation is shown in table 6 which shows the degree of stability and the hazardousness of each area.

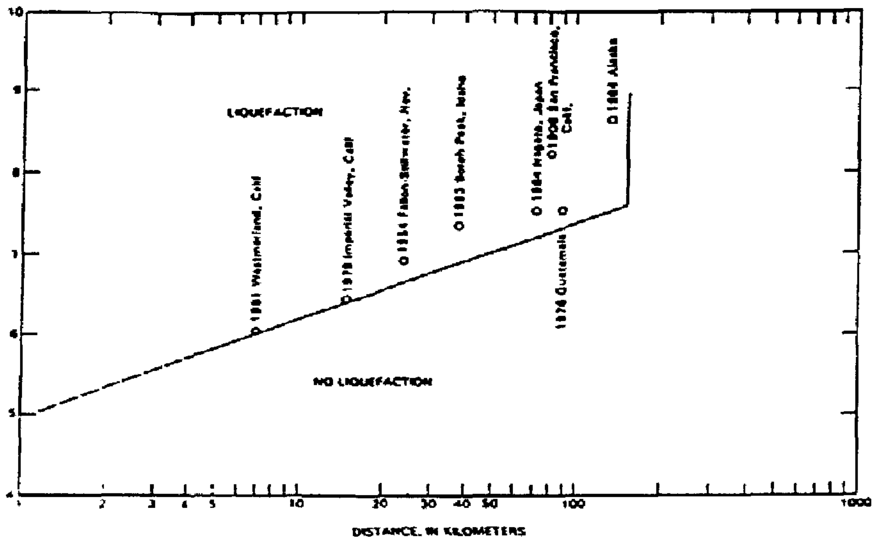

Figure 19. Earthquake magnitude vs distance at which liquefaction has been observed in past earthquakes. From Tinsley et al. 1985.

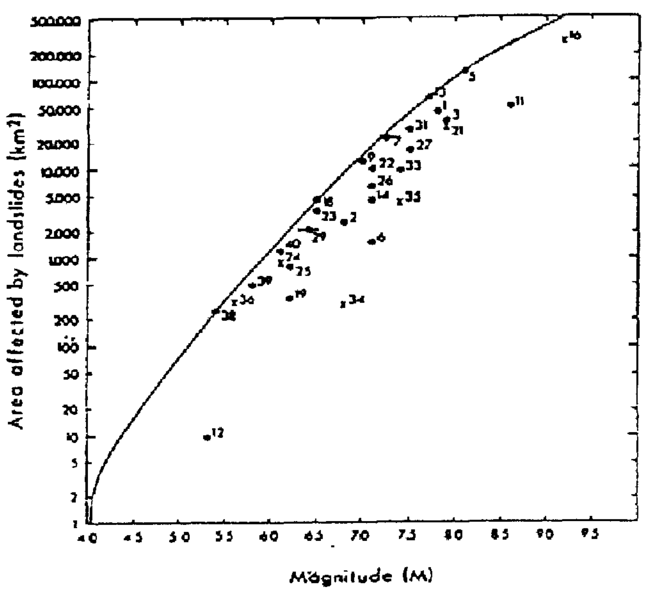

Figure 20. Area affected by landslides in earthquakes of different magnitudes. The solid line is the aproximated uppper bound enclosing all data. From Keefer, 1984.

Table 6. Landslide Potential in the Mayagüez-Rosario Area.

Rock Formations	No. of Slides	% of Total	Approx. Area
Yauco (Ky)	393	50.1%	40.4%
Maricao (Kmr)	111	14.1%	13.3%
Porphyritic andesite-diorite (Tkpa)	107	13.6%	9.5%
Serpentinite (Jse)	85	10.8%	13.8%
Basalt (TKpb)	62	7.9%	6.1%
Sabana Grande (Ksg)	14	1.7%	6.6%
Others (Kr, Tkab, Kjsp, Kmsg, TKab)	12	1.5%	10%

Units like the porphyritic andesite-diorite, basalts, and formations such as Yauco and Maricao, shows the greatest potential for landslides. A more detailed study concerning the gradients and the area should be done to evaluate the landslide potential in the Mayagüez Quadrangle (so the results of this study should be considered preliminary), since landslide susceptibility varies spatially and temporally.

The most important elements that change the behavior of slopes and generate landslides during an earthquake are; the magnitude of the accelerations, the duration of the quake, the degree of rock weathering, and time and duration of the rains. During the field check it was observed that weathering has produced two kinds of effects in soils that inhibit or facilitate the development of landslides. First, in several places weathering has formed a highly altered clayey mantle which give the slopes more resistance to shear stress during dry periods. Second, weathering has developed weak zones in rocks making them more susceptible to landslides during dry or wet periods.

The amount of rain that has fallen in the zone before an earthquake dictates the predominant type of landslides due to the amount of moisture in the soil. Soil slumps, earth and debris flows, rock slides, and lateral spreads could be the most common mass wasting in the Mayagüez region during a wet period. During a dry period the landslides induced by earthquakes may cause less damage, with the occurrence of rock falls, debris slides, debris slumps, rock slides,lateral spreads (maybe caused by liquefaction), soil slumps, and soil block slides being more probable.

A significant number of slides may occur along mountain roads where steep cuts and fills have been placed over potentially unstable materials. A large number of roadside structures are likely to be affected, and old landslides may be reactivated.

In the mountainous areas, poorly designed structures over weak foundations present a serious risk. It is common to have houses constructed on long columns whose height exceeds thirty feet. Strong ground shaking is likely to collapse or tilt these structures. A typical scenario may be one in which the fall of one structure will cause the collapse of others located downslope. In the case of some steep areas, a combination between landslides and structural damage may produce serious property damages to small buildings.

According to evidence found in the region the amount of earthquake damage in rural areas could be as significant as those in the urban zone of Mayagüez.

Tsunami Hazard- Historically, the Caribbean region have been affected by tsunamis. In the 1918 earthquake a big tsunami struck the western coast of Puerto Rico, and killed about 40 persons. The effects of this tsunami were studied by Reid and Taber (1919a) and they found that the wave runup and the arrival time varied for different points along the west coast. Reid and Taber found that in some places north of Mayagüez the water marks indicated that the wave reached a height of 6.0 meters above sea level, but to the south of Mayagüez the water mark reached only 1.5 meters above sea level.

In this work, as a preliminary estimate a height of two (2) meters above sea level along the Mayagüez coast has been defined as the change in sea level caused by the tsunami in 1918. This preliminary estimate is based upon the Reid and Taber descriptions, and the descriptions found in the chronicles of the Redentorist Fathers, (who described the damage to the Del Carmen Church) when the tsunami wave reached this area. The Del Carmen Church is located approximately 400 meters from the beach on the alluvial plain.

For now, the change in sea level of 6 meters (18 ft) can be considered the maximum for tsunami effects along the west coast, as occurred in Aguadilla. It is probable that the 1918 tsunami in the coastal zone had washed away some other earthquake effects such as liquefaction or lateral spreads located on the beach or near the mouth of the Yagüez River.

McCulloch (1985), using a global dataset, presents a classification of tsunami magnitude and the maximum runup height in meters based on earthquake magnitude (Figure 21). The same author presents the relationship between earthquake magnitude and tsunami magnitude (Figure 22). Based on the McCullogh data, the 1918 event would have generated a tsunami with a magnitude of .5 to 1.0 (tsunami magnitude) with a maximum runup height between 1.5 to 3 meters in Aguadilla. More studies to evaluate the damage potential of tsunamis must be done in the area, since at the moment there are many

Tsunami magnitude classification[1]	Tsunami energy, in ergs (foot-pounds)	Maximum runup height, in meters (feet)
5	25.6×10^{23} (18.9×10^{14})	>32 (>105)
4.5	12.8×10^{23} (9.4×10^{14})	24–32 (79–105)
4	6.4×10^{23} (4.7×10^{14})	15–24 (52.5–79)
3.5	3.2×10^{23} (2.4×10^{14})	12–16 (39.2–52.5)
3	1.6×10^{23} (1.2×10^{14})	8–12 (26.2–39.2)
2.5	$.8 \times 10^{23}$ ($.59 \times 10^{14}$)	6–8 (19.7–26.2)
2	$.4 \times 10^{23}$ ($.29 \times 10^{14}$)	4–6 (13.1–19.7)
1.5	$.2 \times 10^{23}$ ($.15 \times 10^{14}$)	3–4 (9.9–13.1)
1	$.1 \times 10^{23}$ ($.074 \times 10^{14}$)	2–3 (6.6–9.9)
.5	$.05 \times 10^{23}$ ($.037 \times 10^{14}$)	1.5–2 (4.9–6.6)
0	$.025 \times 10^{23}$ ($.018 \times 10^{14}$)	1–1.5 (3.2–4.9)
-.5	$.0125 \times 10^{23}$ ($.0092 \times 10^{14}$)	.75–1 (2.5–3.2)
-1	$.006 \times 10^{23}$ ($.0044 \times 10^{14}$)	.50–.75 (1.6–2.5)
-1.5	$.003 \times 10^{23}$ ($.0022 \times 10^{14}$)	.30–.50 (1.0–1.6)
-2	$.0015 \times 10^{23}$ ($.0011 \times 10^{14}$)	<.30 (<1.0)

Figure 21. Magnitud, energy, and runup heights of tsunamis. From Iida (1949) cited by McCullogh, 1985.

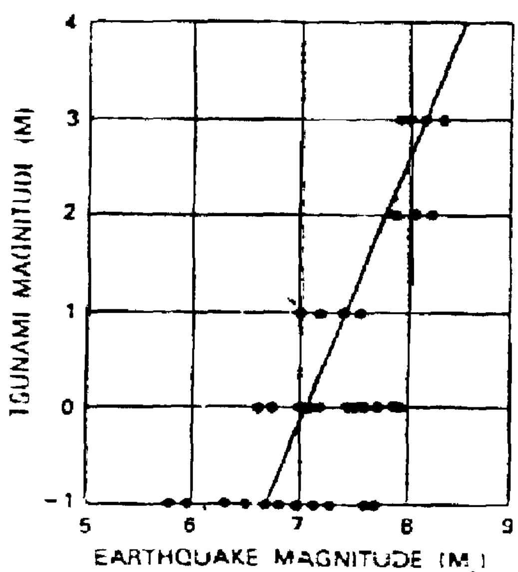

Figure 22. Tsunami Magnitude vs. Earthquake Magnitude. From McCullogh, 1985.

buildings and facilities (commercial, housing and industrial) on the waterfront that are potentially exposed to seismic sea waves. The Mona Passage must be considered as one with high potential to generate tsunamis.

Flood Hazard- Extensive areas in the Mayagüez alluvial plain correspond to areas of swamp, mangrove, and lowlands susceptible to flooding by both the Yagüez River and the Guanajibo River. Some combinations may produce natural floods in the alluvial zones caused or associated with the effect of the earthquakes: a) heavy rains during or before the event; b) water outflow by liquefaction effects in the alluvial zones; and c) floods near shore caused by tsunami; d) landslide blockage on the banks of the Yagüez River.

Hickenlooper (1968) has defined areas of two catastrophic floods in the Mayagüez plains associated with heavy rains (1933 and 1963) (Figure 23). The most vulnerable zones are the western portion of the town of Mayagüez, the Rio Guanajibo alluvial plain and the swamp and mangrove zones. However, channelization and mitigation works have been completed in some areas along the Rio Yagüez.

During the 1918 earthquake, the alluvial zones were flooded due to ground water outflow resulting from the effects of liquefaction (Reid and Taber, 1919a). Immediately after the 1918 earthquake, the alluvial plain of Añasco was filled by an outflow of water. The water continued to flow in the ditches of the zone for several weeks. The ditches of the cane fields were dry before the quake (Reid and Taber, 1919a).

In the case of another earthquake occurring in the zone with the same magnitude as the 1918 earthquake, the lowlands near to the shore are the most prone to be affected by the runup of tsunamis. This runup may affect areas such as beaches, marshes, swamps, and

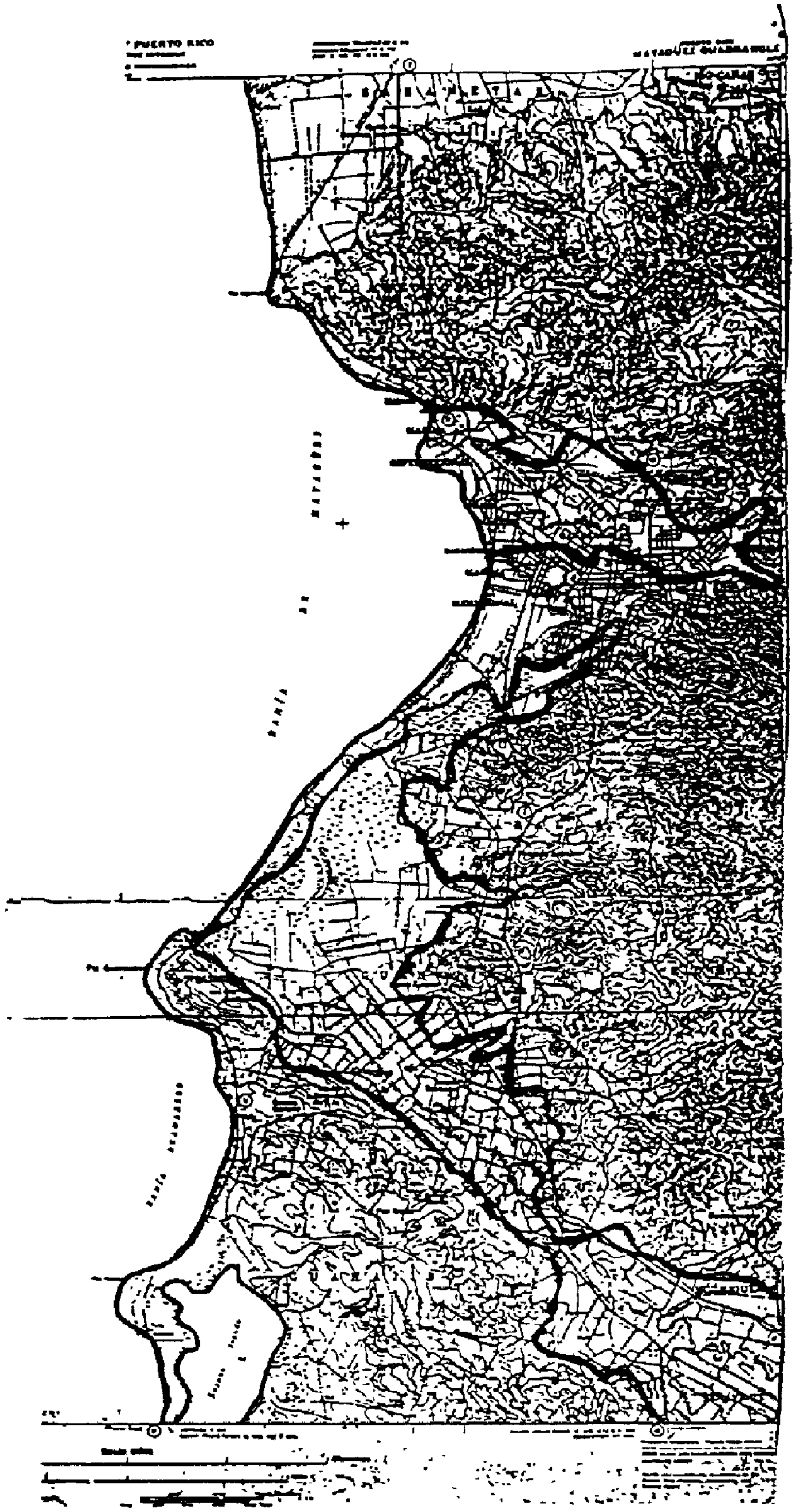

Figure 23. Limit of the catastrophic floods occurred in this century in the Mayagüez Region. After Hickenlooper, 1968.

the mouths of rivers. Many of these areas at the moment have been modified by construction and housing activities. Thus, the lowlands could be severely affected by flooding and other hazards such as liquefaction and ground shaking. The consequences of floods (by liquefaction effect, by heavy or prolonged rains, or tsunamis during or before the quake) may block traffic in some segments of routes #2, #102, or #341, located in the lowlands, complicating rescue efforts if the event was very large.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions- Three major earthquake sources must be taken into consideration when planning for the Mayagüez Area. They are:

1. Puerto Rico Trench, 70 kilometers distance, maximum magnitude event about $8.0M_S$.

2. Mona Canyon, about 35 km distance, maximum magnitude event about $7.5M_S$.

3. Mayagüez and Cordillera Faults, about 0-10 km distance, maximum magnitude event about $6.5M_S$.

Due to their distance and size, the first two sources would generate similar intensities in rock throughout the area. The third source(s) could generate significantly higher intensities in limited areas near the faults themselves, with intensities decreasing rapidly with distance from the fault. Accelerations are estimated by using the source magnitude in the attenuation relation of Donovan (1973) to obtain acceleration (Appendix C). Intensities are estimated from accelerations using the relation of Richter (1958). The maximum peak acceleration and intensity to be felt on rock in the Mayagüez area corresponding to a maximum earthquake in one of the three source zones is as follows:

1. Puerto Rico Trench, accel. 0.15g, intensity VIII (MM).

2. Mona Canyon, accel. 0.21g, intensity VIII (MM).

3. Mayagüez or Cordillera Fault, accel. 0.26 to 0.41g for distances of 0-10 km from the fault, intensity VIII-IX (MM).

These accelerations are maxmimum peak accelereations and not rms accelerations. Therefore, accelerations cited above should not be used in their absolute sense for plannng purposes, but rather as a measure of relative acceleration levels potentially generated by any given source.

Accelerations in zones classified as being A-3-S, B-2 and B-3 would be higher than those noted above due to amplification of ground shaking. In the Mayagüez area, these zones correspond to most of the urbanized part of the city, the area roughly delimited by route 2 and the Guanajibo River to the south, and a thin coastal strip to the north of the city as well as the Añasco River valley. Effects will be more severe in the filled areas to the south of Punta Algarrobo, Marina Septentrional, the area of Caño Corazones and the area near Caño Majagual near Vista Verde.

Zones with a high potential for liquefaction have been defined based on Arroyo's study as well as geomorphologically. These zones correspond to areas classified as A-3, A-3-S, B-2, and B-3. They also correspond to most of the areas previously mentioned for ground shaking amplification.

The slopes of the area allow the division of the mountainsides into two categories, C-1 and C-2. The area to the south of the Guanajibo river is classified as C-1 and the remained of the mountainous area is C-2. Landslides induced by strong ground shaking would occurr mainly in zones C-2. Mountainsides modified by oversteepening will be more likely to slide during a major earthquake that low grade slopes.

The tsunami threat in Mayagüez, as seen in historic records, is limited to the coastal area within 300 to 400 meters of the coast and 2-6 meters above sea level. The distance to which the sea may penetrate will depend upon the steepness of the coastal profile, both offshore and onshore, and the earthquake magnitude and location.

A combination of tsunami and liquefaction induced expulsion of water from below the water-level could complicate rescue efforts after a major earthquake. This effect would be observed mainly near the mouths of the Yagüez and Guanajibo Rivers.

The coastal zone of Mayagüez is more prone to suffer severely during a major earthquake because of the likely combination of different earthquake induced geologic hazards. Extreme care should be taken when developing the coastal strip affected by the 1918 tsunami.

Recommendations-

Recognizing the implications of the conclusions stated above, we have defined some topics that deserve prompt attention. Seismically, geologically and geomorphologically there is sufficient evidence of Ouaternary faulting in Western Puerto Rico. More studies of the geology, geomorphology and seismic activity of the Mayagüez, Cordillera and other suspect faults is urgently needed. The general archives of Puerto Rico contain the damage reports for the 1918 earthquake, the exact data needed to begin a microzonation program for Mayagüez as well as other cities in Western Puerto Rico.

One of the least understood parts of this study is the attenuation of acceleration from the potential sources in the island. Studies of velocity and acceleration attentuation should be undertaken as soon as possible.

The authors have found a fault cutting material of probable Quaternary age that should be dated. The fault is to be found on kilometer 3 of route 100 south of the Guanajibo River. The description of the fault is not included in this work because its' study is in the preliminary stages. However, we can recommend that the materials cut by the fault be dated so as to determine the seismic history of the fault.

It is necessary to do more studies to better understand the maximum limits of tsunami hazards. These studies include potential sources in Mona Passage, and effects of the near coast profiles on run-up height.

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REFERENCES

Arroyo, E.N., 1991, Liquefaction Analysis Potential on some site on the Mayagüez Area based on geotechnical reports. Research project presented to the Geology Department, University of Puerto Rico, Mayagüez Campus. 27p.

Asencio, E. Jr., 1980, Western Puerto Rico Seismicity. U.S. Department of the Interior Geological Survey, Open File Report 80-192.

Bolt, B. A., 1978, Earthquakes- A Primer. Ed. W. H. Freeman and Company, San Francisco.

Bonilla, M. G., Marck, R. F., and Lienkaemper, J. J., 1984, Statistical Relations Among Earthquake Magnitude, Surface Rupture Length and Surface Fault Displacement. Bull. Seism. Soc. of Amer., 74, 2379-2411.

Boore, D.M., 1973, The effect of simple topography on seismic waves: implications for the accelerations recorded at Pacoima Dam. San Fernando Valley, California: Bull. Seism. Soc. Amer.,63,1603-1610.

Bouchon, M. P., 1973, Effect of topography on surface motion: Bull. Seism. Soc. Amer.,63, 615-637.

Briggs, R. P., 1964, Provisional Geologic Map of Puerto Rico and Adjacent Areas: U.S. Geological Survey Misc. Geol. Invest. Map I-392.

Budhu, M., Vijayakumar, V., Giese, R. F., and Baumgras, L., 1990, Liquifaction Potential for Sites in Manhattan and Buffalo, New York, Bull. of the Ass. of Eng. Geol. Vol. XXVII, No. 1,61-72.

Byrne, D. B., Suarez G., and McCann, W. R., 1985, Muertos Trough Subduction-Microplate Tectonics in the Northern Caribbean, Nature,317,6036,420-421.

Capacete, J.L., and A. Herrera, 1972, The 1918 Earthquake; An Engineering Study. CIAA. Vol. XXII, No.1. p.41-48. Puerto Rico.

Chen, A. T. F., 1988, PETAL3 Program. U.S.G.S. Open File Report 88-540.

Colón, E., and Quiñones Márquez, F., 1985, A Reconnaissance of the Water Resources of the Central Guanajibo Valley, P. R. U.S. Geological Survey, Water Resources Investigations Report 82-4050.

Curet, A. F., 1986, Geologic Map of the Mayagüez and Rosario Quadrangles, Puerto Rico Department of the Interior, U.S. Geological Survey, 1:20,000 Map I-1657.

Krushensky, R.D., 1978, Geologic map oof the Peñuelas and Punta Cuchara quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1042, scale 1:20,000.

Krushensky, R.D. and Curet, A., 1984, Geologic map of the Monte Guilarte quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1556, scale 1:20,000.

Kuribayashi, E., and Tatsuoka, F., 1975, Brief review of liquefaction during earthquakes in Japan: Soil and Foundations, V. 15, No. 4, p. 81-92

Kuribayashi,E., 1977, History of Earthquake-induced soil liquefaction in Japan: Ministry of Construction of Japan, Public Works Researc Institute Bulletin, V. 31, 26p.

Marrero, A., López, R., and Jiménez, R., 1983, Amplification Study of the Rio Grande de Arecibo Alluvial Deposits. Univ. of Puerto Rico, Mayagüez.

Masscn, D. G., and Scanlon, K. M., 1991, The Neotectonic Setting of Puerto Rico. Geol. Soc. Ame. Bull. v. 103, p.144-154.

Mattson, P. H., 1960, Geology of the Mayagüez area, Puerto Rico: Geological Society of America Bulletin, v.71, No.3, p. 319-361.

McCann, W. R. and Sykes, L. R. 1984, Subduction of Aseismic Ridges Beneath the Caribbean Plate: Implications for the Tectonics and Seismic Potential of the Northeastern Caribbean. Journal of Geophysical Research, Vol. 89, No. B6, pp-4493-4519.

McCann, W. R., 1985, On the Earthquake Hazards of Puerto Rico and the Virgin Islands. Bull. Seism. Soc. Am. Vol.75, No. 1, pp-251-262.

McCann, W. R., 1987, Historic Earthquakes and the Earthquake Hazard of Puerto Rico. Published in "A Workshop on Assessment of Geologic Hazards and Risk in Puerto Rico", Open File Report 87-008. Reston, VA.

McCann, W. R., Joyce, J., Lithgow, C., 1987, The Puerto Rico Platelet at the Northeastern Edge of The Caribbean Plate, Trans. Am. Geophys. U., EOS, 68, p1483.

McCann, W. R., 1989, Preliminary Seismic Hazard Map of Puerto Rico.

McCann, W. R., Feliciano, J. and Carlo M., 1991, Neotectonics, Seismicity and Seismic Hazard of Western Puerto Rico. In prep.

McCulloch, D. S., 1985, Evaluating Tsunami Potential: Evaluating Earthquake Hazards in the Los Angeles Region-An Earth- Science Perspective., U.S. Geological Survey Professional Paper 1360., p. 375-414.

McGuiness, C. L., 1946, Records of Wells in Puerto Rico. U.S. Geological Survey. Study prepared for Aqueduct and Sewer Service.

McIntyre, D. H., 1974, Concepcion and Palma Escrita Formations, Western Puerto Rico, Geological Survey Bull. 1394-D.

Molinelli, J, 1985, Earthquake Vulnerability Study for the Metropolitan Area of San Juan, Puerto Rico. Department of Natural Resources, Puerto Rico.

Molinelli, J., 1988, Earthquake Vulnerability Study for the Areas of Ponce, Arecibo and Aguadilla, Puerto Rico. Department of Natural Resources, Puerto Rico. 82 pp.

National Research Council, 1989, Estimating Losses From Future Earthquakes. National Academy Press, pp. 195-215, Washington.

Obermeier, S. F., 1984, Liquefaction Potential in the Central Mississippi Valley. Proceedings of the Symposium on "The New Madrid Seismic Zone". U. S. Geological Survey, Reston Virginia, 1984.

Reid, H. and Taber, S., 1919a, The Porto Rico Earthquake of 1918, with Descriptions of Earlier Earthquakes (Report of the Earthquake Investigation Commission), House of Rep. Doc. 269, Washington, D.C., 74 p.

Reid, H. and Taber, S. 1919b, The Porto Rico Earthquakes of October-November 1918, Bull. Seism. Soc. Amer., 9, 95-127.

Richter, C. F., 1958, Elementary Seismology, W.H. Freeman and Co. San Francisco, California, 768p.

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

Seed, H. B., 1968, Landslides during earthquakes due to soil liquefaction: American Society of Civil Engineers, Journal of the Soil Mechanics and Foundation Division, ASCE, V. 94, SM5, Proc. Paper 6110, p. 1053-1122.

Seed, H. B., and Idriss, I. M., 1971, Simplified Procedure for Evaluating Soil faction Potential, Journal of the Soil Mechanics and Foundations Division. ASCE, Vol. 97. No.9.

Seiders, V. M., Briggs, R. P., and Glover, L., 1972, Geology of Isla Desecheo, Puerto Rico, with notes on the Great Southern Puerto Rico Fault Zone and Quaternary stillstands of the sea: U.S. Geological Survey Proffesional Paper 739, 22p.

Soto, A. E., García, C. and Gonzalez, C. 1985. Liquefaction Potential Map of the San Juan

Der Kiureghian, A. and H. S. Ang, 1975, A line source model for seismic risk analysis. Civil Engineering Studies, SRS #419.

Díaz, J. R. and Jordan, D. G., 1987, Water Resources of the Río Grande de Añasco-Lower Valley, Puerto Rico. U.S. Geological Survey Water Resources Investigations Report 85-4237.

Donovan, N. C., 1973, A statistical evaluation of strong motion data including the February 9, 1971 San Fernando earthquake: World Conf. on Earthquake Engineering, 5th, Rome, Proc., v. 2, paper 155, 10 p.

Frankel, A., 1982, The effect of attenuation and site response of the spectra of microearthquakes in the northeastern Caribbean, Bull. Seismol. Soc. Am., 72, 1379-1402.

Garrison, L.E., 1969, Structural geology of Muertos Insular Shelf. Puerto Rico: U.S. geological Survey Open-file Report No. 1270, 9 p.

Geomatrix Consultants, 1988, Earthquake Ground Motions for the Portugues Dam, Puerto Rico. Geological-Seismological Evaluation to Assess Potential. Department of the Army, Jacksonville District, Corps of Engineers, Jacksonville, Florida.

Hays, W. W., 1980, Procedures for Estimating Earthquake Ground Motions. U.S. Geological Survey Professional paper 1114.

Hickenlooper, I.J, 1968, Floods in the Mayagüez Area of Puerto Rico. U.S. Geological Survey, Hydrologic Investigations Map. Atlas HA-288.

Housner, G.W., 1973, "Report on Earthquake Requirements for the Building Code of Puerto Rico". Junta de Planificación.

Jibson, R. W., and Keefer, D. K., 1984, Earthquake-Induced Landslides in the Central Mississippi Valley, Tennessee and Kentucky. Proceedings of the Symposium on "The New Madrid Seismic Zone". U.S. Geological Survey, Reston Virginia, p. 353-390.

Joyce, J., W. McCann, and C. Lithgow, 1987, Onland Active Faulting in the Puerto Rico Platelet, Trans. Am. Geophys. U., EOS, 68, p1483.

Kaye, C. A., 1959, Shoreline Features and Quaternary Shoreline Changes Puerto Rico. U.S. Geological Survey Professional Paper 317-B.

Keefer, D. K., 1984, Landslides caused by earthquakes, Geol. Soc. Amer. Bull., 95,406-421.

Kiureghian, A. D. Der, and Ang, A. H-S., 1975, A line Source Model for Seismic Risk Analysis. Grant GK-36378. National Science Foundation.

Metropolitan Area, Puerto Rico. U.S. Geological Survey Contract No. 3. 9910-1190. Engineering Research Center of the University of Puerto Rico. Mayagüez.

Sykes, L. R., McCann W. R., and Kafka A. L., 1982. Motion of Caribbean Plate During Last 7 Million Years and Implifi- cations for Earlier Cenozoic Movements. Journal of Geophysical Research, Vol. 87, No. B13, pp. 10,656-10,676.

Tinsley. J. C., Youd, T. L., Perkins, D. M. and Chen A.F., 1985, Earthquake-Triggered Ground Failure, Evaluating liquefaction Potential: Evaluating Earthquake Hazards in the Los Angeles Region-An Earth-Science Perspective., U. S. Geological Survey Professional Paper 1360, p. 263-316.

Trumbull, J.V.A., (compiler) 1981, Oceanographic data off Puerto Rico and the Virgin Islands: Lawrence Berkeley Laboratory Publications 360, Berkeley, California.

Varnes, D. J., 1978, Slopes Movements and Types and processes. In: Landslides:Analysis and Control, Transportation Res. Board Nat. Ac. Sci. Washington Spec. Rep. 176.

Volckman, R. P., 1984, Geologic Map of the Puerto Real Quadrangle, Southwest Puerto Rico 1:20,000 Map I-1559. U. S. Geological Survey.

Western Geophysical Research, 1974, Seismicity Investigation, Aguirre Nuclear Plant Site, Puerto Rico Water Resources Authority Amendment #11 to preliminary facility description and safety analysis report, Aguirre Plant #1, UA AEC Docket #50-376.

Wilson, R. C., and Keefer, D. K., 1983, Dynamic analysis of a slope failure from the 6 August 1979 Coyote Lake, California earthquake: Seismological Society of America Bulletin, v. 73, no. 3, p. 863-877.

Youd, T.L., and Perkins, D. M., 1978, "Mapping liquefaction-Induced Ground Failure Potential", Journal of Geotechnical Engineering Division.

APPENDIX A.

Mayaguez Area

1524-28 Date and Time Unknown
The author states that it is probable that the house of Ponce de Leon at Anasco was destroyed by a violent earthquake between 1524 and 1528. The quake also destroyed other strong buildings. The shock was felt strongest in the north over all the region from Mayaguez to Anasco (12).

1831 September 7 0500 60 MT
Aguadilla. Strong shock (V?) lasting 3 seconds (1).

1848 Date and Time Unknown
Mayaguez. Several light shocks felt during the month (1). Listed as Mayaguez, Puerto Rico (3).

1850 April 8 0900 60 MT
Mayaguez, where church bells rang. The shock reported from Martinique on this date must have had a different origin (1).

1860 October 23
Mayaguez. Rather strong shock with some damage, VI-VII (1).

1864 May 30
Mayaguez. Light shock, III (1).

1866 February 7 0800 60 MT
Mayaguez, IV (shocks at 0800, 1300, 2015, and 2300). The report for January 7 and February 7 may refer to the same shock (1).

1901 June 1 0935 60 MT
San German, III (1).

1901 November 27
Felt at Las Marias (28).

1901 December 27
Las Marias, III (1). Felt at Las Marias. No damage (28).

1902 August 29
San Salvador and San German, III (1). Felt at San Salvador and San German. Slight (28).

1902 September 2
San German, III-IV (1). Light earthquake felt at San German (28).

1903 February 15
Las Marias (1). Light earthquake felt at Las Marias (28).

1904 June 9
Las Marias, III-IV (1). Light earthquake felt at Las Marias (28).

1906 January 18 0615 60 MT
San German, III-IV (1). San German. Light; duration about 8 seconds (28).

1912 September 24
San German and San Salvador (1). Weather Bureau reported this quake on December 24, 1912, showing felt reports from San German and San Salvador (28).

1913 August 5 2030 60 MT
Cabo Rojo (1). Felt at Cabo Rojo (28).

1916 November 18
Maricao (1, 28).

1917 October (or November)
Dates unknown. Mayaguez, VI; cracked walls in some houses. Vertical movement (1).

1920 March 7, April 12, June 1, June 29, August 7, September 9
Las Marias (28).

1921 March 19 1815 60 MT
Felt at Cabo Rojo (28).

1922 January 3 2120 60 MT
Mayagüez reported an earthquake January 3 at 9:30 p.m. It was felt strongly, and the public was alarmed. Another shock was felt at approximately 10:00 p.m. There was no damage, but both shocks caused considerable panic (22, 28).

1922 May 4 0750 60 MT
Reported felt at Mayaguez; about 5 seconds duration; direction east-west. Also reported from Canovanas at 0737 and from Jayuya (28).

1922 November 3 0145 60 MT
Mayaguez reported the shock as having a trembling nature; intensity II; duration 5 seconds; direction east-west (28).

1922	December 9 0035 60 MT Mayaguez reported seismic tremor of rocking nature; duration 2 seconds; intensity II (28).
1922	December 30 0205 60 MT Felt in Mayaguez; duration about 3 seconds; direction east-west. Aftershock of rocking nature also reported by Mayaguez with intensity of III; duration 7 seconds; direction east-west (28).
1923	February 26 0630 60 MT Felt at Mayaguez. Three shocks of rocking nature. Onset gradual with duration of about 6 seconds; direction east-west; intensity III (28).
1923	June 10 2130 60 MT Shock of rocking nature reported by San Juan and Rio Piedras; onset abrupt. Mayaguez reported four shocks beginning at 2109 of rocking nature, each shock of about 1 second duration; direction east-west; intensity III; onset gradual. Also, Mayaguez reported three shocks of rocking nature at 1700 on June 14; onset gradual; direction east-west; duration 2 seconds each; intensity III (28).
1923	October 25 0824 60 MT Felt at Mayaguez. Onset gradual; trembling nature; duration 5 seconds; intensity V; direction east-west (28).
1925	January 25 1305 60 MT Three moderate shocks were felt at Mayaguez. Direction east-west; duration about 3 seconds; rocking nature with an intensity of III (28).
1928	April 13 1920 60 MT Two shocks at Mayaguez. Rapid onset; trembling nature; felt by many.(28).
1931	September 19 2350 60 MT Moderate shock at Mayaguez felt as a gently rhythmic motion and in a pronounced north-south direction. Felt at Santurce with less intensity. Recorded at San Juan. Four shooks recorded on September 19 and 20 (1). Felt in Mayaguez and San Juan (31).
1931	September 25 1435 60 MT Moderate shock at Mayaguez. Bumping and slight swaying (1).

1936 December 11 2219 60 MT
Mayaguez, IV. Recorded at San Juan (seismograph?) (1).

1937 September 9 2020 60 MT
San German. Aftershock at 2400, same date (1).

1937 September 11 0638 60 MT
Slight shock at San German. Probably an aftershock of September 9 shock (1).

1937 October 4 0477 60 MT
Tremor at Ponce and San German. Awakened observers (1).

1939 January 1 0400 60 MT
Sabana Grande. Slight, but felt by many (33).

1955 October 10 0030-0100 60 MT
A high intensity earthquake was felt in Mayaguez that caused great concern. It lasted about 30 seconds. It started with a high tremor reducing in intensity in its final stages. El Mundo newspaper notes that the Coast and Geodetic Survey Observatory at Guaynabo said it recorded no earthquake on this date (22).

1958 July 16
Weak. Felt at Mayaguez (35).