Geotechnical Reconnaissance of the January 7, 2020 M6.4 Southwest Puerto Rico Earthquake and Associated Seismic Sequence

Geotechnical Reconnaissance of the January 7, 2020 M6.4 Southwest Puerto Rico Earthquake and Associated Seismic Sequence

A report of the NSF-Sponsored Geotechnical Extreme Event Reconnaissance Association

GEER Team Members

Juan Bernal, UPR Mayaguez

K. Stephen Hughes, UPR Mayaguez

Alesandra C. Morales-Velez, UPR Mayaguez

Miguel Pando, Drexel University

Jan C. Perez, UPR Mayaguez (undergraduate student)

Luis A. Rodriguez, FEMA Consultant

Collaborating Authors

Luis E. Suarez, UPR Mayaguez

GEER Team Leader and Report Editor: Alesandra C. Morales-Velez, UPR Mayaguez

Report GEER-066

June 26, 2020

TABLE OF CONTENTS

Acknowledgements

The work of the GEER Association is based in part on work supported by the National Science Foundation through the Geotechnical Engineering Program under Grant No. CMMI-1826458. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF or of their respective employers. The GEER Association is made possible by the vision and support of the NSF Geotechnical Engineering Program Directors: Dr. Richard Fragaszy and the late Dr. Cliff Astill. GEER members also donate their time and resources to collect timesensitive field observations of the effects of extreme events.

We would like to thank the University of Puerto Rico at Mayaguez (UPRM) and the Civil Engineering Department Chair, Prof. Pagán-Trinidad, for all the resources and accommodations provided to the GEER Team. Special thanks are given to Dr. Kate Allstadt and the USGS Landslides Hazards Program Office and UPRM Geology students Desireé Bayouth, Edwin Irizarry, and Eduardo Cruz for sharing preliminary findings that were very important to this mission. In addition, we would like to extend our gratitude to Mr. Angel Perez, Chief Engineer at Costa Sur Power Plant, for the guided tour of their facilities. We would like to thank Juan Rodriguez, PhD candidate at UPRM, and Edward Cruz, graduate student at UPRM, for their invaluable help working with the ground motion records.

Our deepest gratitude to the people of Puerto Rico. No matter what circumstances are thrown at you, you always find a way to overcome adversity. Thanks for welcoming us academics and researchers and sharing your stories and initial findings.

Introduction

A seismic sequence located along the southwestern coast of Puerto Rico began on 28-December-2019 with a M 4.7 event. This foreshock was followed by an event of M 5.0 on the following day. On 6-January2020 there was a M 5.8 event and then events of M 6.4 and M 5.6 on 7-January-2020 (Lopez et al., 2020a). The seismic sequence has included thousands of events with hundreds of these being felt by residents. Table 1 lists all events larger than M 4.5 from 28-December-2019 until 15-May-2020. The M 6.4 earthquake on 7-January-2020 is considered the "mainshock" for the sequence and triggered the most shaking throughout the southwestern region of Puerto Rico. Although the sequence began in 2019, we refer to it as the "2020" earthquake sequence because most of the events occurred after the new calendar year. Because there are a host of moderate to stronger earthquakes, with one definable main shock, the events together represent a sequence, rather than a swarm.

Puerto Rico is a small island territory of the United States and lies about 1,600 km southeast of the state of Florida. It is home to more than 3 million residents and very densely populated. The largest urban areas are the San Juan metropolitan area in the Northeast coast, the city of Ponce on the south-central coast, and the city of Mayagüez on the western coast. For the 2020 sequence, the seismicity appears to have initiated along the Punta Montalva strike-slip fault and then transitioned onto previously unrecognized normal faults, some of which may be related with the offshore Guayanilla Canyon (Lopez et al., 2020b). The location of the seismic sequence (Figure 1) is along the coastal areas just offshore of the municipalities of Guánica, Guayanilla, Yauco, and Peñuelas. This area lies only a few tens of kilometers from the larger city of Ponce. Widely reported structural damage was centered in the municipalities mentioned above. This included the complete or partial collapse of homes, schools, churches, and government buildings. Many bridges were structurally compromised, and some have been subsequently demolished. Thousands of citizens temporarily sheltered in makeshift camps after their residences were affected. The fear of aftershocks also led many to sleep outside for weeks. The shaking damaged power generation facilities along the south coast and caused intermittent electrical service issues for thousands more beyond the epicentral area.

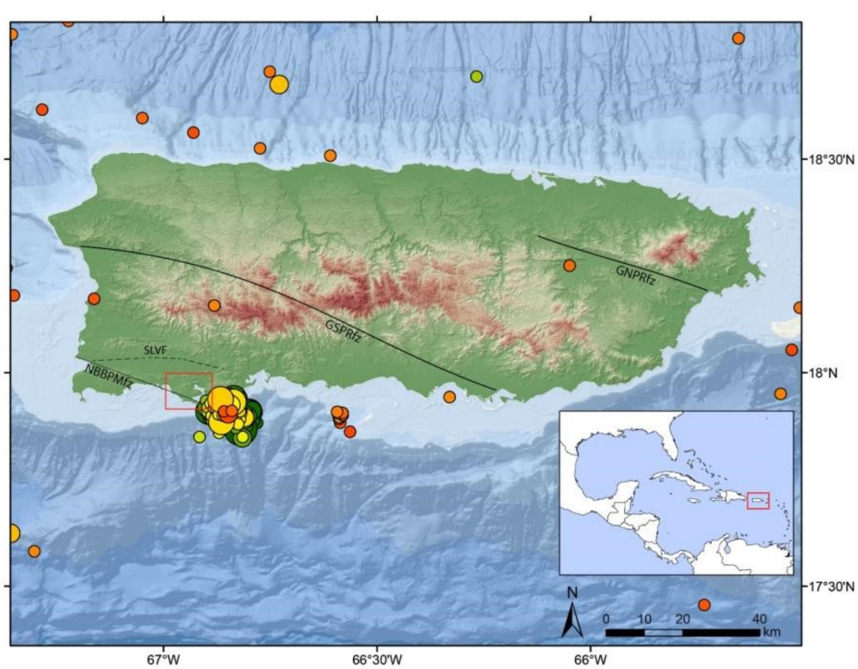


Figure 1: Shaded relief map of the island of PR. The location of the events in the seismic sequence are shown. Size corresponds to magnitude. Red events are 28December-2019 or earlier and colors fade to yellow and green into January-2020. Modified from López et al. (2020a). GNPRfz= Great Northern Puerto Rico fault zone. GSPRfz=Great Southern Puerto Rico fault zone. SLVF=South Lajas Valley fault. NVVPMfz=North Boquerón

Bay – Punta Montalva fault zone. Red polygon inset shows the extent of Fig 8.

Table 1: Summary of events greater than M 4.5 in the seismic sequence				
Magnitude	Date (m/d/y)	Lat (N)	Lon (W)	Depth (km)
4.7	12/28/2019	17.9371	66.8661	6
4.7	12/29/2019	17.9308	66.8363	3
5	12/29/2019	17.8846	66.864	6
4.5	1/2/2020	17.9148	66.8333	7
4.7	1/3/2020	17.9006	66.8261	2
4.9	1/6/2020	17.9075	66.799	6
5.8	1/6/2020	17.8675	66.8193	6
4.6	1/7/2020	17.9645	66.8256	8
4.7	1/7/2020	17.9315	66.927	8
5.6	1/7/2020	18.0223	66.776	9
4.7	1/7/2020	17.9128	66.6898	10
5	1/7/2020	17.9418	66.6754	10
5.6	1/7/2020	17.8919	66.7217	10
4.6	1/7/2020	17.9206	66.767	10
5	1/7/2020	17.8685	66.7029	10
6.4	***1/7/2020***	***17.9578***	***66.8113***	***6***
4.7	1/8/2020	17.915	66.7035	6
5.2	1/10/2020	17.935	66.883	9
4.6	1/11/2020	17.9423	66.8395	8
5.2	1/11/2020	17.8238	66.7941	10
5.9	1/11/2020	17.949	66.8508	5
4.8	1/11/2020	17.9923	66.7946	4
4.5	1/12/2020	17.9033	66.8765	7
4.9	1/12/2020	17.9556	66.8865	8
4.5	1/13/2020	17.9638	66.8131	9
4.6	1/14/2020	17.8548	66.8686	10
5.2	1/15/2020	17.9155	67.0171	5
4.5	1/20/2020	17.9618	66.7425	14
4.6	1/20/2020	17.9748	66.7528	7
4.5	1/20/2020	17.977	66.7408	7
5	1/25/2020	18.0105	66.8188	13
4.5	1/25/2020	17.9245	66.9401	6
5	2/4/2020	17.8388	66.8751	7
4.6	5/2/2020	17.9508	66.6981	7
5.4	5/2/2020	17.937	66.7266	9
Data from the Puerto Rico Seismic Network and USGS				

Tectonic Setting

The island of Puerto Rico is part of the Puerto Rico – Virgin Islands (PRVI) micro plate that lies along the oblique convergent boundary of the Caribbean and North American tectonic plates. The PRVI region is seismically active but has not experienced a major shaking event since the October 1918 M7.1 event that occurred off the northwestern coast of the island, in the Mona Passage. During that event, lives were lost both from the shaking, which leveled structures, and a subsequent tsunami, which reached a maximum height of 6m in the northwest coast of the island. In the 100+ years since this event, the island has experienced abundant micro-seismicity and infrequent small to minor events.

The PRVI block is bounded by offshore fault systems along the Puerto Rico Trench, the Muertos Trough, and both the Mona and Anegada passages (Figure 2). North of the island, the Puerto Rico Trench is accommodating oblique left-lateral convergence. The tectonic margin along southern Puerto Rico is home to narrow shelf and steep slope that descends to the Muertos Trough which represents the southern margin of the PRVI micro plate (Figure 3). The Mona Passage between Puerto Rico and Hispaniola is the site of active extension. Extensional rifting is also evident along the east of the PRVI microplate. All of these first and second order structures that demarcate the lager plate and smaller microplate boundaries represent sites of potential seismicity.

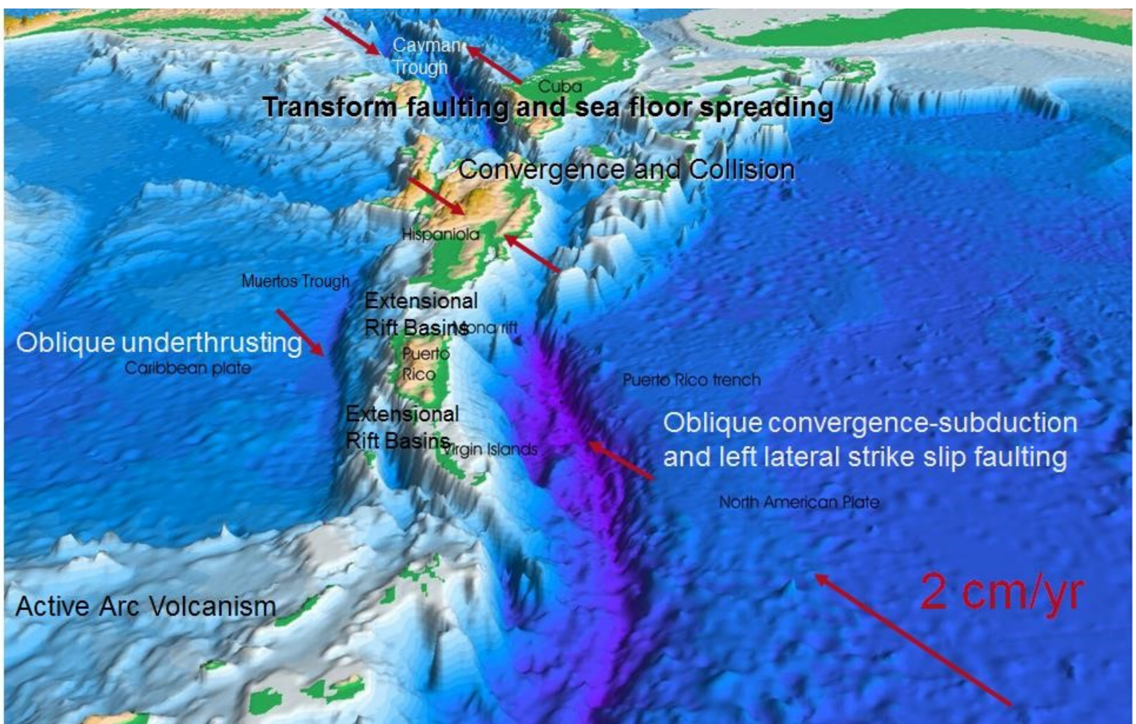


Figure 2: Vertically exaggerated topography and bathymetry of the northeastern Caribbean region. Modified from Ten Brink et al., 2005. Annotations by James Joyce (UPRM Department of Geology). View is looking to the West.

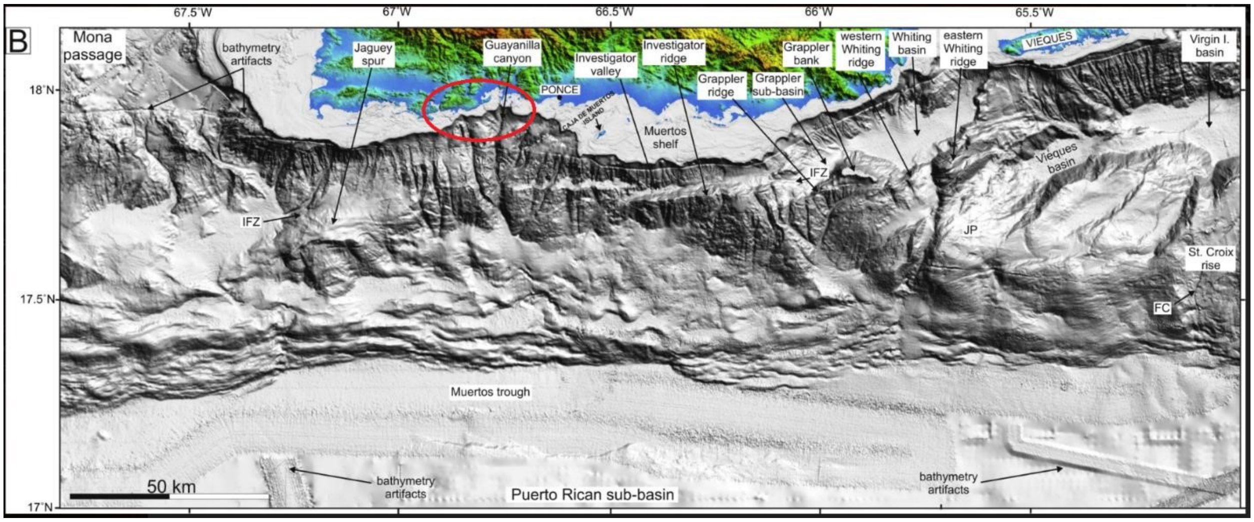


Figure 3: Bathymetry of the sea floor to the south of Puerto Rico. Modified from Granja Bruña et al., 2015. Red circle represents the epicentral area for the 2020 earthquake swarm.

There are also numerous capable inactive and active faults that lie on land (Figure 4). The most prominent of these onshore features are the Northern and Southern Puerto Rico fault zones (displayed on Figure 1). These zones of highly fractured rock are expressed as strong topographic lineaments where chemical weathering has exploited these fractured zones. Additional faults that have been highlighted as recent or active are mostly in the west and southwest of the island. A half-graben system expressed in the topography of western Puerto Rico has been studied by many workers and includes the North Rio Añasco valley fault (Cerro Goden fault) and the Lajas valley fault. In addition, the North Boquerón Bay – Punta Montalva fault in southwestern Puerto Rico has also been studied and evaluated by local geologists in the past 20 years because of its topographic expression. This is the fault that was initially activated in the 2020 seismic sequence.

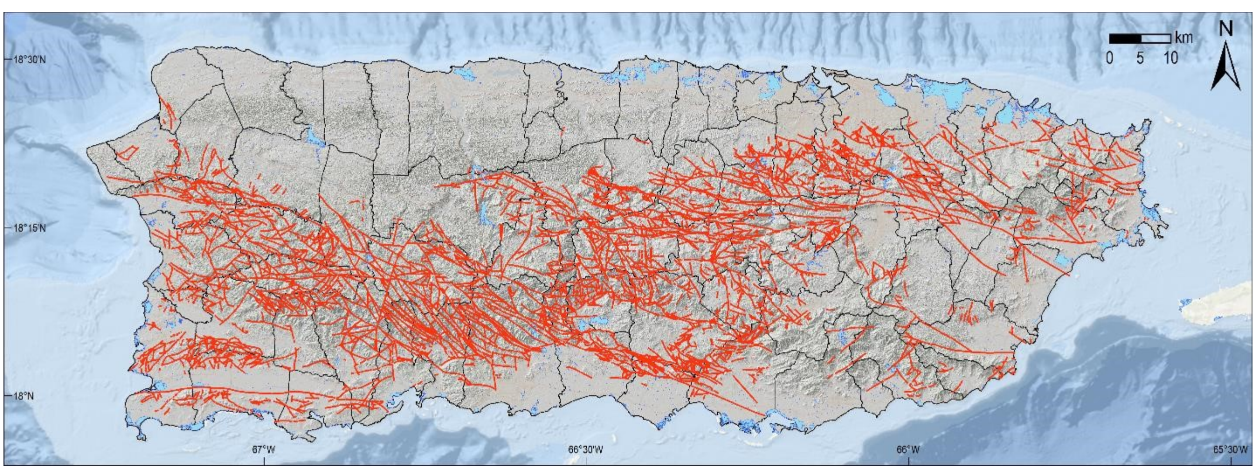


Figure 4: Mapped faults in Puerto Rico. Data from USGS.

Geology, Geomorphology, and Climate of the Epicentral Area

Most of the south coast of Puerto Rico is underlain by the Oligocene to Pliocene (Tertiary) cover sequence rocks of the Juana Diaz Formation and Ponce Limestone (Figure 5). The Juana Diaz Fm. is a mixture of terrigenous conglomerates, chalks, and limestone layers. The package was deposited unconformably over the island's basement arc complex. The Ponce Limestone is almost exclusively limestone and lies stratigraphically above the Juana Diaz Fm. In the study area, both units are highly faulted, even more so that depicted on the fault maps presented above. One fault system that is not included in the USGS fault database is the Punta Montalva-North Boquerón Bay fault (Figure 6). This fault has been recognized to be active based on the geologically young rocks that it offsets and geomorphological features in the area (Addarich, 2009: Roig, 2010; Roig et al., 2013; Adames, 2017; Figures 7-8). Based upon the geometric characteristics of the fault, Adames (2017) estimated that the largest magnitude earthquake on the fault would have a magnitude of Mw6.03 if it did not continue offshore or Mw6.45+ if it continued offshore.

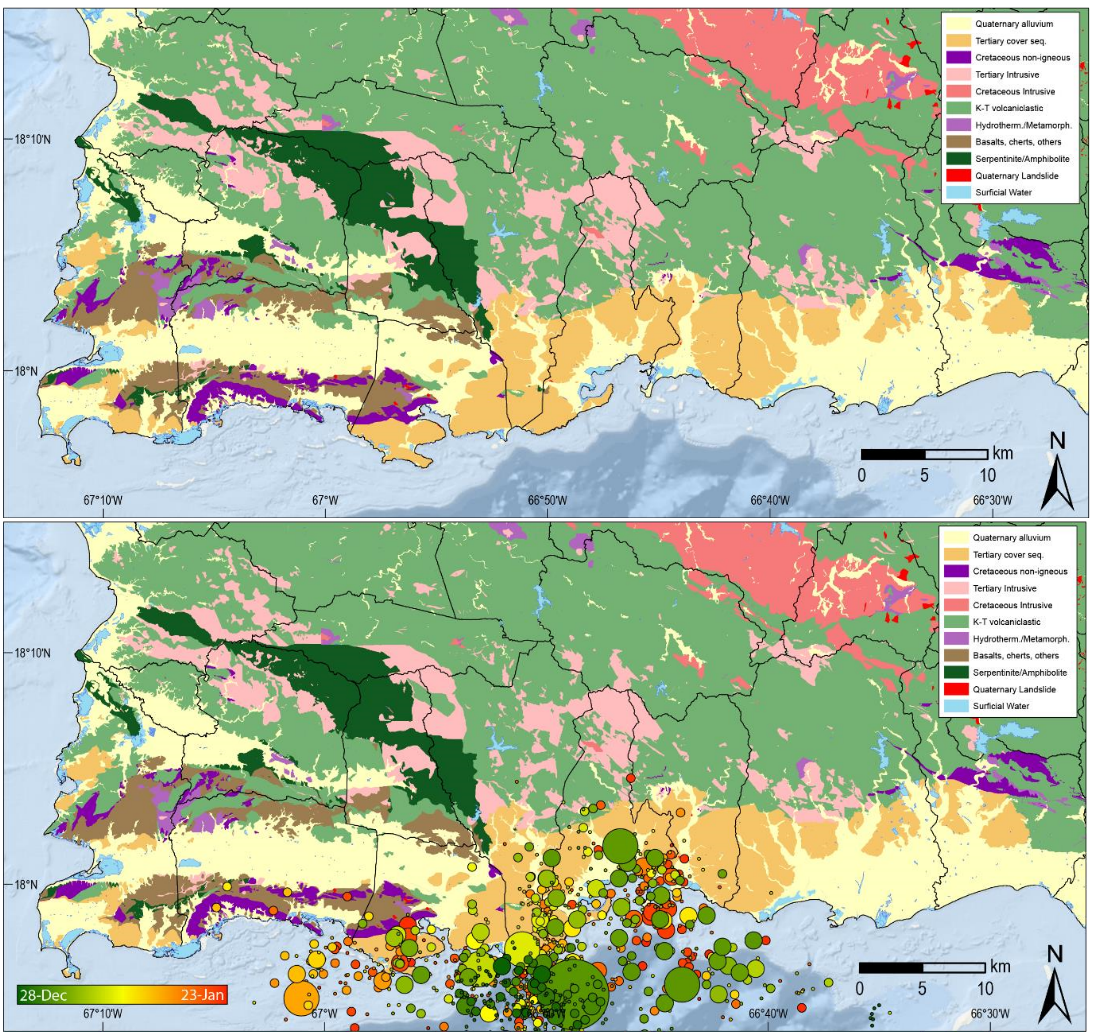


Figure 5: Simplified geological map of southwestern Puerto Rico. Bottom map shows the seismic sequence events plotted over the geological map. Digital map data from USGS and the Puerto Rico Office of Management and Budget.

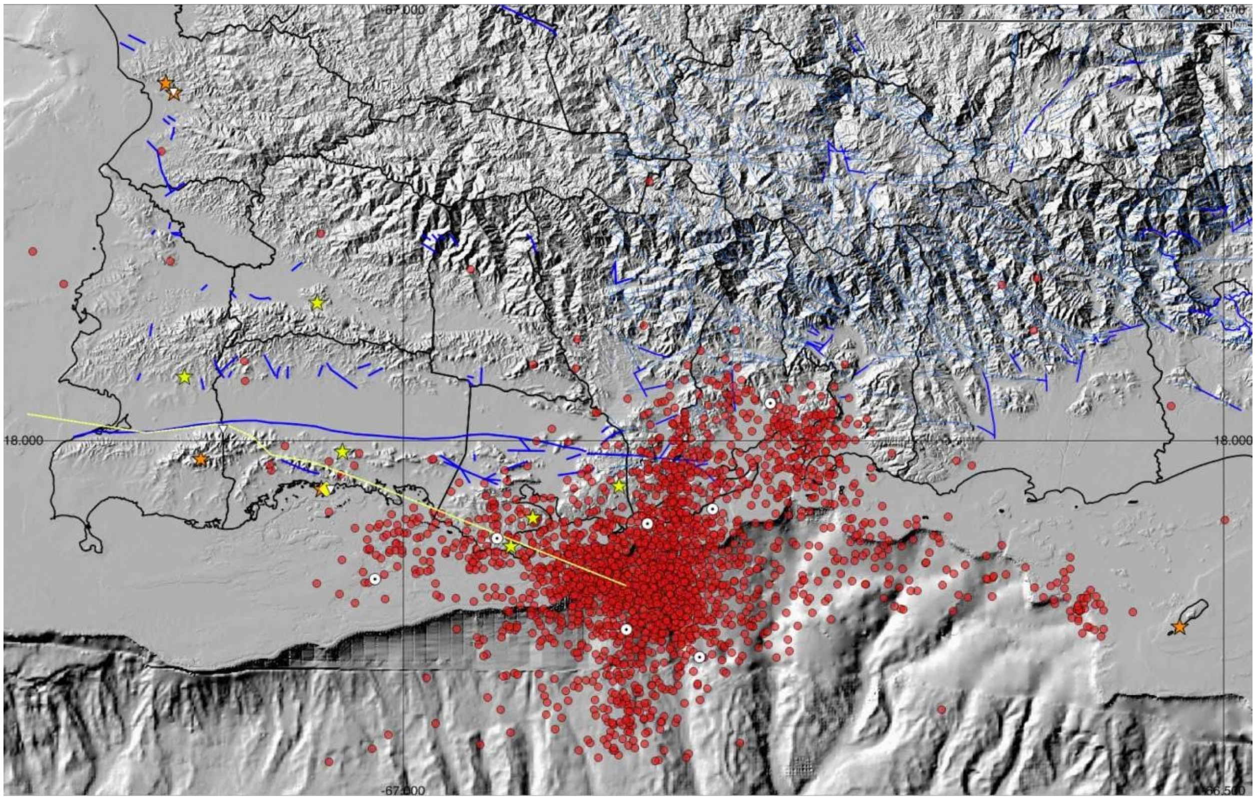


Figure 6: Shaded relief of the southwestern region of Puerto Rico. Yellow line is the left lateral strike slip Punta Montalva fault. More than 2,000 red dots are seismic events between 28-Dec-2019 and 22-Jan-2020. White dots are the events larger than M5.0. Blue lines are the same faults as seen in Figure 4. Map from López et al., 2020b.

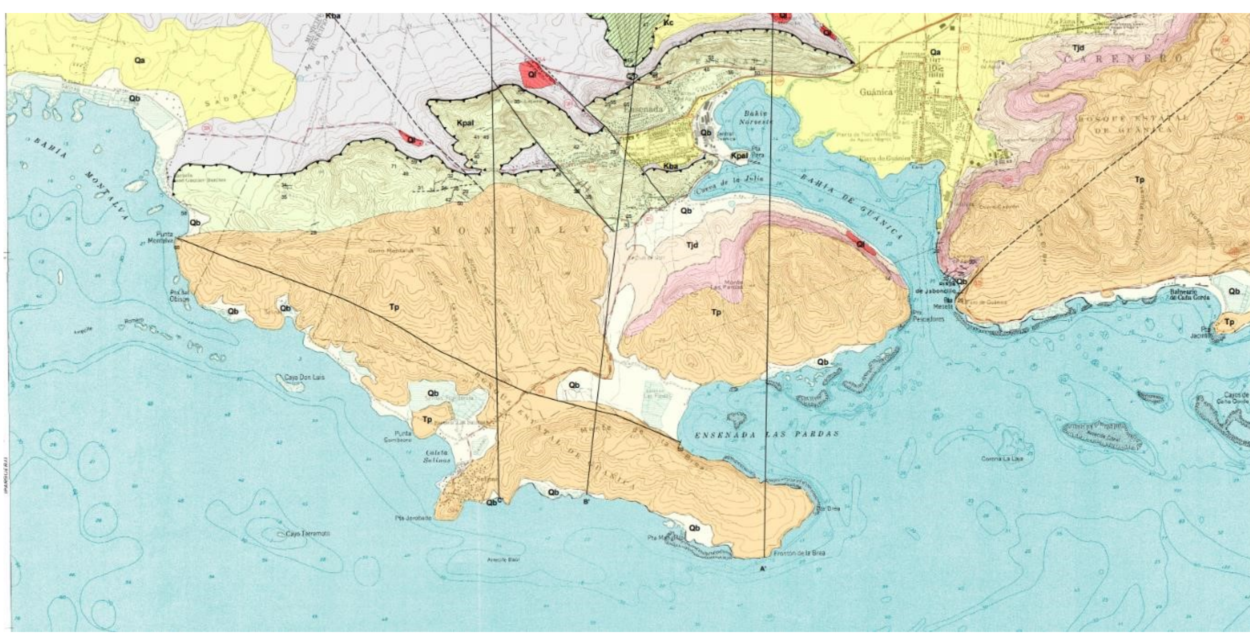


Figure 7: Geologic map of the Guanica Quadrangle by Addarich (2009). The Punta Montalva fault deforms and offsets the Ponce Limestone and has a general WNW-ESE strike. It is near the center left of the map.

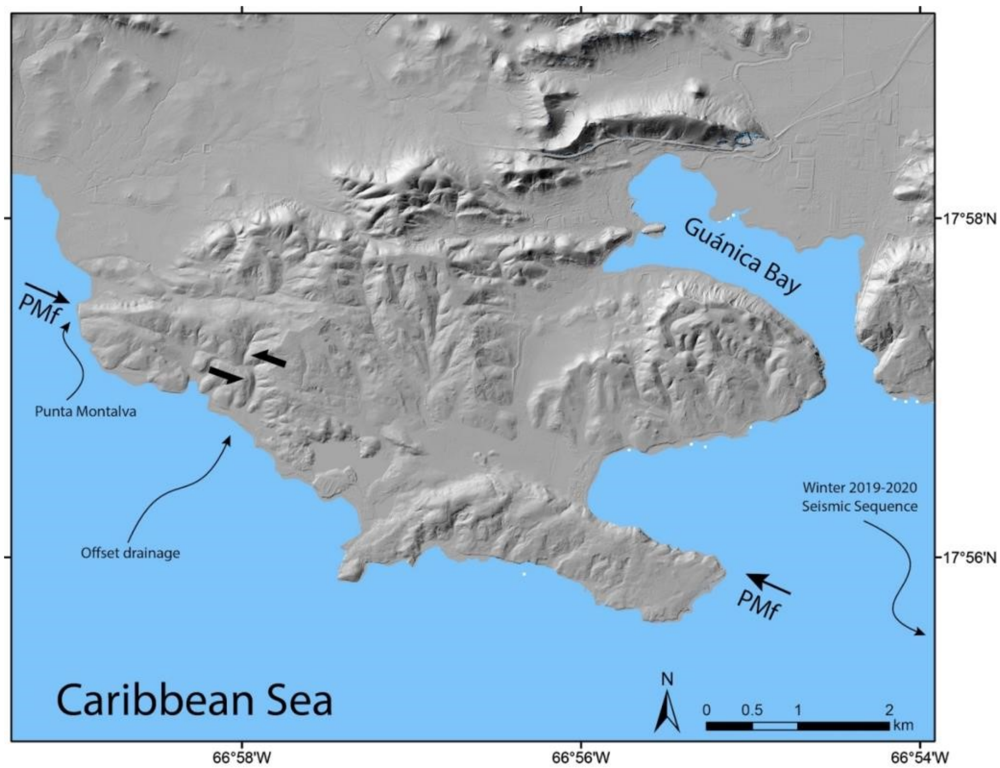
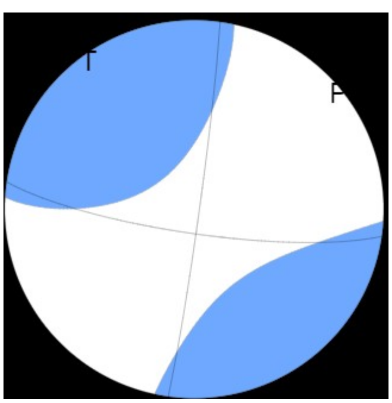


Figure 8: Shaded relief map of the Punta Montalva fault (PMf). Digital elevation data from USGS LiDAR 2016. Map from López et al. (2020a). Offset drainage is labeled and a shutter ridge is located near the center of the fault trace length.

The main shock of the earthquake sequence on 7-Jan-2020 was a Mw6.4 event. It appears most likely that the early strike slip motion on the Punta Montalva fault (Figure 9a) loaded a nearby NNE trending normal fault that produced the Mw6.4 event (Figure 9b). Most events in the sequence between 28-Dec2019 and prior to 7-Jan-2020 were likely associated with the Punta Montalva fault, based upon their location to the ESE of the onshore trace of the fault and also several focal mechanisms generated by the USGS that agree with left lateral strike slip motion on a near vertical plane striking approximately ~100 degrees. A later trend of NNE-SSW striking events may loosely define the normal fault structure that caused the mainshock of the sequence (seen in Figure 6).



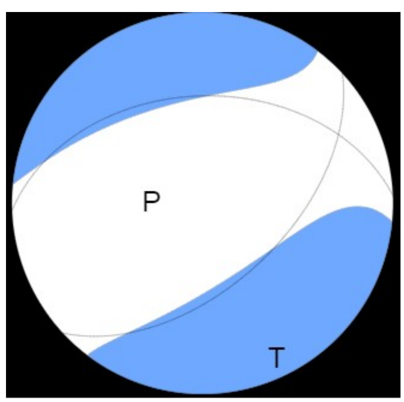


Figure 9: (a) Focal mechanism for the 2-Jan M 4.5 earthquake along the seaward projection of the Punta Montalva Fault. From USGS. Model shows a solution for left lateral motion on a nearly vertical fault plane that strikes 98 degrees. (b) Focal mechanism for the 7-Jan M6.4 main event. Shows motion on a NNE striking normal fault.

The bedrock units of the south coast are locally overlain by more recent alluvial sediments in the valleys of the Rios Loco, Yauco, Guayanilla, and Tallaboa. Along cut banks of these valleys, there are prominent steep bluffs of both geological units. The south coast region is home to the driest microclimate zone in Puerto Rico and receives an average of only about 30-40 inches of rainfall per year. This drier environment results in relatively less chemical weathering and soil development than most of the remainder of the island.

Recorded Ground Motions

Two separate organizations, both housed at the University of Puerto Rico at Mayaguez (UPRM), were operating and collecting data at the time of the M 6.4 earthquake on the morning of January 7, 2020. The Puerto Rico Seismic Network (PRSN), affiliated with the Geology Department, has 25 stations (analog and digital) operating in PR, Dominican Republic, and British and US Virgin Islands. Their stations are equipped with three main different sensors: short term, broadband and accelerometers. The Puerto Rico Strong Motion Program (PRSMP), affiliated with the Department of Civil Engineering and Survey, has 107 stations operating in PR, Dominican Republic, and British and US Virgin Islands. Figure 10 shows the distribution of the PRSMP stations. Not all stations were functioning properly due to damages caused by Hurricanes Irma and María in 2017, mostly to their remote data communication systems. Currently (May-2020), the PRSMP has made available the data from 65 stations. This information is depicted on Figure 11 and can be accessed through the following link to the PRSMP web page (https://prsmp.uprm.edu/M6-4/).

For each seismic station, the ground acceleration, velocity, and displacement records can be accessed on the PRSMP web page, for the two horizontal (E-W and N-S) and the vertical accelerograms. An Intensity map is shown in Figure 12, which displays contours of the peak ground acceleration (PGA) recorded at the 65 stations of the PRSMP. A summary of the PGA's and PGV's for some of the seismic stations near the epicenter of the earthquakes is shown in Table 2. PGA's as high as 0.398g and PGV's as high as 30.17 cm/sec were experienced during the earthquake. A USGS station near the Eco-Eléctrica Power Plant in Peñuelas, PR reported the highest PGA, 0.5902g, for the whole island during this event. Pseudoacceleration spectra and Fourier spectra are shown in Figure 11 for the seismic station YAC2 located in Yauco, which experienced the highest PGA (0.398g) among reporting PRSMP sites.

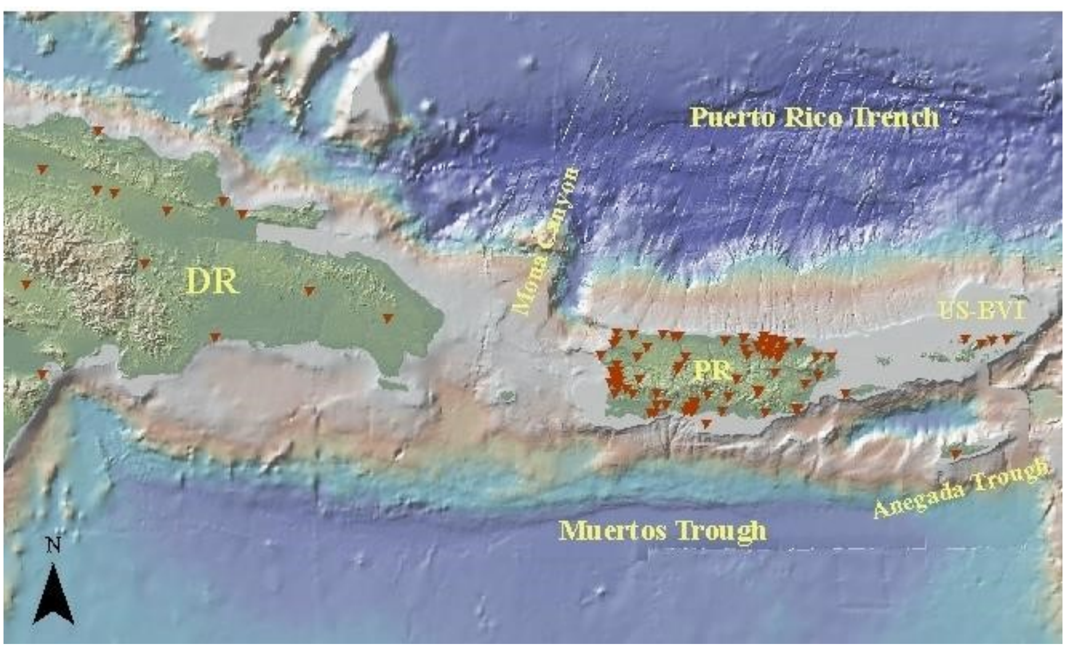


Figure 10: Map of stations operated by the PRSMP. From prsmp.uprm.edu.

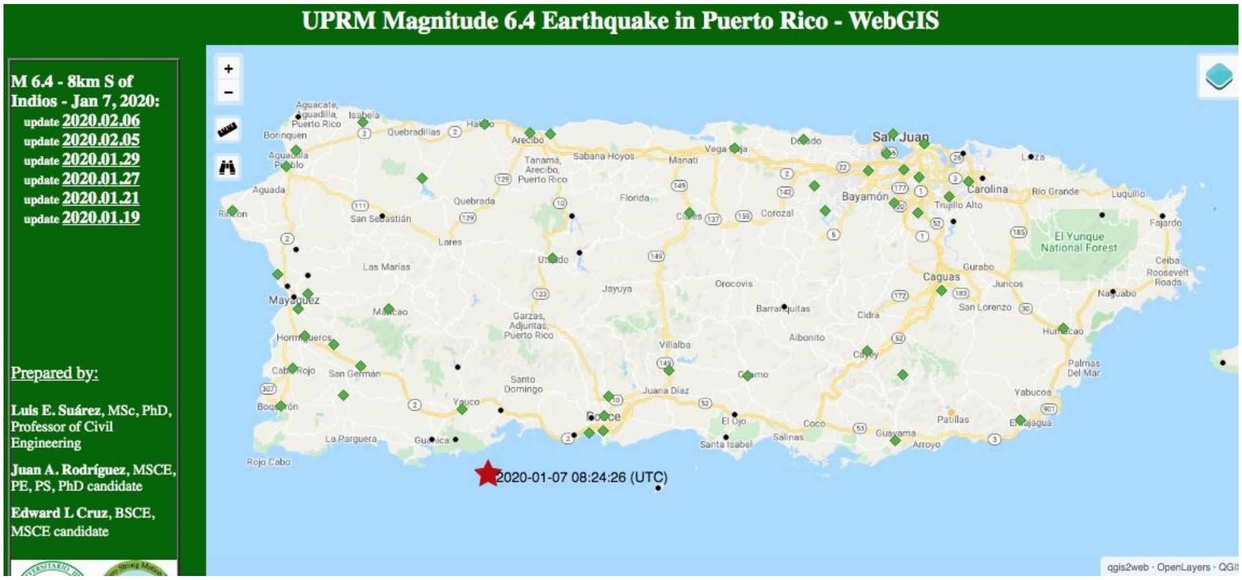


Figure 11: Stations at full operating capacity during the M 6.4 mainshock on 7-January-2020. Image from prsmp.uprm.edu/M6-4/

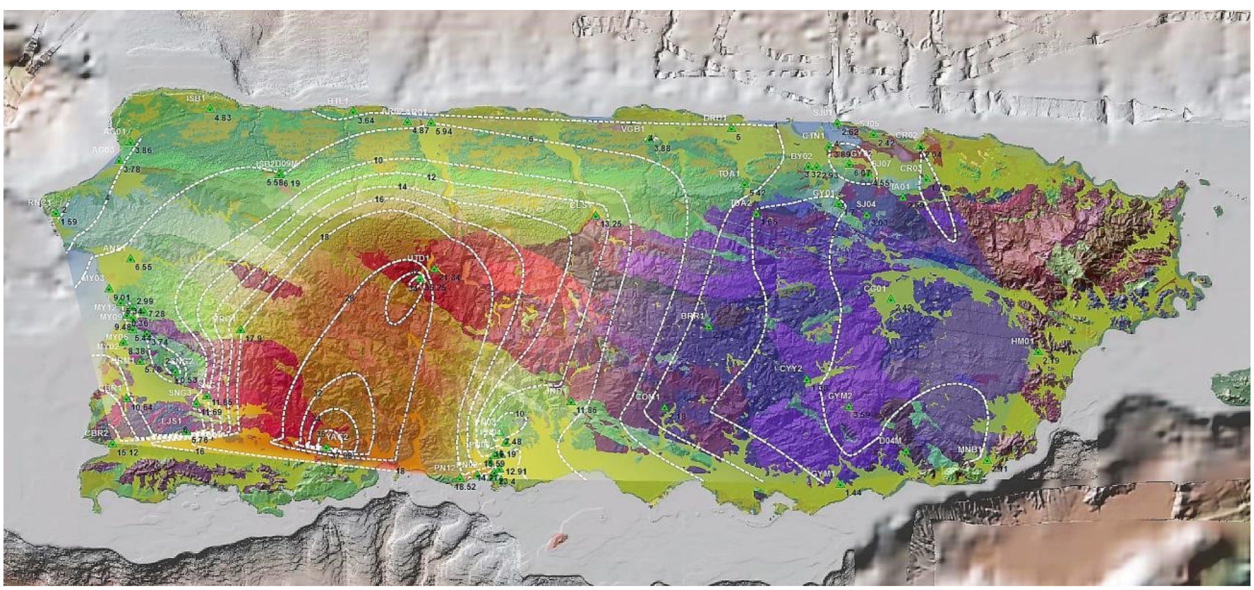


Figure 12: Intensity map showing isolines of PGA overlain on the generalized geologic map of the island. Values shown in the map are the accelerations in percentage of g and are the resultant of the maximum accelerations in the E-W and N-S directions. Image courtesy of Dr. C. Huertas of the UPRM-PRSMP.

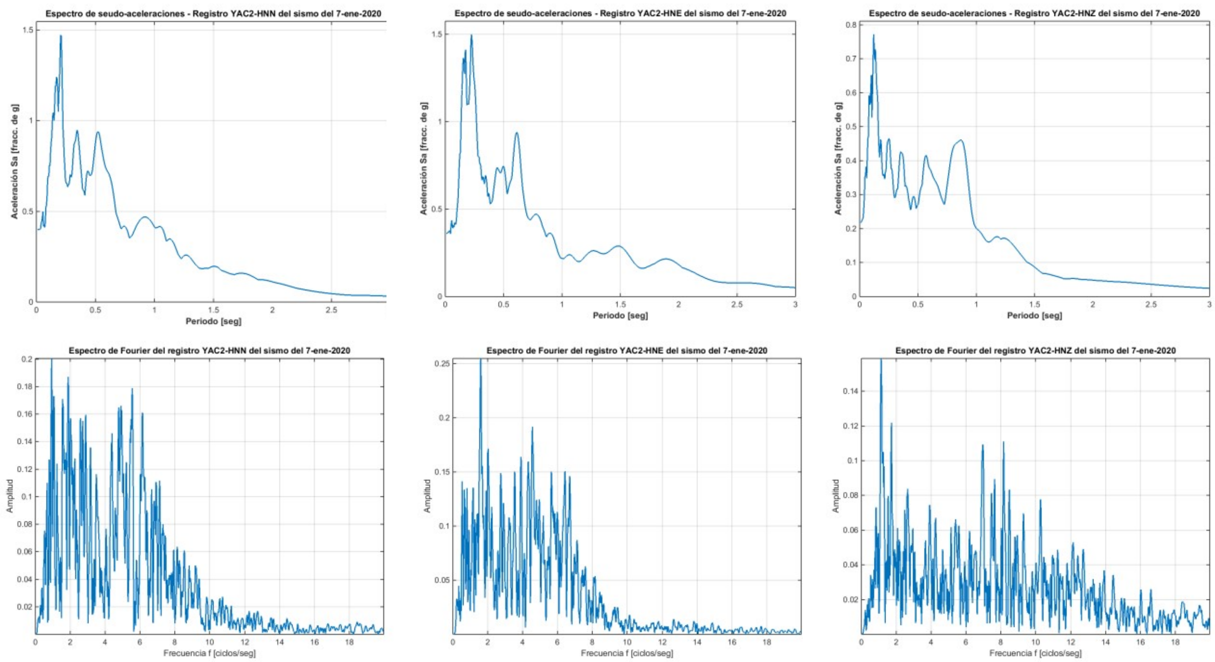


Figure 13: Pseudo-acceleration (above) and Fourier (below) spectra for station YAC2 for the mainshock event.

Table 2: Summary of Peak Ground Accelerations and Velocities near epicenter

Station	Latitude (N) Longitude (E)	Municipality	Station Name	Dist. from Epicenter [km]	Sensor Direction	PGA [g]	PGV [cm/s]
YAC2	18.023 -66.857	Yauco	Yauco Fire station	8.7	N-S	0.398	27.78
					E-W	0.362	26.57
PN02	17.984 -66.639	Ponce	Water & Sewage Authority	18.5	N-S	0.212	24.47
					E-W	0.191	23.95
PN06	18.003 -66.621	Ponce	Santa María Reina Parish	20.8	N-S	0.152	11.39
					E-W	0.151	17.9
PN10	17.987 -66.615	Ponce	Highway 52 Tollgate	21.1	N-S	0.244	25.13
					E-W	0.224	28.34
PN08	18.012 -66.614	Ponce	Ponce Cathedral	21.7	N-S	0.157	12.42
					E-W	0.155	18.43
PN13	17.993 -66.607	Ponce	UPR Ponce Campus	21.9	N-S	0.116	14.33
					E-W	0.175	20.63
PN11	17.978 -66.605	Ponce	San Martin de Porres	22.0	N-S	0.126	16.5
					E-W	0.132	17.11
PN04	18.029 -66.598	Ponce	del Carmen Parish	23.9	N-S	0.182	30.17
					E-W	0.222	21.17

*Data from the PRSMP

Summary of the observations made by the GEER-Team

This section presents the most important and common observations regarding the following types of ground failure related to the 2020 Puerto Rico seismic sequence:

1. Ground Deformations
    a. Ground settlement
    b. Lateral spreading
    c. Soil liquefaction
2. Landslides and Slope Stability
3. Performance of Bridges
4. Performance of Dams

1. Ground Deformations

In general, the GEER-Team observed three types of ground deformation in the epicentral area: (a) ground settlement, (b) lateral spreading, and (c) soil liquefaction. Extensive ground deformations were observed in the following municipalities where the reconnaissance team focused their efforts: Guayanilla, Guánica, and Ponce.

Lateral spreading was observed in the "*Paseo Tablado – La Guancha*" boardwalk (17.966N, 66.615W) along the coastline in Ponce. Figure 14 shows the ground cracks at the site. The "*Paseo Tablado – La Guancha"* is lying on a layer of artificial fill beside the sea. The ground cracks are present the entire length of the boardwalk, extend all the way through the flexible pavement, and end at a boat ramp near the vicinity. The ground cracks originate at the location of a previously excavated trench for a petroleum pipeline. The most dramatic ground cracks were observed along the boardwalk. The depth of the cracks was very variable and ranged in between a couple of inches to a couple of feet (56" maximum depth observed). The width of these cracks was also variable, ranging from as little as one inch to up to three feet wide. Ground water table at sea level could be observed at the bottom of some cracks. Figure 15 shows a typical soil profile at the site. A separation of the boardwalk sidewalk and the structure was also observed. This gap ranged in size and was approximately eight inches maximum. This can be observed in Figures 16 and 17. Exposed rebar was observed in the joint of the boardwalk structure and the wood deck area (Figure 18).

Figure 14. Sequence of the observed ground cracks due to potential lateral spreading at *Paseo Tablado - La Guancha*. Ground cracks follow the path of a petroleum pipeline.

Figure 15. Typical soil profile at the site.

Figure 16. Ground cracks and separation of the boardwalk structure and sidewalk slab.

Figure 17. Separation of the sidewalk slab and the boardwalk structure.

Figure 18. Exposed rebar at the joint of the concrete-wood structure.

Adjacent to the *Paseo Tablado – La Guancha*, is the "*Las Américas Port*". The construction of this port dates back to the early 2000's. A very detailed site investigation, which included numerous standard penetration tests with sample collection and cone penetration tests were carried out the site during that time. These tests revealed a three-layer soil system up to 200 feet below sea level and soft soils were encountered up to approximately 125 feet below sea level. Figure 19 shows a schematic interpretation of the soils found at the site with their respective N-values.

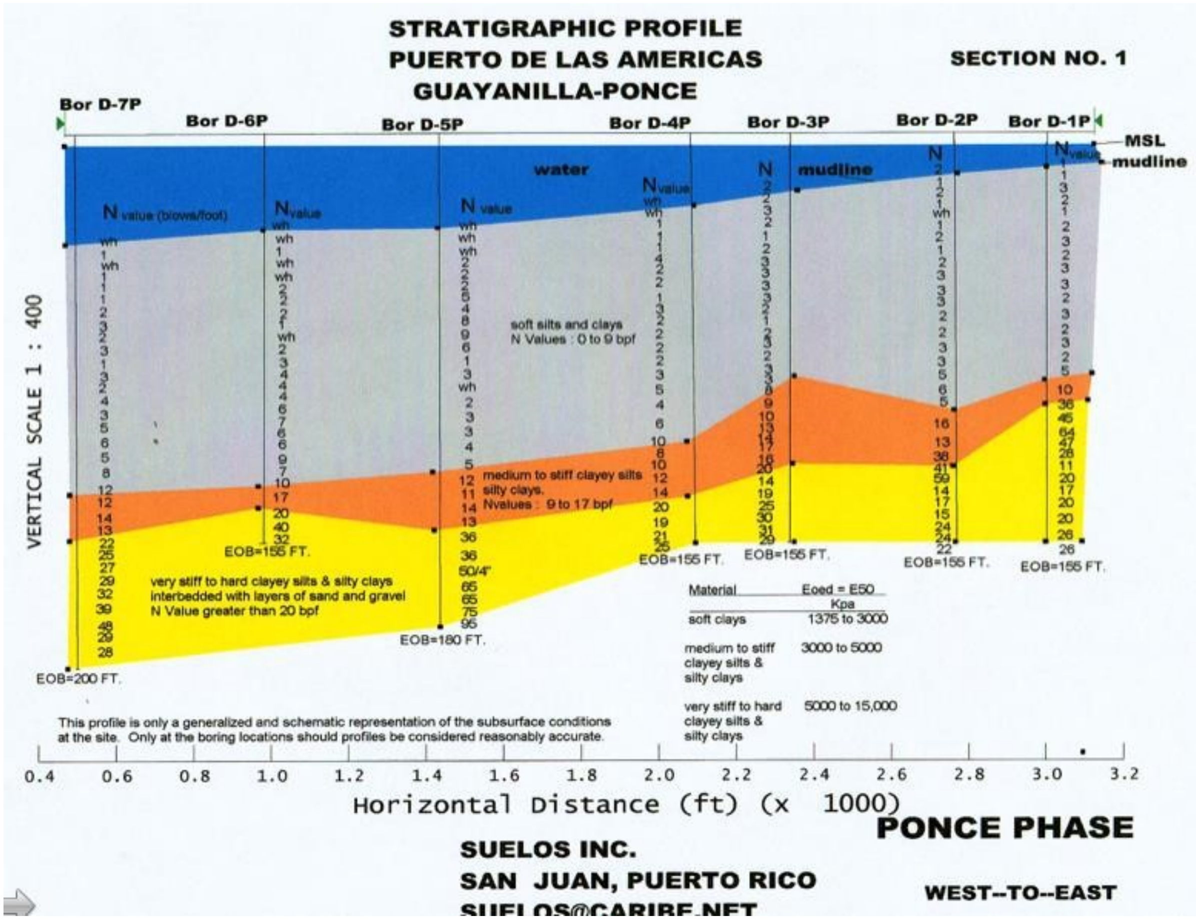


Figure 19. Typical soil profile at the Las Americas Port. Courtesy of Suelos Inc.

In addition, a series of analyses and numerical models were carried out to investigate pile performance and liquefaction potential at the port site. These analyses revealed that: (1) large piles were needed to support structural and incidental loads, (2) factors of safety for liquefaction on the order of less than one in some layers, for both sand-like and clayey-like soils, and (3) deformations on the sheet piles were too large and ground improvement techniques were to be implemented. Different ground improvement techniques, such as, surcharges, wicked drains and stone columns, were used to stabilize the soils at that time. It is important to document that there were ***no damages*** observed at this site by the GEER team.

Ground settlement was observed at the "*Centro Vacacional AEELA"* at Playa Santa, Guánica (17.938N, 66.955W) throughout the perimeter of the large multi-story structure. Evidence such as ground cracks along the soil surface of the surrounding areas, subsidence of concrete slabs, broken water lines, and hanging tiles were observed at the site. This had an effect on the structure itself and cracks in the walls of the structure were observed. The shear walls performed extremely well during the event, showing little to no damage but the concrete block walls exhibited typical shear failure. This building had added structures both in the front side and back side and failure was observed in the connection with the main structure, such as separation between the concrete walls of the new structure and the original structure. Figures 20 through 27 illustrate the findings at this site.

Figure 20. Cracks due to ground settlement at the site. Cracks like this were observed all around the perimeter of the structure.

Figure 21. Separation between ground surface and staircase in the back of the building due to ground settlement

Figure 22. Detail of the separation shown in the previous figure. A gap of approximately 2 inches can be observed.

Figure 23. Displacement between a column and the main structure.

Figure 24. Gap in the connection of the original structure and the added structure in the back side of the building.

Figure 25. Subsidence of the floor slab due to ground settlement.

Figure 26. Cracks in column and broken PVC pipe due to ground settlement.

Figure 27. Hanging tile due to ground settlement. Gap in between the floor slab and the wall of approximately 1.5 inches.

The GEER team also visited the “Costa Sur” electrical power generation facility (18.002N, 66.754W) along the Guayanilla/Peñuelas coastline on 15-January-2020. The facility is owned and operated by the Puerto Rico Electric Power Authority (PREPA). This site was immediately shut down when the mainshock occurred on 7-January-2020 and has not been reinstated in service since that time, due to alleged major structural damages in the main tower. While some structural damage did occur in the operational portion of the plant, our focus was on the ground surface reaction to the shaking. The dominant characteristics observed in the facility were lateral spreading and ground settlement. At least part of the facility is built upon fill graded into the Caribbean Sea. Soils and concrete block walls, especially in the area of the boat dock, were observed to have suffered lateral spreading. Very minor settlement was observed around the base of some support columns and other foundations. The earthen foundation beneath one of the onsite water tanks was partially scoured out because of the rupture of a water pipe. Across the highway from the facility, one large water tank appears to have suffered very slight tilting during the shaking as the result of water moving inside the tank and settled on the order of a few inches. Figures 28 through 39 illustrate the typical findings at this site.

Figure 28. View looking south towards the Costa Sur facility boat dock. Vertical fracture in wall is an expression of seaward lateral spreading (18.002N, 66.754W).

Figure 29. Looking down and generally to the south. The sea is immediately to the right. Unconsolidated soil (desiccated crust) material shows lateral spreading (18.002N, 66.754W).

Figure 30: Looking south. The wall of the Costa Sur facility's cooling water outflow channel suffered fractures parallel to the water line. Adolescent iguana for scale (18.002N, 66.754W).

Figure 31. Looking southwest. One of the columns near the waterline. Pavement has detached and settled, as visible along paint line. At the Costa Sur facility (18.002N, 66.754W).

Figure 32. Similar to the previous photograph, pavement settlement at the base of a support structure. At the Costa Sur facility (18.002N, 66.754W).

Figure 33. Settlement around the foundation of a small building near the natural gas pipeline at the Costa Sur facility (18.002N, 66.754W).

Figure 34. At one of the two water tanks immediately adjacent to the plant the center pipe piece (seen here without paint) was damaged and resulted in water discharge around the base of the tank. At Costa Sur facility (18.002N, 66.754W).

Figure 35. Scour of earthen material between pile cap and corrugated piles. New replacement section (pipe) seen in upper right of photograph (without paint). Scour was mainly on the north side of the structure (18.002N, 66.754W).

Figure 36: Members of the GEER team study the foundation scour site. Pile tilting seems to have occurred during pile driving (18.002N, 66.754W).

Figure 37: Close view of one of the piles showing some corrosion at the scour site. At the Costa Sur facility.

Figure 38: Larger water tank located across the highway just north of the main Costa Sur facility. Humans on the left for scale. View is to the north (18.002N, 66.754W).

Figure 39: On the eastern base of the tank seen in previous figure, a severed PVC pipe displays a few inches of offset, suggesting minor settling of the structure (18.002N, 66.754W).

Liquefaction features, mostly sand boils, sand ejecta and lateral spreading, and some small water line ruptures were observed in the municipalities of Guánica and Guayanilla. A rapid UAV (Unmanned Aerial Vehicle) reconnaissance was conducted two days after the earthquake along the floodplains of the Río Yauco and Río Guayanilla but no overwhelming clear evidence of liquefaction was immediate discernable in the footage. Days later, the Tropical Fruits farm (17.988N, 66.815W) in the community of Indios (Guayanilla) contacted the GEER Team with some concerns of ground deformations along the mango fields. Once the GEER team arrived, the evidence of liquefaction, sand boils, ground cracks and lateral spreading at this site was extensive. This farm is within 2 km of the epicenter of the main shock, located just offshore. This area is also where the maximum vertical subsidence was estimated to have occurred according to NASA InSAR estimates. Figures 40 through 44 show our findings at this site.

Figure 40. Typical ground cracks with sand ejecta at the mango fields in Tropical Fruit farms.

Figure 41. Ground cracks showing enormous amounts of sand ejecta at the mango fields in Tropical Fruit Farm.

Figure 42. Series of sand boils and sand ejecta in the mango fields at Tropical Fruit Farm.

Figure 43. Sand boils at the mango fields in Tropical Fruit Farm.

Figure 44: Ground cracks in road fill material in a low lying area between the Tropical Fruit farm and nearby Punta Verraco (17.988N, 66.815W).

The commercial and residential community of “El Triángulo” (18.006N, 66.771W) in Guayanilla is a small coastal zone that depends mostly on local food tourism and local fishing. This area was greatly impacted and some of the businesses are still closed at present (May 2020; also COVID-19 pandemic). Residential houses, which are a bit further from the coastline, did not suffer extensive structural damage but liquefaction features were observed in their backyards and in the crawl spaces. Minor features due to liquefaction induced settlement were observed inside the residential properties such as misaligned doors and settlement of columns. In addition, ground cracks with sand ejecta were found in the community basketball court, parking lots, and other places. Some broken water lines were also present here. Members of the community told the GEER team that water started to flow out of the ground cracks during the earthquake and continue for days after. The GEER Team felt a M 5.2 aftershock on 15-Jan at 11:36am local time at this site. Figures 45 through 50 illustrate the findings at this site.

Figure 45. Ground cracks and sand ejecta at the community basketball court. Sand at this site was a silty sand. This crack ran through the whole width of the basketball court.

Figure 46. More ground cracks and sand ejecta at the community basketball court.

Figure 47. Sand boils in the crawl space of a private residence. This was seen all through the crawl space of the residence and in the backyards of multiple houses.

Figure 48. Sand ejecta in the parking lot of a restaurant.

Figure 49. Broken water pipe and sand ejecta.

Figure 50: Liquefaction blow in the parking lot of a restaurant in "El Triangulo" neighborhood. Same as Figure 48. Photo by colleague Kate Allstadt (18.006N, 66.771W).

2. Landslides and Slope Stability

Landslides, rock falls, and other gravity-driven movements of soil and bedrock can be provoked by ground shaking. During the 1918 event offshore of northwestern Puerto Rico, there were scattered reports of rock falls in the limestone units of the northwest of the island (Reid and Taber, 1919). The same type of failures occurred during the 2020 event in southwestern Puerto Rico. The mechanism of movement in sites triggered by the ground movement is almost exclusively rock falls and slumps. The dry climate, thin soil mantle, and limestone composition of the bedrock in the epicentral region are all factors that contribute to the style of mass wasting triggered by the seismicity.

Rock falls and slumps occurred along road cuts and natural slopes. Generally, the movements on natural slopes were larger. The deposit material observed was exclusively limestone boulders and smaller fragments. The run-out distance of the larger limestone boulders is longer due to their shape and momentum accumulated during fall. In several sites, the track of impressions in the soil surface and of broken trees and/or fences was seen.

Mass wasting materials mostly affected roads and houses. The most important road affected was PR-2 at the limit of Peñuelas and Ponce municipalities, where it passes between a steep limestone cut and the Caribbean Sea (Figure 51). The site was also suffering periodic reactivation during aftershocks during the reconnaissance days. This was also the largest observed road cut failure. Most other road cut failures were much smaller. Several houses built on surfaces cut into the natural slopes were impacted by rock falls. A rock fall on a natural slope behind a high school in Guayanilla on PR-127 did not affect the school buildings (Figures 52 and 53). Scattered small rock falls were observed on PR-2, PR-132, PR-335, PR-384, PR-385, and other roads. Some mass wasting occurred in an abandoned quarry near PR-116 in Guánica but was not examined in detail.

Complex mass movement sites on PR-333 and PR-334 happened in Guánica. Both of these roads lead to the Bosque Seco State Forest. On PR-333 at km 2.7, many large boulders fell in the road. In addition, there are new fractures in the steep hill above the site as well as surface extension in the roadway. A very similar situation exists along PR-334 in a switchback after entering the state forest from the "La Luna" community. Both sites could be susceptible to future failures.

Figure 51: Part of the cut slope failure along the PR-2 landslide. The site suffered continuous failures during aftershocks and the 4 lanes of the roadway were shifted seaward.

Figure 52: Slump in the foreground and twin rock falls in the center of the photo. Location along PR-127 in Guayanilla. White building at the right center of photograph is the Escuela Secundaria Asunción Rodríguez de Sala. Photograph is modified from López et al., 2020b.

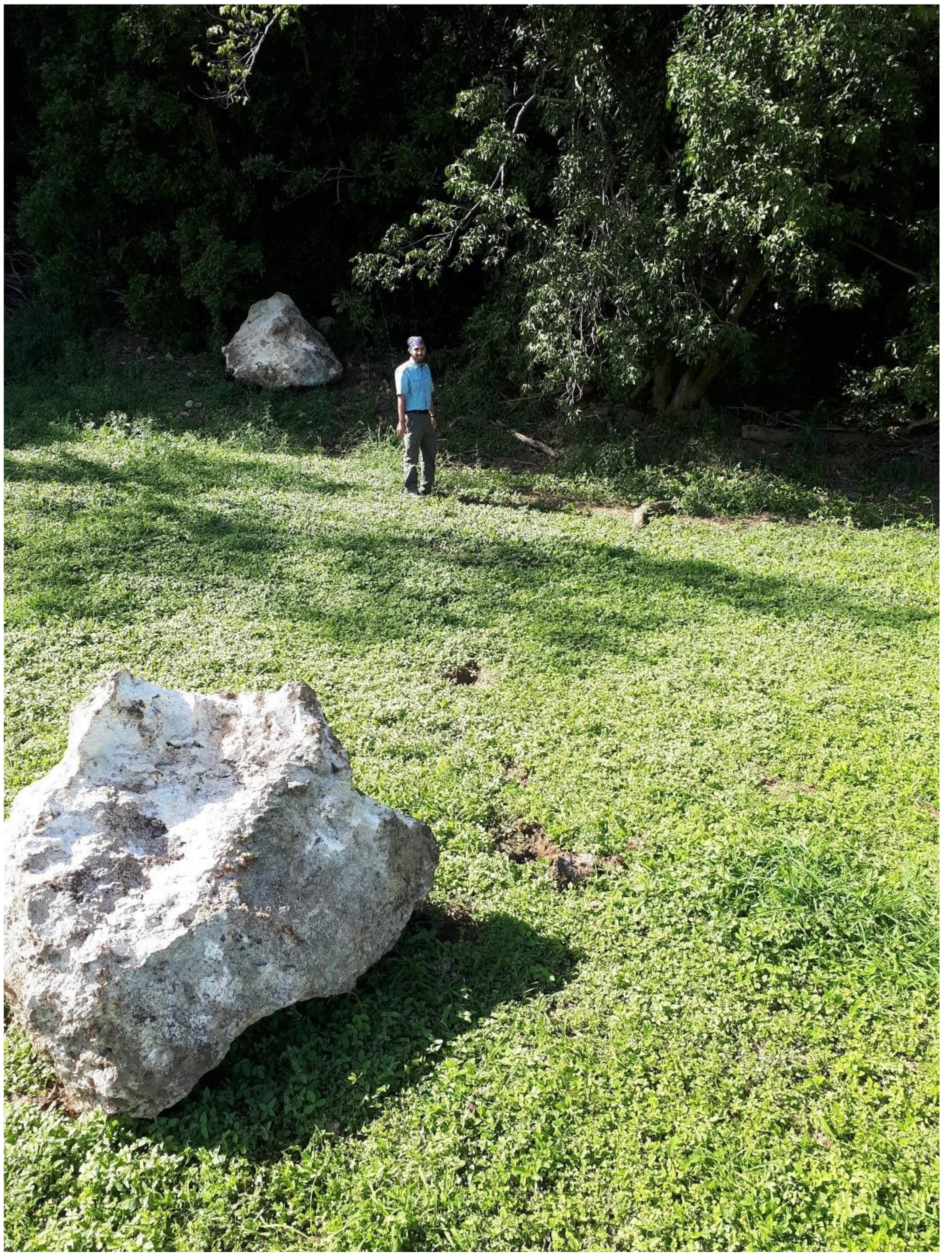


Figure 53: Boulder with track of indentations as it rolled out into the open field. The site is near the slump landslide seen in the previous image. UPRM graduate student Edwin Irizarry for scale.

Figure 54: Rock fall along PR-333 km 2.7 in Guánica.

Figure 55: Rock fall boulder that came to rest in a small channel. Location along PR-335R in Yauco.

3. Performance of Bridges

Bridges performed relatively well during the January 7, 2020 earthquake and aftershock. One of bridges examined by the GEER-Team was the PR-127 bridge over the Rio Guayanilla in the municipality of Guayanilla. This bridge is one of few roadways that provide direct access to the town of Guayanilla, therefore it was classified as an “emergency project” to be addressed immediately and the team was not able to collect data of the original failure to the abutment. The GEER-UPRM-Team members visited this site for the first time on 9-January-2020, and the ACT-PR (Highway Authorities of PR) had already demolished the east-side abutment (Figure 56). Upon further inspection of the area, the team observed some damage to one of the columns on the side contrary to where the abutment apparently failed. The columns were approximately 5 feet in diameter. During the shaking, the soil around the column experienced cyclic softening and a gap of approximately 3 inches developed around the structure and the surrounding soils. The pavement of the bridge presented transversal ground cracks, along both lanes.

Also, PR-127, both east and west bound, showed transversal ground cracks, and lifting of the pavement, along both lanes and the sidewalk. Some small bridges along PR-335R near the epicentral community of Indios also exhibited damages (Figures 57-63).

The bridge on a private road at the mango farm (Tropical Fruit Farm) which is the main access to *“Punta Ventana”* beach, also suffered some damages, mostly due to settlement of the ground. The bridge abutment was undergoing partial repairs when the GEER-Team arrived at the site (Figures 64-66)

Figure 56. PR-127 bridge over Rio Guayanilla showing the east abutment already demolished.

Figure 57. PR-335R bridge over the Rio Yauco south abutment showing damage near the joint between flexible and rigid pavement. Also, the sidewalk shows major displacement.

Figure 58. Side view of the sidewalk displacement.

Figure 59. Ground cracks parallel to the lanes in the PR-335R bridge. These ground cracks ran almost throughout the whole bridge span.

Figure 60. Detail of the ground cracks show in the previous figure.

Figure 61. PR-335R bridge over the Rio Yauco north abutment showing ground settlement near the joint between flexible and rigid pavement. This settlement lead to a complete break of the sidewalk.

Figure 62. Detail of the sidewalk damage in the north abutment of PR-335R bridge over the Rio Yauco.

Figure 63: Lateral spreading at the same PR-335R bridge site as previous photo. The Rio Yauco is just a few meters to the right of the field of view (17.987162N, 66.840456W).

Figure 64. Settlement and ground cracks due to lateral spreading in the mango fields bridge in Tropical Fruit farm that gives access to Playa Ventana.

Figure 65. Ground settlement in the bridge north abutment also seen in Figure 64.

Figure 66. Detail of the ground settlement in the main road and north abutment connection shown in previous figure.

4. Performance of Dams

Concrete dams and earth dams performed very good during the earthquake sequence. The GEER-Team visited two dams, located near the epicenter of the M6.4 Punta Montalva earthquake: (1) Guayabal Dam and (2) Cerrillos Dam. The location of these dams is shown in Figure 67.

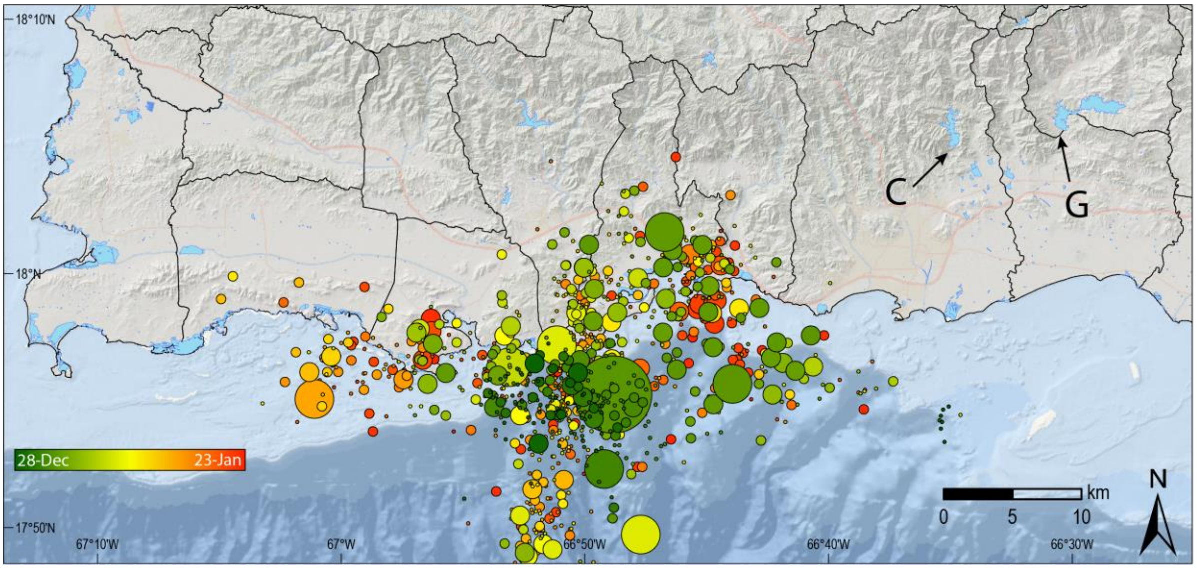


Figure 67: Map of the seismic sequence events and the location of Lago Cerrillos (C) and Lago Guayabal (G), to the northeast of the epicentral area.

The Guayabal dam is a concrete dam located along the boundary of the municipalities of Juana Díaz and Villalba. This dam was built in 1912 for irrigation and flood control. It is own and maintained by PREPA (Puerto Rico Electricity and Power Authority). Guayabal is the longest concrete dam in PR; having 22 gates that span approximately one kilometer. Site inspections of the surrounding downstream area revealed no damages at all in the perimeter. This is shown in Figure 68.

The Cerrillos dam is an earth dam located in Ponce. Cerrillos was built in 1992 by the US Army Corps of Engineers for irrigation, flood control and recreational purposes. It is managed and maintained by the PR DRNA (Department of Natural Resources) and has a total capacity of 59 million cubic meters. The dam is 323 feet high (98 m) and 1555 feet wide (474 m). It is located 12.5 km from the coast of Ponce at 323 feet (98 m) above sea level. Site inspections of the surrounding downstream area and the discharge tunnel area revealed no damages at all in the perimeter. This is shown in Figures 69-70.

Figure 68. Downstream area at Guayabal dam. No damage was reported.

Figure 69. Downstream area at Cerrillos dam. No damage was reported.

Figure 70. Discharge tunnel area at Cerrillos dam. No damage was reported.

References Cited

Adames Corraliza, A.R., 2017, Geomorphic and geophysical characterization of the north Boquerón Bay – Punta Montalva fault zone: A capable fault system in southwestern Puerto Rico, University of Puerto Rico at Mayagüez unpublished MS thesis, 178 p.

Addarich-Martinez, L., 2009, The geologic mapping and history of the Guánica Quadrangle, southwestern, University of Puerto Rico at Mayagüez unpublished MS thesis, 73 p.

Bawiec, W.J., 1998, Geology, Geochemistry, Geophysics, Mineral Occurrences and Mineral Resource Assessment for the Commonwealth of Puerto Rico, Open-File Report 98-38.

Bruna, J. G., Ten Brink, U. S., Muñoz-Martín, A., Carbó-Gorosabel, A., & Estrada, P. L., 2015, Shallower structure and geomorphology of the southern Puerto Rico offshore margin. *Marine and Petroleum Geology*, v. *67*, p. 30-56.

López, A.M., Hughes, K.S., & Vanacore, E., 2020a, Puerto Rico's Winter 2019-2020 Seismic Sequence Leaves the Island On Edge, Temblor, http://doi.org/10.32858/temblor.064.

López, A.M., Vanacore, E., Hughes, K.S., Báez-Sánchez, G., and Hudgins, T.R., 2020b, Response and initial scientific findings from the southwestern Puerto Rico 2020 Seismic Sequence, Temblor, http://doi.org/10.32858/temblor.068

Reid, H. F., & Taber, S., 1919, The Porto Rico Earthquakes of October-November, 1918. *Bulletin of the Seismological Society of America*, *9*(4), p. 95-127.

Roig Silva, C.M., 2010, Geology and Structure of the North Boquerón Bay – Punta Montalva Fault System, University of Puerto Rico at Mayagüez unpublished MS thesis, 206 p.

Roig-Silva, C. M., Asencio, E., and Joyce, J., 2013, The Northwest Trending North Boquerón Bay-Punta Montalva Fault Zone; A Through Going Active Fault System in Southwestern Puerto Rico, Seismological Research Letters, v. 84, p. 538-550.

Uri ten Brink, William Danforth, Christopher F. Polloni, Castle Eugene Parker, Toshihiko Uozumi, and Glynn F. Williams, 2005, Project PROBE Leg II - Final Report and Archive of Swath Bathymetric Sonar, CTD/XBT and GPS Navigation Data Collected During USGS Cruise 03008 (NOAA Cruise RB0303) Puerto Rico Trench 18 February - 7 March, 2003, USGS Open-File Report 2004-1400.