

INTRODUCTION

Landslides in Puerto Rico have caused considerable damage to property and some loss of life. The industrial development of the island since 1950 has necessitated excavation of slopes that has produced many potentially dangerous areas. Landslides are relatively common in a variety of rock types. The largest slides, several hundred cubic meters in volume, happen where limestone rests on clay that becomes plastic when wet; mudflows and rockfalls, on the other hand, are common in areas of deeply weathered volcanic and intrusive rock.

Puerto Rico is a tropical island, elongate east-west and lying between the Caribbean Sea and the Atlantic Ocean. A central mountainous upland is composed of extensive and intrusive igneous rocks and minor amounts of limestone, sandstone, and conglomerate of Early Cretaceous to Eocene age. The upland separates belts of limestone of middle Tertiary age cropping out near the southern and northern coasts. Along the coasts, relatively narrow coastal plains (fig. 1) are made up of beaches, swamps, sand dunes, alluvial fans, and alluvial fans. These features consist of sand, gravel, and clay.

Different rock types and unconsolidated materials have different weathering characteristics. The alluvium, in general, is completely weathered to sand and clay. Limestone is dissolved in acid rainwater, and the impurities in the rock remain as a residual of clay. Commonly the residual cover developed on limestone is washed away during heavy showers, leaving bare rock exposed. This exposed limestone is soon case hardened (Monroe, 1976, p. 17, 44), and further solution and weathering is retarded. The intrusive rocks, largely granodiorite and quartz diorite, weather very rapidly into ferruginous sandy clay, which is subject to rapid gullying, where the natural slope has been disturbed, small landslides occur. Residual boulders and concretions on much of the quartz diorite terrane are likely to move downhill during rainy periods. Concretions also form on some thicker lava and some tuffaceous sandstone. Most of the other rocks, such as lava, volcanic breccia, tuffaceous sandstone, claystone, siltstone, and conglomerate made up of volcanic debris, weather into tough clay that resists gullying. In the central mountainous portion of the island, the weathered material has been eroded into deep canyons; the walls of the canyons slump in massive landslides.

by rockfalls at the head of the slide slope. Similar but less continuous landslides are a little farther north along a smaller escarpment where the Aguada Limestone (Miocene) rests on clay and sandy clay of the Cibao Formation (Oligocene and Miocene). Somewhat similar conditions have produced a very large landslide on the southern slope of the Cordillera Central at Hacienda Limón (Briggs, 1971), about 6 km northeast of Villalba, where highly weathered tuffaceous conglomerate is overlain by massive tuffaceous limestone. The conglomerate sloughs away, and the limestone slides downhill, carrying with it a large quantity of the weathered conglomerate. Many of these landslides are old, (geologically) but some are now being reactivated by recent excavations.

Landslides of a few cubic meters are present throughout the area underlain by weathered volcanic rock and sediments derived principally from volcanic materials. Stability of most slopes in this area varies from good to fair (Briggs, 1971). In areas of outcropping Cretaceous to lower Tertiary rocks, stability is poor where rocks are underlain by hydrothermally altered rock (Pease and Briggs, 1960; Briggs, 1971), and stability is best in areas underlain by very fine lava and lava breccia. Very few landslides occur in areas underlain by limestone, except where the limestone rests on plastic clay.

The large masses of intrusive rock, mainly quartz diorite and granodiorite, readily weather to sandy clay and clayey sand that slump into roadcuts and other excavations after most large rainstorms; no large landslides, however, are known to have occurred in this weathered soil. Some intrusive rocks are jointed and weather into large concretions, some of which are several meters in diameter; these boulders tend to slide downhill during heavy rains, especially those accompanying hurricanes. Large accumulations of these boulders have moved downhill and crushed houses on the slopes of the Cuchilla de Piedras in the southeastern corner of Puerto Rico.

In western Puerto Rico in some of the quadrangles that have not yet been mapped geologically, several landslides are present in large masses of serpentine.

SUSCEPTIBILITY TO LANDSLIDING

Puerto Rico areas of high susceptibility to landsliding generally coincide with areas of high incidence of landslides. Four categories of susceptibility were mapped by using published geologic maps and by personal observation. Mapped units include: (1) areas of highest susceptibility (including recent and active slides); (2) areas of high susceptibility; (3) areas of moderate susceptibility; and (4) areas of low susceptibility. These categories indicate the relative potential of downslope movements occurring in an area after excavation.

Areas of highest susceptibility.—The areas of greatest potential of landsliding are the areas consisting of landslide material. Excavation in these areas almost invariably causes new slides in old slide deposits. Probably all these landslides are of Holocene age, but some are no longer active. A few appear to have been reactivated into fairly stable terraces. Because of the danger of disturbing present stability, the areas shown on the map as existing landslides should either be avoided or special precautions should be taken to prevent new movement during excavation. The map shows only the larger masses, and detailed geologic maps of areas of high or moderate susceptibility should be used to locate smaller landslides. Puerto Rico Route 149 is built on a large recent mudflow or debris avalanche north of Villalba (Briggs, 1971; Matton, 1968). Parts of that supposedly stable area may be highly susceptible to landsliding, so extra precautions should be taken before large areas around the highway are excavated.

Areas of high susceptibility.—Almost all areas having slopes greater than 50 percent should be included in the area of high susceptibility except in the arid southwest. In addition, areas of slide-prone rock and soil types are mapped as areas of high susceptibility. They include the belts of outcrop of the San Sebastian and Cibao Formations in northern Puerto Rico (Monroe, 1973b) and the areas underlain by intrusive and volcanic rocks (Briggs and Ackers, 1963). In the mountains of northeastern Puerto Rico, where sections of several roads have been destroyed by landslides and mudflows, excavations can be made in some of these areas, but special precautions against sliding should be taken during excavation. The map shows only the larger masses, and detailed geologic maps of areas of high or moderate susceptibility should be used to locate smaller landslides. Puerto Rico Route 149 is built on a large recent mudflow or debris avalanche north of Villalba (Briggs, 1971; Matton, 1968). Parts of that supposedly stable area may be highly susceptible to landsliding, so extra precautions should be taken before large areas around the highway are excavated.

Areas of moderate susceptibility.—The areas of moderate susceptibility are those areas consisting of landslide material. Excavation in these areas almost invariably causes new slides in old slide deposits. Probably all these landslides are of Holocene age, but some are no longer active. A few appear to have been reactivated into fairly stable terraces. Because of the danger of disturbing present stability, the areas shown on the map as existing landslides should either be avoided or special precautions should be taken to prevent new movement during excavation. The map shows only the larger masses, and detailed geologic maps of areas of high or moderate susceptibility should be used to locate smaller landslides. Puerto Rico Route 149 is built on a large recent mudflow or debris avalanche north of Villalba (Briggs, 1971; Matton, 1968). Parts of that supposedly stable area may be highly susceptible to landsliding, so extra precautions should be taken before large areas around the highway are excavated.

Areas of low susceptibility.—The areas of low susceptibility are those areas consisting of landslide material. Excavation in these areas almost invariably causes new slides in old slide deposits. Probably all these landslides are of Holocene age, but some are no longer active. A few appear to have been reactivated into fairly stable terraces. Because of the danger of disturbing present stability, the areas shown on the map as existing landslides should either be avoided or special precautions should be taken to prevent new movement during excavation. The map shows only the larger masses, and detailed geologic maps of areas of high or moderate susceptibility should be used to locate smaller landslides. Puerto Rico Route 149 is built on a large recent mudflow or debris avalanche north of Villalba (Briggs, 1971; Matton, 1968). Parts of that supposedly stable area may be highly susceptible to landsliding, so extra precautions should be taken before large areas around the highway are excavated.

Areas of moderate susceptibility.—Most of the areas mapped as having moderate susceptibility can be considered stable except where it is disturbed by steep-sided excavations; it also includes many unstable slopes that are near faults but are too small to map at the present scale. Because of the local complexity of the geology in the "moderate" area, detailed geologic maps and accompanying tables (Briggs, 1971; Pease and Briggs, 1960; and Briggs and Gelabert, 1962) should be consulted before beginning excavations in any part of the area.

Many natural slopes in the "moderate" category are unlikely to be unstable, but may slide if steepened by excavation. In this category is the slope of Rio Piedras Station (Pease and Monroe, 1977) that collapsed and destroyed several houses at the foot of an east-west ridge about 4 km east southeast of Rio Piedras in 1970. Usually the Rio Piedras is stable except for soil creep, but the excavation for sewers and houses created a steep slope that moved as a combination landslide and mudflow after a heavy rain.

Areas in which the rocks have been weathered to soil or to saprolite, which at places is more than 30 m thick, may be stable until excavation disturbs the stability (Briggs, 1971). Then heavy rainfall will nearly always cause minor sliding into road cuts; in some areas, heavy rainfall will cause entire roads to slide downhill, as happened on one place on Puerto Rico Route 157, 4.5 km west northwest of Orocoso (Briggs, 1971); this road is not shown on accompanying map. Shattering of the rocks along the Damien Arriba fault led to development of a thick plastic soil that in itself is unstable; excavation for a highway made the slopes too steep to stand, and the highway slipped several times into a nearby steep-sided valley. A somewhat similar situation on a new road from Caguas to Cidra in the east-central part of Puerto Rico caused successive slides that stopped only after several road relocations resulted in a greater grade.

Rockfalls (too small to map) are hazards on almost all slopes steeper than 75 percent in the area of moderate susceptibility, and they are almost impossible to foresee. They are especially common where steep slopes are overlain by concretions formed by weathering of intrusive rocks and of some lava beds. Conditions leading to movement of concretions can be anticipated, and warnings of the danger of falling rock on roads along the sides or bottoms of canyons is practicable. Rockfalls on Puerto Rico Route 167, along the Rio de la Plata between Bayamon and Comerio, have destroyed cars and have killed the driver.

Areas of low susceptibility.—The areas of low susceptibility to landsliding are nearly flat or are underlain by unweathered stable rock. Most of the alluvium, the coastal deposits, such as beach deposits, swamp deposits, and the very wide alluvial fans along the southern coast of Puerto Rico are so flat that there is little need to make large excavations for highways and other structures. Most of the materials are unconsolidated and have such low stability that any deep excavation is likely to cave in. Included in the "low" category along the Atlantic coast are extensive deposits of dune sand and volcanic, both of which have steep slopes. Excavations into these materials may lead to slides. Because the deposits are thin, collapse generally does not involve structures, but there is a slight danger that people could be buried by collapse of steep rock cuts.

The most stable rock in Puerto Rico is unweathered limestone. Along the northern and southern coasts, large areas are underlain by limestone of Oligocene and Miocene age, and in the interior there are several deposits of Cretaceous and Eocene limestone. Most deep road cuts do not collapse or slough off because after a few months the limestone becomes case hardened by solution and immediate precipitation in place (Monroe, 1976, p. 17, 44). Although the limestone itself is not subject to landsliding, limestone blocks are involved in the large active slides where limestone rests on clay that becomes plastic when wet. In some large sinks having nearly vertical sides, limestone spalls off the walls, and excavations in such places may be hazardous. The only sink of this type that has been excavated is at the Arecibo cosmophysics observatory, 14 km south of Arecibo, but to date there have been no rockfalls into the bowl.

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Offshore islands.—Most of the small islands around Puerto Rico have slopes that are either too gentle to offer much danger from landslides or that have been so beaten by heavy storms that highly weathered material has been eroded away. The exceptions are Culebra and Vieques, east of Puerto Rico, and Isla de Mona west of Puerto Rico. All three islands have relatively little rainfall. Isla de Mona (Briggs and Seiders, 1972) is composed of limestone and dolomite, except on the southern side where there is a narrow sandy coastal plain. On the eastern, northern, and western coasts nearly vertical cliffs of dolomite and limestone rise about 20-80 m directly out of the sea. Erosion and solution by ocean waves and tides have undercut these cliffs, so that at the bottom they have large masses of partly submerged and submerged fallen rock. The collapse of the cliffs is progressive and poses a threat to any structures placed near the coastal rim of the upland. These areas are too small to show on the accompanying map.

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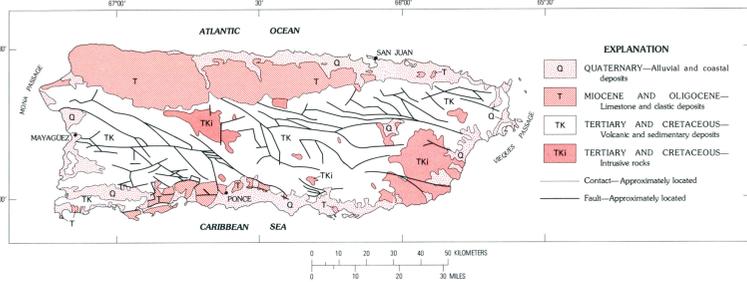


FIGURE 1—GENERALIZED GEOLOGIC MAP OF PUERTO RICO

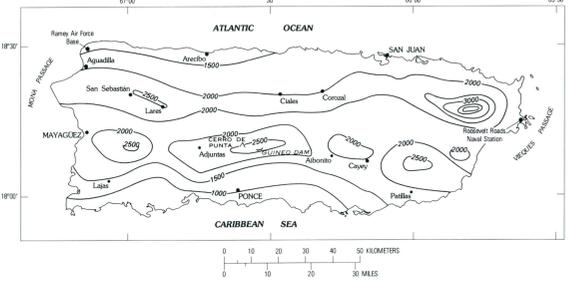


FIGURE 3—MAP SHOWING ANNUAL RAINFALL IN PUERTO RICO, CONTOURED IN MILLIMETERS. (Data from U.S. National Weather Service)

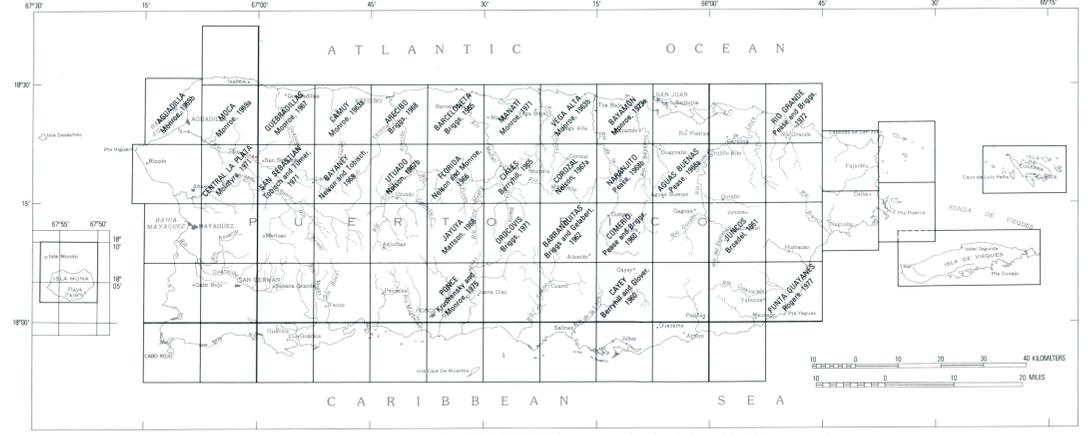
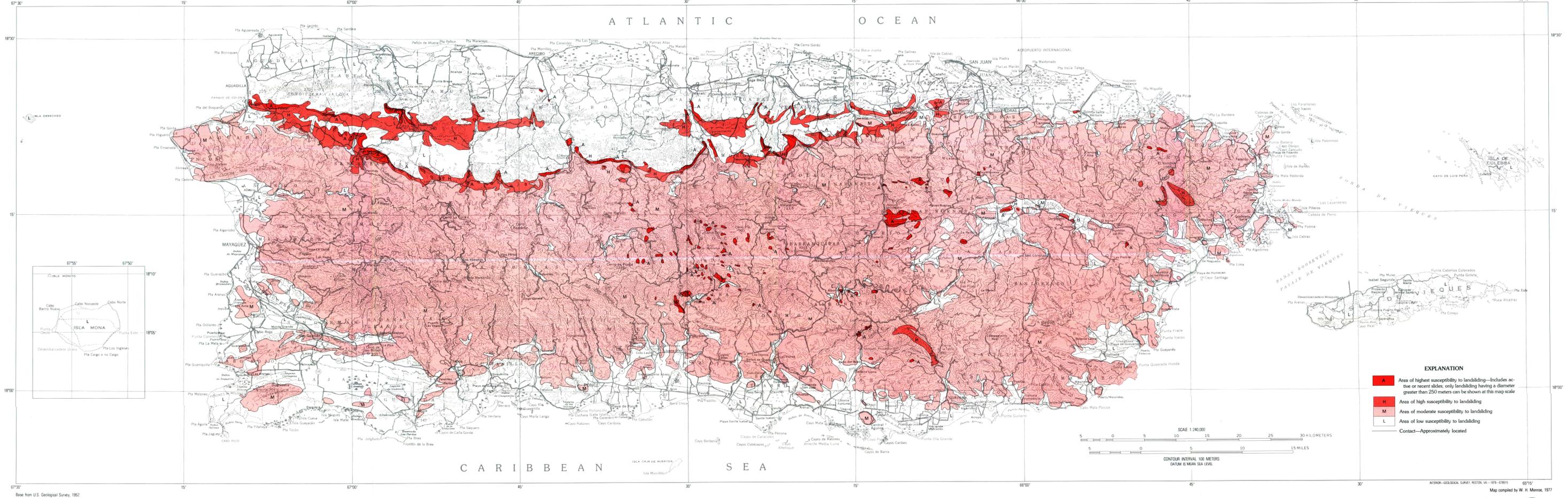


FIGURE 2—MAP OF PUERTO RICO SHOWING 7 1/2 MINUTE QUADRANGLES. (Geologic maps of quadrangles in which landslides are mapped, are referenced)



MAP SHOWING LANDSLIDES AND AREAS OF SUSCEPTIBILITY TO LANDSLIDING IN PUERTO RICO

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