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INTRODUCING SHAKEMAP TO POTENTIAL USERS IN PUERTO RICO USING SCENARIOS OF DAMAGING HISTORICAL AND PROBABLE EARTHQUAKES

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ABSTRACT

The island of Puerto Rico has a long history of damaging earthquakes. Major earthquakes from off-shore sources have affected Puerto Rico in 1520, 1615, 1670, 1751, 1787, 1867, and 1918 (Mueller et al, 2003; PRSN Catalogue). Recent trenching has also yielded evidence of possible M7.0 events inland (Prentice and Mann, 2005). The high seismic hazard, large population, high tsunami potential and relatively poor construction practice can result in a potentially devastating combination. Efficient emergency response in the event of a large earthquake will be crucial to minimizing the loss of life and disruption of lifeline systems in Puerto Rico and facilitate a faster recovery.

The ShakeMap system (Wald et al, 1999a) developed by the USGS to rapidly display and disseminate information about the geographical distribution of ground shaking (and hence potential damage) following a large earthquake has proven to be a vital tool for post earthquake emergency response efforts, and is being adopted and emulated in various seismically active regions worldwide. Implementing a robust ShakeMap system is among the top priorities of the Puerto Rico Seismic Network. However, the ultimate effectiveness of ShakeMap in post-earthquake response depends not only on its rapid availability, but also on the effective use of the information it provides.

We developed ShakeMap scenarios of a suite of damaging historical and probable earthquakes that severely impact San Juan and Mayagüez, two largest cities in Puerto Rico. Earthquake source parameters were obtained from McCann and Mercado (1998), Zahibo et al (2003) and Huérfano (2003). For historical earthquakes that generated tsunamis, wave height and travel time mareograms were generated using the Tsunami Inundation Modeling for Exchange (TIME) method (Goto and Ogawa, 1992). A new ShakeMap brochure (in Spanish) was presented to local and regional governmental and emergency response agencies at the 2007 Annual Conference of the Puerto Rico Emergency Management and Disaster Administration in San Juan, PR, and at numerous other emergency management talks and training sessions. Economic losses for San Juan and Mayagüez are estimated using the ShakeMap scenario ground motions (Gerbaudo, 2007). The calibration tasks necessary in generating these scenarios (developing the Vs30 grid, selection of appropriate attenuation relationships) complement the on-going efforts of the Puerto Rico Seismic Network to generate ShakeMaps in real-time.

INTRODUCTION

The US Commonwealth of Puerto Rico has a population of 3.8 million (2000 Census), which amounts to a higher population density than any US state. The island, approximately 160km from east to west by 50km from north to south, is bounded by off-shore active faults on all sides. Numerous local and regional events in the recorded history with M>7.0 (1670, 1751, 1787), some of which have generated tsunamis (1867 and 1918), have caused extensive damage to local infrastructure; the last significant ground motions were felt on-shore in 1918, the Mona Canyon Event. Recent trenching has also yielded evidence of possible M7.0 events inland (Prentice and Mann, 2000). The USGS hazard maps (Mueller et al, 2003) indicate that the seismic hazard is similar to the Basin and Range province in the Western USA, and the island is assigned Seismic Zone 3 in the current standard Building Code in Puerto Rico, the 1997 UBC. The high seismic hazard, large population, high tsunami potential and relatively poor construction practice can result in a potentially devastating combination. Efficient emergency response in the event of a large earthquake will be crucial to minimizing the loss of life and disruption of lifeline systems in Puerto Rico.

The first step in providing an appropriate response to such a disaster is a timely knowledge of the magnitude, location and expected ground shaking and damage patterns from the event. This requires a modern and dense seismic network, capable not only of recording the earthquake ground motion without saturation, but also doing so in real-time and then providing data for near-immediate analysis, which can be made available to the emergency services and community at large. ShakeMap was developed by Wald et al (1999) in response to lessons learned from the Loma Prieta and Northridge, California events, as well as the Kobe, Japan earthquake, where rescue and recovery efforts were hampered by lack of information regarding the distribution of ground shaking. Since then, it has proven effective in assisting emergency response communities in Northern and Southern California in making decisions regarding the allocation and deployment their resources after potentially damaging events. For instance, following the 1999 M7.1 Hector Mine event, rapidly available ShakeMaps made it clear to that, while the event was large, there was no need for large-scale emergency response mobilization, since the areas affected by large ground motions were sparsely populated (Wald et al, 2004).

Efficient use of ShakeMaps will improve rescue and recovery efforts following a large earthquake in Puerto Rico. The rapid generation of ShakeMaps is a high priority area of collaboration between the two networks operating on the island - the Puerto Rico Seismic Network (PRSN) and the Puerto Rico Strong Motion Program (PRSMP). However, the ultimate effectiveness of ShakeMap in improving post-earthquake response depends not only on its rapid availability, but also on the efficient use of this information. Until recently, the emergency response communities, government bodies, and agencies in charge of critical lifelines and infrastructure have had no experience with ShakeMaps or how the information they provide can be used to guide rescue and recovery efforts after a large event. Neither were the media familiar with the ShakeMap format or how they could be used to communicate earthquake information to the general public. This is in part was due to the lack of large earthquakes in recent times.

We developed ShakeMap scenarios of a suite of damaging historical and probable earthquakes that severely impact San Juan and Mayagüez, two largest cities in Puerto Rico. Earthquake source parameters were obtained from McCann and Mercado (1998), Zahibo et al (2003), and Huérfano (2003). For historical earthquakes that generated tsunamis, wave height and travel time mareograms were generated using the TIME method of Goto and Ogawa (1992).

Oral presentations were held and a new ShakeMap brochure (in Spanish) was presented to local and regional governmental and emergency response agencies at the 2007 Annual conference of the Puerto Rico Emergency Management and Disaster Administration in San Juan, PR, and at numerous other emergency management talks and training sessions. PRSN maintains its own "Did You Feel It?" webpage in Spanish, which allows the public to post felt reports following an earthquake. These felt reports can be used as additional constraints for ShakeMap. Economic losses for San Juan and Mayagüez are estimated using the ShakeMap scenario ground motions (Gerbado, 2007). The calibration tasks necessary in generating these scenarios (developing the Vs30 grid, selection of appropriate attenuation relationships) complement the on-going efforts of the Puerto Rico Seismic Network to generate ShakeMaps in real-time.

SEISMIC INSTRUMENTATION

The Puerto Rico Seismic Network (PRSN) and the Puerto Rico Strong Motion Program (PRSMP) jointly monitor seismic activity in the northeastern Caribbean region. Clinton et al (2007) provide a detailed description of seismic monitoring efforts in Puerto Rico. The primary duty of the PRSN is to identify and provide information on local, regional, and teleseismic earthquakes and provide tsunami messages for Puerto Rico and the Virgin Islands. As of March 2008, the PRSN is staffed 24 hours a day, 7 days a week, to provide earthquake information and tsunami messages for Puerto Rico and the Virgin Islands. PRSN is the reporting authority for event locations and magnitudes, and maintains the authoritative event catalogue in this region. The PRSN operate real time (EarthWorm software, Johnson et al, 1995) vault stations primarily in low noise locations, 15 broadband or intermediate period stations and 10 short period stations. The objective of the PRSMP is to record on-scale ground motions from earthquakes affecting the island with the highest quality and station density as possible. The PRSMP maintain a dense urban network with both free-field stations and structural arrays, 10 of those stations are monitored in real time throughout the Antelope system (Boulder Real Time Technologies, BRRT). There are 10 real time co-collocated broadband seismic stations with accelerometers and seismometers (Figure 1). Both networks share the common goal of providing high-quality data and information in response to needs of the emergency management, engineering, and scientific communities, as well as the general public.

The PRSMP and PRSN run complimentary operations and share all continuous data in real-time. This exchange provides an essential level of redundancy and robustness that will be important in ensuring timely and accurate information following a large earthquake or tsunami. In addition to the seismic instrumentation the PRSN operates a network of 6 tsunami-ready tide gauge stations in Puerto Rico which complement 10 such stations operated by the National Oceanic and Atmospheric Administration (NOAA) in Puerto Rico and the Virgin Islands, all received in the PRSN via GOES satellites (von Hillebrandt, 2008).

SHAKEMAP INSTALLATION IN THE PRSN

In January 2006, PRSN installed the ShakeMap package (version 3.1) and is currently generating near-real time ShakeMaps for felt events in Puerto Rico and the Virgin Islands (PRVI). Automatic or reviewed earthquake locations are provided by the multiple systems installed in the network, such as EarthWorm, EarlyBird and Puerto Rico Data Analysis and Information System (PR DANIS). Using the *gmew* earthworm module, and based on an automatic location, the system starts the computation of peak ground motions from the raw waveforms. The instrument response is removed, and acceleration, velocity and displacement traces are computed. In addition, 5% damped response spectra is computed at of 0.3, 1.0, and 3.0-second periods. All ground motion waveforms are computed in the frequency domain. The spectral response traces are computed by generating the response function for a single degree of freedom harmonic oscillator with the specified free period and damping. All these time series are then transformed back to the time domain via an inverse Fast Fourier Transform. Peak amplitudes are identified in the time domain. The search for peak amplitudes is done within a time window related to the estimated S-phase arrival time and specified in the *gmew* configuration file (GMEW Overview, 2006).

The initial ShakeMaps produced using the PRSN automatic locations (typically available within 1 minute of the origin time for local events) are purely predictive. Once the scientist-in-charge reviews the event location and the peak ground motion calculations, the PR DANIS BroadCast system takes the output from the GMEW earthworm module or other XML ground motion file format, opens a socket connection to the ShakeMap server, then starts a ShakeMap calculation using the peak ground motion and reviewed location as inputs. The PR DANIS broadcast system is an earthquake and tsunami notification program designed to provide subscribers with near real-time information following a significant event located in the PRSN area of responsibility (AOR) or in the Caribbean. As shown in Figure 2, users can select from preconfigured options like the generation of purely predictive ShakeMaps or, if ground motion data is available, the instrumentally constrained ShakeMaps.

The predictive ShakeMaps based on automatic locations are usually available within 3-5 minutes after the earthquake. These are normally reviewed minutes to hours later depending on the availability of new data or significance of the event, and a revised map will usually be and posted on the webpage of the PRSN (http://redsismica.uprm.edu).

PRSN maintains its own “Did You Feel It?” webpage in Spanish, which allows the public to post felt reports following an earthquake on its webpage (http://redsismica.uprm.edu). These felt reports can be used as additional constraints for ShakeMap.

SITE CONDITIONS

We followed the approach of Wills et al (2000) in assigning average shear wave velocity in the upper 30 meters (Vs30) values to geologic units (Table 1). Puerto Rico has geologic units that date back at least 150 million years. The central part of the island is primarily composed of volcaniclastic and sedimentary sequences cut by younger intrusives. To the north and south are the coastal plains which consist primarily of sandstones, calcareous clastic rocks and limestones. Quaternary beach, swamp, alluvial and aeolinite sands are concentrated mostly along the near shore areas and along the major river beds and in the intermountain valleys. A generalized geologic map (Renken et al, 2002) is presented in figure 3.a. Shear wave data were recorded at 22 sites to determine Vs30 of many of the main geological units across the island (Odum et al, 2007). These measurements complemented the Vs30 determined at 6 of the joint PRSN/PRSMP stations (Jaca and Sierra, 2002). NEHRP classes (B through E) were assigned to the lithologies of the geologic map for Puerto Rico (Schellekens, 1998) based on the available Vs30 measurements and input from geologists at the University of Puerto Rico Mayagüez. Figure 3.b. shows estimated Vs30 grid throughout the island as used in the ShakeMap installation.

ATTENUATION RELATIONSHIP

Motazedian and Atkinson (2005) (to be subsequently referred to as MA2005) developed attenuation relationships based on Puerto Rico ground motion observations in the magnitude range $3.5 < M < 5.5$, and based on stochastic simulations for $M > 5.5$. As part of this project, a ShakeMap regression module implementing the MA2005 relationship was developed and submitted to Bruce Worden at the United States Geological Survey (USGS).

Subduction zone events contribute significant earthquake hazard to Puerto Rico. Upon consultation with David Wald at the USGS, a ShakeMap regression module implementing the Kanno (2006) subduction zone attenuation relationship (based on a large dataset of Japanese earthquakes) was developed and submitted to Bruce Worden for possible inclusion in subsequent releases of ShakeMap.

COMPARISIONS WITH OBSERVED INTENSITIES

Velez and Huérfano (2007) compared the intensities estimated by ShakeMap with felt reports for five events located in the Puerto Rico region. They found that ShakeMaps generated using the MA2005 and Kanno (2006) relationships underestimated the observed intensities. The observed intensities were best fit using the HazusPGV regression module included in the ShakeMap distribution. The HazusPGV relationship is identical to the Boore, Atkinson, and Fumal (1997) relationship (referred to subsequently as BJF97) for PGA, and 5% damped spectral acceleration at 0.3, 1.0, and 3.0 second periods, and derives PGV from 1.0-second pseudospectral acceleration.

The effects of the 1918 Mona Canyon event across Puerto Rico were documented in the Reid and Taber (1919a, 1919b) reports. These observed intensities were compared with the ShakeMap-estimated intensities using MA2005, Kanno (2006), BJF97, and HazusPGV ShakeMap regression modules. Figure 4 shows observed peak ground velocity (PGV) values included in the Next Generation Attenuation (Power et al, 2008) database, as well as the median PGV levels predicted by various attenuation relationhships: Motazedian and Atkinson (2005), Kanno (2006), Boore, Atkinson, and Fumal (1997), the HazusPGV ShakeMap regression module (Wald et al, 2005), Boore and Atkinson (2008), and Cua and Heaton (2008). The best agreement between the Mona Canyon observed intensities and the (purely predictive) ShakeMap-estimated intensities were obtained using the HazusPGV module. The HazusPGV relationship was then subsequently used to generate the ShakeMap scenarios considered in this study. The 1787 event on the Puerto Rico Trench subduction zone has an estimated depth of 20 km; this is shallow enough to justify use of ground motion relationships meant for shallow, crustal seismicity.

EARTHQUAKE SCENARIOS

ShakeMap was developed by Wald et al (1999) in response to lessons learned from the Loma Prieta and Northridge, California events, as well as the Kobe, Japan earthquake, where rescue and recovery efforts were hampered by lack of information regarding the distribution of ground shaking. Since then, it has proven effective in assisting emergency response communities in Northern and Southern California in making decisions regarding the allocation and deployment their resources after potentially damaging events. For instance, following the 1999 M7.1 Hector Mine event, rapidly available ShakeMaps made it clear to that, while the event was large, there was no need for large-scale emergency response mobilization, since the areas affected by large ground motions were sparsely populated (Wald et al, 2004). Efficient use of ShakeMaps will improve rescue and recovery efforts following a large earthquake in Puerto Rico. The rapid generation of ShakeMaps is a high priority area of collaboration between the two networks operating on the island - the Puerto Rico Strong Motion Program (PRSMP) and the Puerto Rico Seismic Network (PRSN). However, the ultimate effectiveness of ShakeMap in improving post-earthquake response depends not only on its rapid availability, but also on the efficient use of this information. Until 2007, the emergency response communities, government bodies, and agencies in charge of critical lifelines and infrastructure had no experience with ShakeMaps or how the information they provide could be used to guide rescue and recovery efforts after a large event. Neither were the media familiar with the ShakeMap format or how they can be used to communicate earthquake information to the general public. This is in part was due to the lack of large earthquakes in recent times. The scenarios we developed has provided these various sectors with the exposure and familiarity with ShakeMap such that, when the real-time ShakeMaps can be generated by the PRSN, they can be utilized efficiently in the post-earthquake response following the next large earthquake that affects the region.

The Puerto Rico microplate is located in the northeastern corner of the Caribbean plate. The main sources of seismic activity in the region are at the supposed boundaries of the microplate; the subduction zones to the north (the Puerto Rico Trench, which is the location of the largest gravity anomaly on earth), the Muertos Trough to the south, and zones of extension at the Anegada Trough to the east, and the Mona Canyon region to the west. All regions are capable of producing events greater than M7.0, and all have evidence of having done so in the recorded history of the island (Figure 5). Given a selected event in terms of magnitude, we need to assume a fault. With that information, the ShakeMap package estimates the ground shaking at all locations in the chosen grid and present the results visually via images, grd files and web pages. In table 2. we summarize the fault geometry as used in the tsunami modeling.

Lajas Valley scenario

In addition to these offshore sources, recent trenching shows evidence of 2 surface-rupturing events on the inland South Lajas fault at the southwest of Puerto Rico (Prentice et al., 2000, Prentice and Mann, 2005), predominantly along a normal fault with a component of strike-slip motion, both within the last 5000 years. This 50-km long inland fault segment can produce M7.0 events.

Virgin Islands scenario

On the afternoon of November 18, 1867, a magnitude 7.5 earthquake occurred in the Anegada trough, located between the US Virgin Islands of St. Croix, and St. Thomas (Zahibo et al, 2003). The earthquake had its greatest intensity in the general region of the Virgin Islands and eastern Puerto Rico (Reid and Taber, 1920). The main shock generated a tsunami with waves that were recorded at several Island locations across the eastern Caribbean region, most notably on the islands of St. Thomas and St. Croix. Felt and damage reports were used to constrain the ShakeMaps for this event.

Mona Canyon scenario

The most recent large event to cause widespread damage across the island occurred in the Mona Passage in October of 1918, with M_S7.3 (Pacheco and Sykes, 1992). This event caused substantial structural damage to the large towns of Mayagüez and Aguadilla on the West of the island. Reid and Taber (1919a,b) estimated that the economic loss associated with this event exceeded 4 million (1918) dollars (equivalent to the total state budget at the time). The associated tsunami had a run-up of 6 m in Aguadilla, and 2 m in Mayagüez (Mercado and McCann, 1998). 118 people were officially reported as killed, 40 due to the tsunami and 78 as a result of the earthquake, oral report suggest additional 100 people died as consequence of the tsunami. Felt and damage reports were used to constrain the ShakeMaps for this event.

Puerto Rico trench scenario

Possibly the largest earthquake that has affected Puerto Rico since the beginning of colonization occurred on May 2, 1787. This was felt strongly throughout the Island and may have been as large as magnitude 8.0. Its epicenter was probably to the north, in the Puerto Rico Trench (Huérfano, 2003). It demolished the Arecibo church along with the El Rosario and La Concepcion monasteries and damaged the churches at Bayamon, Toa Baja and Mayaguez. It also caused considerable damage to the castles of San Felipe del Morro and San Cristobal in San Juan.

Figures 6 shows the ShakeMap-estimated intensities from these 4 events. ShakeMaps for the Mona Canyon and Virgin Island (Anegada Passage) events are constrained by available felt reports. We used the estimated ground motions from these ShakeMap scenarios as inputs for economic loss calculations. Losses are calculated in Mayaguez and San Juan for the Lajas Valley, Mona Canyon, and Virgin Islands scenarios.

TSUNAMI MODELING

There are three phases in the life of a tsunami: generation (initial conditions), propagation, and run-up. Tsunamis can be generated by various causes: submarine earthquake, underwater explosions from volcanoes, subaerial landslides impinging on the sea, submarine landslides and celestial impacts.

In the scenarios considered for this project, the initial conditions applied consist of a sea surface deformation which is due to a vertical displacement of the sea bottom, as a result of an submarine shallow earthquake. The initial vertical static displacement of the sea bottom, which is calculated with the Mansinha and Smylie method (1972), is assumed to propagate instantaneously to the sea surface and with no energy dissipation. This assumption is valid because the horizontal size of the initial profile is sufficiently large compared with the water depth at the tsunami source, and the rupture velocity is assumed very short compared with the tsunami propagation velocity (Shuto, 1991). Kowalik and Whitmore (1991) have shown that the consideration of a finite (versus infinite) rupture velocity (also called a moving rupture versus an instantaneous uplift) has a small effect on the energy flux distribution (or directionality) of the tsunami and on the tsunami itself.

The Tsunami Inundation Modeling for Exchange (TIME) model of Goto and Ogawa (1992) was used to propagate the sea wave to the shore. Long wave theory is used (where the ratio of water depth to wavelength is small), for which the vertical acceleration of water particles is negligible compared to the gravitational acceleration, and the hydrostatic pressure approximation is used. The non-linear terms are kept for use where needed, which is the case in very shallow water (from the tsunami point of view). In addition, we are interested in this study on near-field tsunamis, that is, those whose propagation distance is less than 1000 km. Henceforth, Cartesian coordinates can be used.

In this study, three nested grids to model topography and bathymetry were used to facilitate the execution of the TIME model. The topographic and bathymetric models used were 1) the USGS Puerto Rico DEM (Digital Elevation Model) with 3 sec/arc resolution, 2) ETOPO2 and 3) National Ocean Survey (NOS) depth soundings as digitized from the original "smooth4 sheets" by Mercado (1994) for shelf regions. For the very near shore we used recently acquired SHOALS data.

The tsunami run up modeling for the 1787 Puerto Rico trench scenario predicts wave heights of 1.6 meters in the San Juan Bay within about 12 minutes of the earthquake rupture (Figure 7). Run up models for the 1918 Mona Canyon and 1867 Virgin Islands scenarios were published by Mercado and McCann (1998) and Zahibo (2003).

INTRODUCING SHAKEMAPS TO THE EMERGENCY MANAGERS AND THE GENERAL PUBLIC

Immediately after an earthquake, emergency managers must make quick response decisions using limited information. Near real time empirical or instrumental ShakeMaps provide and opportunity to determine what areas were subject to the highest intensities and probable damages. To familiarize various response and public sectors on what ShakeMaps are and how they might be used after a significant earthquake, a Spanish flyer describing the ShakeMap webpage and the various available data products, Community Internet Intensity Maps, and interpretation of the modified Mercalli intensity scale was created and distributed to state, regional, and local emergency management officials as well as the general public (Figure 8). The ShakeMap tool was officially presented in the Annual Conference of the Puerto Rico Emergency Management and Disaster Administration in San Juan, Puerto Rico in 2007, and at dozens of other emergency management talks and training sessions. In 2008 a workshop was held for the media and the ShakeMap tool was also presented.

EARTHQUAKE SCENARIO LOSSES

We estimate the current day human impact of the scenarios by combining the ground shaking scenarios with modern census data. These datasets are available from the Civil Engineering and Surveying Department at the University of Puerto Rico, Mayaguez. For a given seismic event, using the occupancy load cell methodology described by Guzman et al (1996a,b), the loss in human capital associated with individual buildings may be calculated. Expanded over the test bed areas, and incorporating the population distribution to scale, the number of casualties and injured as functions of magnitude and macroseismic intensity were estimated. Because of the time constraints, our analysis is limited in scope to the test bed cities of Mayaguez and San Juan. Even so, the results should help emergency response communities decide on the scale of rescue and recovery efforts after future earthquakes in Puerto Rico.

EARTHQUAKE SCENARIO LOSSES FOR MAYAGUEZ AND SAN JUAN

Deterministic loss scenarios are the traditional means for accounting for spatial correlation in assessing natural hazard impacts. A building inventory for the city of Mayagüez in the western part of Puerto Rico was created based on the interpretation of satellite images and aerial photos stored in a Geographic Information System by the Center for Collection of Municipal Taxes (CRIM, as per its acronym in Spanish). The census track units for Mayaguez shown in Figure 9 are used as the basic mapping units for the building survey.

For each census track, the following data is extracted:

- The number and size of the buildings are collected using the CRIM database.
- The number of buildings with metal roofs is counted using the satellite images. Industrial buildings are differentiated from residential structures.
- Soil types are obtained from maps developed by the insurance industry in Puerto Rico.
- Wind exposure and topographic effects are assigned, based on the maps developed by the insurance industry in Puerto Rico.
- The zoning classifications are noted.

Combining the information of each census track with certain assumptions described in the thesis by Gerbaudo (2007), it is possible to approximate the percentage of each of the following construction classes in the census. The procedure for the inventory classification is as follows:

1. Industrial buildings are easily distinguished from the satellite images. Summing the areas of the industrial buildings from the CRIM database and dividing it by the total building areas from the sector, the results are expressed as a percentage of the total built areas.
2. The percentage of one story buildings multiplied by the percentage of metal roof buildings is assumed to be wood-zinc house types.
3. The percentage of one story buildings minus the percentage of wood-zinc house types are assumed to be shear wall construction for urbanizations and concrete moment resisting frame for owner-built structures.
4. Two story buildings are assumed shear wall for urbanizations and concrete moment resisting frame for the owner-built structures.
5. The 90 percent of buildings between three and seven stories are assumed concrete multistory type and the other 10 percent are assumed steel frame construction.
6. Buildings of more than seven stories are assumed high-rise steel construction.

The computer Program INSOL developed as part of the Insurance Security Commission Project in Civil Engineering at UPRM was used to calculate the losses in Mayagüez. The catastrophe model implemented in our software has four basic modules: 1) Exposure (or inventory model), 2) Hazard, 3) Vulnerability, and 4) Loss estimation. A schematic diagram of this is shown in Figure 10. The exposure consists of the group of the insured systems and structures. Basic input includes location, age, occupancy, and construction type of a given structure. The Hazard module determines the hazard of each event at each location. The hazard is the consequence of the event that causes damage (for a hurricane it is the wind at ground level, for an earthquake the ground shaking and for flood the water depth and water velocity). Vulnerability is the fragility or the damageability of the buildings. This module determines the degree of loss to a particular system or structure resulting from exposure to a given hazard. The fragility curves are defined based on the building construction class and in some cases are sensitive to additional material and geometric properties. Figure 11 shows the fragility curves for one class of buildings in Puerto Rico. Finally, in the Loss Estimation module, the damage obtained from the vulnerability module is associated to the repair cost and the risk is calculated. We use the PGA estimates from the various ShakeMap scenarios as inputs to INSOL to calculate losses in Mayaguez and San Juan from the respective scenarios.

The expected loss percentage for each construction class in each census track is calculated, combining the fragility curves with the PGA and considering the soil type of the census. Then, using the mean square foot cost data from RMS Means (R.S. Means, 2007) and the area of each building type, the dollar exposure is calculated for each census track. The monetary loss is calculated as the multiplication of the dollar exposure by the loss percentage. The repair ratio is the total loss divided by the total exposure. Examples of loss calculation for two census track are shown in Tables 3 and 4.

The total losses in each census track in Mayaguez are shown in Table 5. The aggregated losses for the entire city of Mayagüez range from 256 million to 2 billion US dollars. The fatalities and injuries tabulated are based on the research by Saffar and Guzman (1996) The injuries are calculated as a function of the damage index squared. Fatalities are calculated as a function of the damage index to the fourth power. Only the extensive and the total damage states are considered when calculating injuries and fatalities. Traffic related injuries and fatalities are not considered. All damage states are considered when calculating monetary losses.

The previously outlined procedure to generate building inventories for the city of Mayagüez is highly labor intensive. Given the much larger size of San Juan relative to Mayagüez, the demands placed on the system by the latter are far more severe. The reporting here is limited to two neighborhoods of San Juan (Santurce and Rio Piedras). In these two neighborhoods, 93 census sectors were considered; only 20 census sectors were required for Mayagüez. Tables 6 and 7 present summaries of monetary losses resulting from our earthquake scenarios. The percentage of losses (relative to total exposure) in Rio Piedras and Santurce for the Mona Canyon 1918 and Lajas M7 scenarios are substantially less than those observed for Mayagüez; about 10 percent for Mona Canyon 1918 scenario and less than 1 percent for the Lajas M7 scenario. However, the losses in of nearly 20 percent in Rio Piedras for the Virgin Islands 1867 scenario are about four times the losses observed for Mayaguez. In this scenario, the losses for Rio Piedras alone exceed 2 billion dollars.

SUMMARY

In this study, we developed ShakeMap scenarios of a suite of damaging historical and probable earthquakes that will severely impact Puerto Rico, the 1787 north of Puerto Rico, the 1867 Virgin Islands, the 1918 Mona Canyon and the Lajas Valley. Earthquake source parameters were obtained from McCann and Mercado (1998), Zahibo et al (2003) and Huérfano (2003). For historical earthquakes that generated tsunamis, wave height and travel time mareograms were generated using the Tsunami Inundation Modeling for Exchange (TIME) method (Goto and Ogawa, 1992). A new ShakeMap brochure (in Spanish) was presented to local and regional governmental and emergency response agencies at the 2007 Annual Conference of the Puerto Rico Emergency Management and Disaster Administration in San Juan, PR, and at numerous other emergency management talks and training sessions. PRSN maintains its own "Did You Feel It?" webpage in Spanish, which allows the public to post felt reports following an earthquake. These felt reports can be used as additional constraints for ShakeMap.

Economic losses for Mayagüez and two neighborhoods of San Juan (Santurce and Rio Piedras) are estimated using the ShakeMap scenario ground motions (Saffar, 2007). The percentage of losses (relative to total exposure) in Rio Piedras and Santurce for the Mayaguez 1918 and Lajas M7 scenarios are substantially less than those observed for Mayaguez; about 10 percent for Mayagüez 1918 scenario and less than 1 percent for the Lajas M7 scenario. However, the losses in of nearly 20 percent in Rio Piedras for the Virgin Islands 1867 scenario are about four times the losses observed for Mayagüez. In this scenario, the estimated losses for Rio Piedras alone exceed 2 billion dollars.

The calibration tasks necessary in generating these scenarios (developing the Vs30 grid, selection of appropriate attenuation relationships) complement the on-going efforts of the Puerto Rico Seismic Network to generate instrumental ShakeMaps in real-time

Tables

Table 1. Average Vs30 assignments to rock types in Puerto Rico

Rock Type	Average Vs30 (m/s)	NEHRP Vs 30 Classification
Marine Tertiary	1145	B
Pliocene/Oligocene Nonvolcaniclastics	985	B
Eocene/Cretaceous Nonvolcaniclastics	925	B
Suareial Volcaniclastic Terranes	760	B
Cretaceous and Tertiary/Cretaceous Intrusives	724	B/C
Ultramafics, Amphibolites, Submarine Basalts	650	C
Alteration Terranes	464	C
Quaternary Landslide and Blanket Sand Deposits	464	C
Quaternary Alluvium	372	C/D
Quaternary Beach Deposits	301	D
Quaternary Swamp deposits and Artificial fill	163	E

Table 2. Fault segments and parameters. [1] McCann and Mercado (1998), [2] Zahibo et al (2003) and [3] Huérfano (2003)

1918 Event[1]									
Segment	**End Points**		**Fault Geometry**						
	Lon.	**Lat.**	**Strike**	**Dip**	**Rake**	**Slip** (m)	**Depth** (km)	**Length** (Km)
1	-67.34 -67.35	19.00 18.88	185	85	-95	4	4.67	13
2	-67.35 -67.38	18.88 18.86	236	34	-146	4	4.71	4
3	-67.38 -67.42	18.86 18.58	188	82	-98	4	4.34	31
4	-67.42 -67.50	18.58 18.44	210	60	-120	4	2.31	18
1867 Event[2]								
Segment	**End Points**		**Fault Geometry**					
	Lon.	**Lat.**	**Strike**	**Dip**	**Rake**	**Slip** (m)	**Depth** (km)	**Length** (Km)
1	-65.66 -64.36	18.00 18.00	90	70	90	8	3.00	120
1787 Event[3]								
Segment	**End Points**		**Fault Geometry**					
	Lon.	**Lat.**	**Strike**	**Dip**	**Rake**	**Slip** (m)	**Depth** (km)	**Length** (Km)
1	-65.573 -66.373	19.298 19.398	91	45	225	2.3	5.00	85

Table 3: Earthquake loss in a census track 821.03 Mayagüez (65% soil type E, 35 % soil type F)

Building type	Footprint Area (%)	Total Area (sqf)	Unit Cost (US$/sqf)	Exposure (US$)	Loss (US$)		
					Mona Canyon	Lajas Valley	Virgin Island
Industrial	9.8%	190480	150	28,572,040	5,951,769	5,121,807	881
Wood	11.6%	223594	33	7,378,598	2,760,024	2,408,924	53,764
Shear Wall 1 S	44.3%	857278	75	64,295,857	32,896,787	30,457,287	6,814,147
Shear Wall 2 S	29.3%	1135427	75	85,157,028	5,520,8640	50,584,897	9,461,020
CMRF 1 S	0.0%	0	45	0	0	0	0
CMRF 2 S	0.0%	0	45	0	0	0	0
LowRise Steel	0.0%	0	68	0	0	0	0
MidRise Steel	0.5%	46883	68	3,188,061	376,341	345,467	0
HighRise Steel	0.1%	1705	68	115,929	15,789	14,180	0
Multistory	4.4%	421949	75	31,646,193	4,777,373	4,474,615	104,748
Total	100.0%			220,353,707	101,986,724	93,407,176	16,434,559
			Repair ratio =		0.46	0.42	0.07

Table 4: Earthquake loss in census track 821.04 Mayagüez (Soil type D)

Building type	Footprint Area (%)	Total Area (sqf)	Unit Cost (US$/sqf)	Exposure (US$)	Loss (US$)		
					Mona Canyon	Lajas Valley	Virgin Islands
Industrial	4.7%	47442	150	7,116,262	1,019,480	945,254	52
Wood	3.0%	29923	33	987,449	300,332	284,485	2555
Shear Wall 1 S	62.0%	623919	75	46,793,898	21,336,972	20,867,031	2,583,231
Shear Wall 2 S	21.1%	423925	75	31,794,405	19,299,657	18,610,911	1,873,998
CMRF 1 S	0.0%	0	45	0	0	0	0
CMRF 2 S	0.0%	0	45	0	0	0	0
Low-Rise Steel	0.0%	0	68	0	0	0	0
Mid-Rise Steel	0.9%	45307	68	3,080,872	103,287	90,946	0
High-Rise Steel	0.0%	0	68	0	0	0	0
Multistory	8.1%	407762	75	30,582,185	1,959,631	1,839,774	25,319
Total	100%			120,355,071	44,019,360	42,638,401	4,485,154
			Repair ratio =		0.37	0.35	0.04

Table 5: Earthquake losses for the City of Mayagüez

Census track	Number of buildings	Exposure	Earthquake Scenarios								
			Mona Canyon scenario			Lajas Valley scenario			Virgin Islands scenario		
			Buildings in a total or extensive damage states		Monetary losses	Buildings in a total or extensive damage states		Monetary losses	Buildings in a total or extensive damage states		Monetary losses
			Total	Extensive		Total	Extensive		Total	Extensive	
801	753	$308,890,739	45	250	$36,336,990	31	216	$29,853,333	0	4	$1,803,974
802	564	$243,640,434	65	341	$111,053,716	51	323	$102,860,692	0	0	$16,116,991
803	559	$109,995,020	79	389	$59,071,652	67	382	$55,878,838	0	0	$8,492,985
804	826	$124,237,251	140	565	$46,628,622	121	551	$43,887,025	0	6	$1,447,737
805	1286	$61,701,218	57	312	$17,988,642	43	282	$15,768,589	0	4	$888,257
806	1643	$61,701,218	35	226	$10,116,667	25	200	$8,795,338	0	2	$414,675
808	566	$229,066,458	129	690	$115,034,920	82	626	$103,819,099	0	1	$21,078,210
809	868	$81,185,579	44	383	$17,807,168	38	379	$16,856,159	0	0	$255,141
810	596	$59,653,668	36	277	$13,934,388	3	123	$3,286,539	0	0	$37,622
811	644	$81,544,470	54	309	$19,509,385	36	267	$16,279,823	0	4	$1,105,018
812	828	$271,191,723	138	600	$143,127,968	115	589	$135,359,013	0	0	$19,351,748
813	942	$238,096,095	88	551	$124,685,601	54	499	$112,807,310	0	0	$23,412,836
815.01	1643	$271,522,255	151	823	$76,650,394	15	414	$26,349,287	0	3	$1,241,468
815.12	1745	$398,154,005	222	1162	$191,085,661	196	1142	$180,716,721	0	0	$23,651,887
815.22	1268	$338,987,147	84	623	$149,700,197	50	553	$134,213,926	0	0	$26,488,025
816.01	259	$42,684,135	20	129	$10,431,532	13	112	$8,726,635	0	2	$637,508
817	1286	$218,640,317	72	554	$45,343,072	63	548	$42,880,432	0	1	$690,999
818	278	$25,661,744	14	123	$5,598,554	12	122	$5,299,880	0	0	$82,118
820.01	1999	$618,055,498	206	1192	$276,586,642	169	1134	$256,111,178	0	0	$37,342,296
820.12	1606	$393,833,290	126	885	$175,961,456	109	879	$169,866,677	0	1	$17,182,054
820.22	861	$157,126,818	65	462	$74,748,623	56	458	$72,248,385	0	1	$7,462,105
821.02	1035	$276,089,803	142	720	$161,047,768	117	700	$151,126,130	0	0	$26,512,388
821.03	1023	$220,353,707	108	574	$101,986,724	81	534	$93,407,176	0	1	$16,434,559
821.04	566	$120,355,071	26	238	$44,019,360	22	236	$42,638,401	0	1	$4,485,154
Total	**22422**	**$4,952,367,661**	**2145**	**12380**	**$2,028,455,700 (40.9%)**	**1568**	**10841**	**$1,829,036,585 (36.9%)**	**0**	**31**	**$256,615,758 (5.2%)**
		Injuries			**5240**			**4278**			**8**
		Fatalities			**730**			**561**			**0**

Table 6: Earthquake losses for Santurce

Census track	Number of buildings	Exposure	Earthquake scenarios		
			Mona Canyon	Lajas Valley	Virgin Islands
9	370	$106,827,526	$7,213,468	$161,905	$11,238,582
10	540	$133,773,867	$9,684,159	$229,149	$15,777,226
11	668	$89,577,214	$9,732,715	$300,724	$18,465,739
12	786	$135,666,962	$14,972,163	$486,288	$27,750,060
13	254	$97,702,875	$9,870,836	$289,789	$18,499,755
14	488	$44,419,425	$5,078,355	$163,065	$9,673,622
15	591	$68,608,275	$7,510,527	$232,106	$14,309,075
16	512	$93,424,790	$8,059,677	$215,332	$14,306,164
18	575	$110,519,273	$10,137,693	$285,254	$18,269,824
19	585	$119,999,775	$9,412,075	$235,282	$16,037,379
20	316	$46,817,392	$5,217,904	$164,332	$9,923,418
21	648	$155,025,759	$14,352,263	$404,361	$26,015,879
22	487	$61,844,308	$6,790,129	$203,883	$13,187,075
23	616	$98,371,164	$9,830,568	$286,304	$18,386,324
24	479	$96,395,362	$9,793,890	$284,798	$18,525,055
25	748	$63,612,961	$7,139,500	$226,405	$13,571,035
26	1044	$88,136,578	$10,187,279	$324,265	$19,629,630
28	1198	$95,043,235	$11,004,034	$365,801	$20,625,746
29	863	$55,776,941	$6,454,469	$215,629	$12,053,772
30	618	$52,885,676	$6,115,755	$198,896	$11,624,956
31	884	$77,182,319	$8,914,734	$282,866	$17,205,339
32	712	$71,520,469	$8,187,045	$253,717	$15,957,951
33	646	$68,521,059	$7,942,592	$249,336	$15,461,104
34	120	$32,747,978	$3,745,331	$114,043	$7,374,545
35.01	729	$89,447,215	$10,135,210	$321,989	$19,344,496
35.02	1271	$81,204,633	$9,403,523	$300,472	$18,092,993
36	646	$61,022,729	$61,022,729	$220,815	$13,595,699
37	1756	$123,254,442	$14,280,078	$467,040	$27,070,546
38	791	$76,017,913	$8,680,888	$276,906	$16,596,090
39	914	$120,811,318	$12,948,519	$393,149	$24,639,542
42	751	$239,585,169	$25,382,099	$773,120	$47,877,236
Total	**21,606**	**$2,855,744,599**	**$349,200,207 (12.2%)**	**$8,927,023 (0.31%)**	**$551,085,857 (19.3%)**

Table 7: Earthquake losses for Rio Piedras

Census track	Number of buildings	Exposure	Earthquake scenarios		
			Mona Canyon	**Lajas Valley**	**Virgin Islands**
43	651	$500,580,376	$44,400,706	$1,235,152	$78,604,801
44	960	$91,973,012	$10,196,534	$328,228	$19,061,773
45	856	$70,806,981	$8,180,228	$263,583	$15,635,202
46	1539	$143,560,724	$16,690,588	$532,753	$32,203,149
47	1953	$197,003,210	$22,778,246	$753,514	$42,805,458
48	147	$33,811,877	$3,951,387	$119,656	$7,893,007
49	638	$109,181,265	$12,600,724	$420,448	$23,517,176
50	1165	$181,025,041	$19,472,557	$677,858	$33,806,064
51-53	5771	$928,172,081	$102,108,747	$3,390,269	$186,070,639
54-60	7581	$1,320,130,035	$139,583,425	$4,445,383	$255,545,184
60-64	4004	$683,328,453	$72,635,788	$2,318,931	$133,192,482
65-69	5596	$921,928,969	$97,091,280	$3,086,324	$177,539,028
70-74	4258	$908,074,758	$96,606,596	$3,085,498	$177,188,545
75-79	5575	$887,534,942	$93,489,393	$2,972,107	$170,964,743
80-84	6579	$1,187,436,091	$125,496,604	$3,995,842	$229,727,158
85-89	5065	$957,407,547	$100,639,503	$3,196,342	$183,922,114
90-94	6866	$1,031,625,894	$109,105,028	$3,475,095	$199,761,564
95-102	5063	$1,217,542,367	$127,979,525	$4,064,605	$233,884,363
Total	**64,267**	**$11,371,123,623**	**$1,203,006,859 (10.6%)**	**$38,361,587 (0.34%)**	**$2,201,322,450 (19.4%)**

Figures

Figure 1. Seismic stations with real-time continuous monitoring at PRSN.

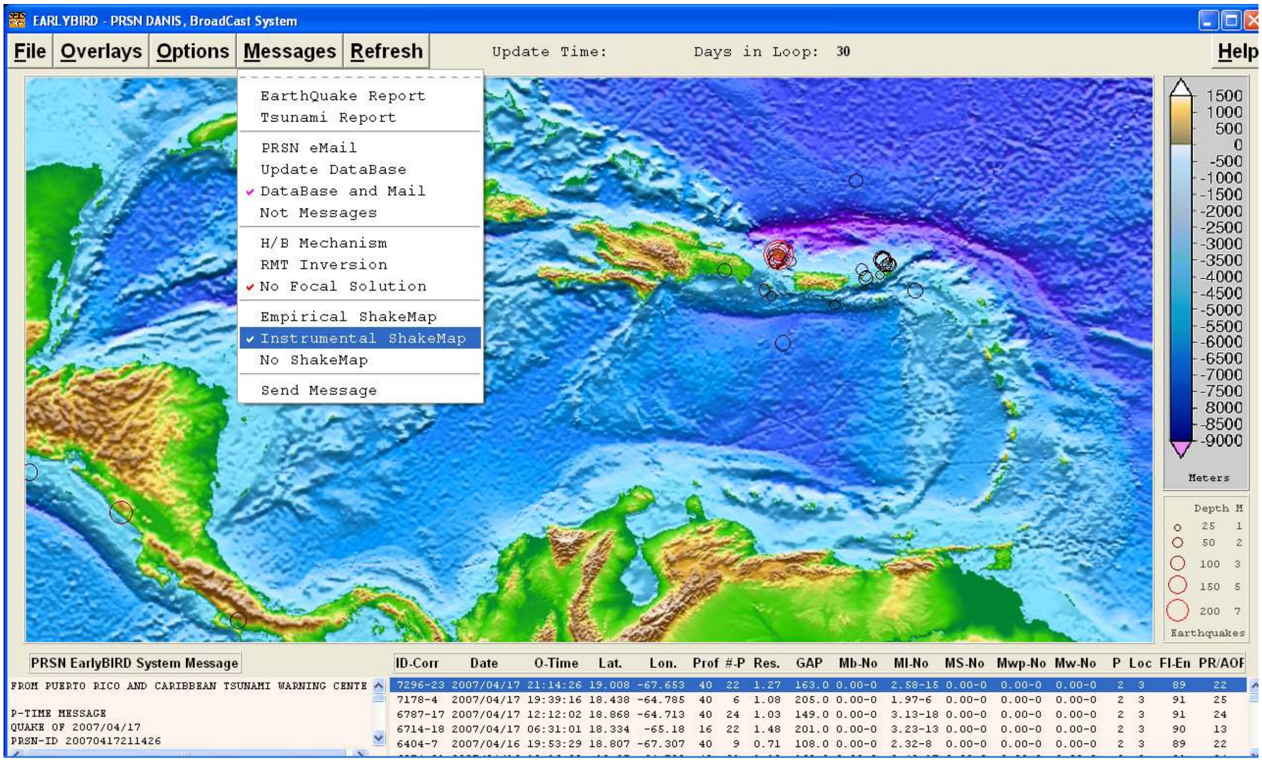


Figure 2. The PR DANIS (Puerto Rico Data Analysis and Information System) broadcast tool is an in-house graphical user interface program allows the geophysicist-in-charge to generate ShakeMaps for manually reviewed (as opposed to automatically located) events. This system also pushes various PRSN data products (earthquake and tsunami alerts, ShakeMaps) to the Puerto Rico Civil Defense Center in San Juan within 1-2 minutes of the event origin time.

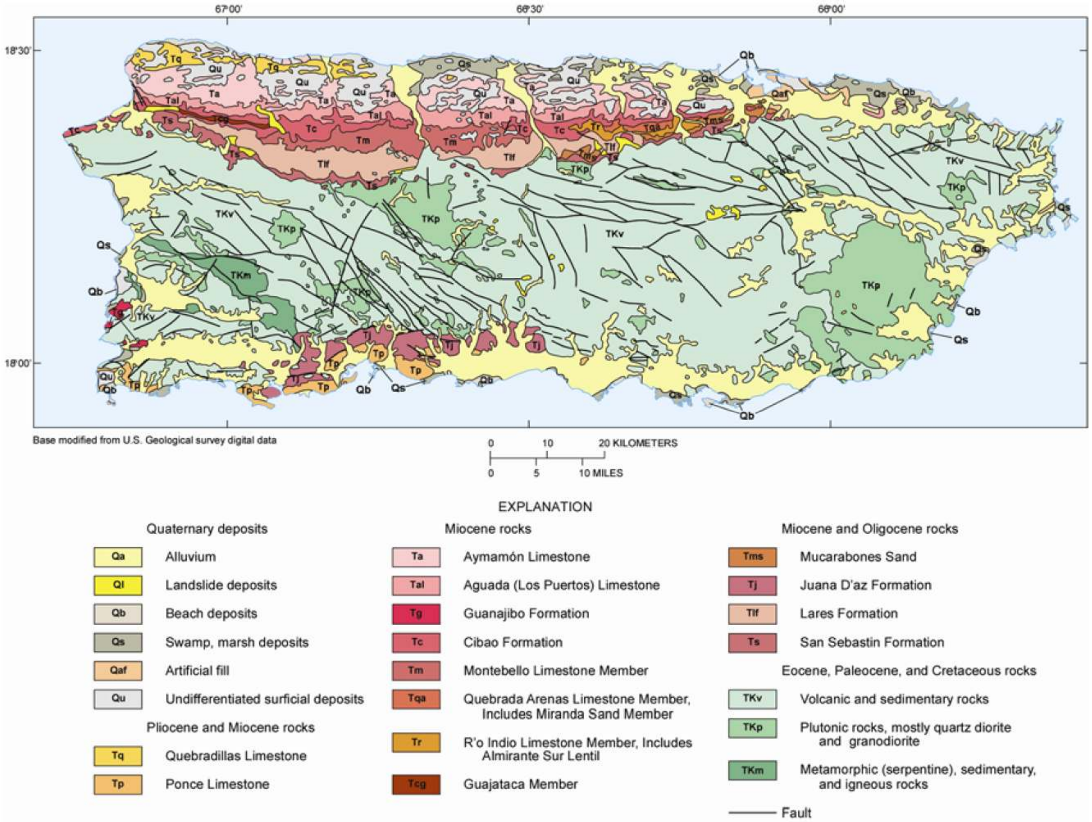


Figure 3.a. Generalized Puerto Rico geologic map from Renken et al (2002).

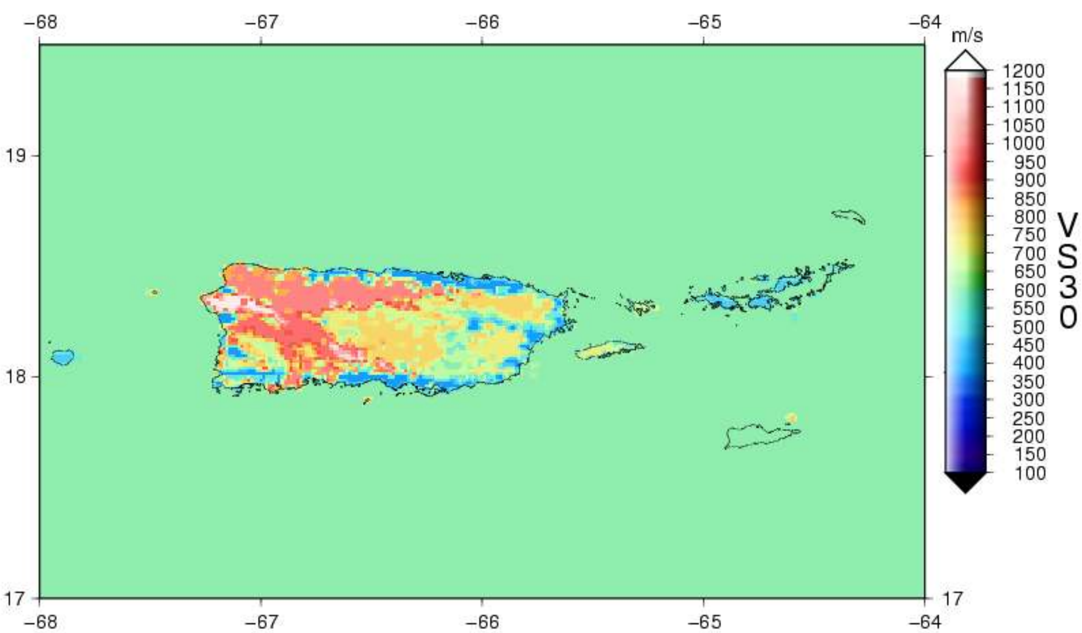


Figure 3.b. Vs30 variations throughout the island (after Velez and Huérfano, 2007)

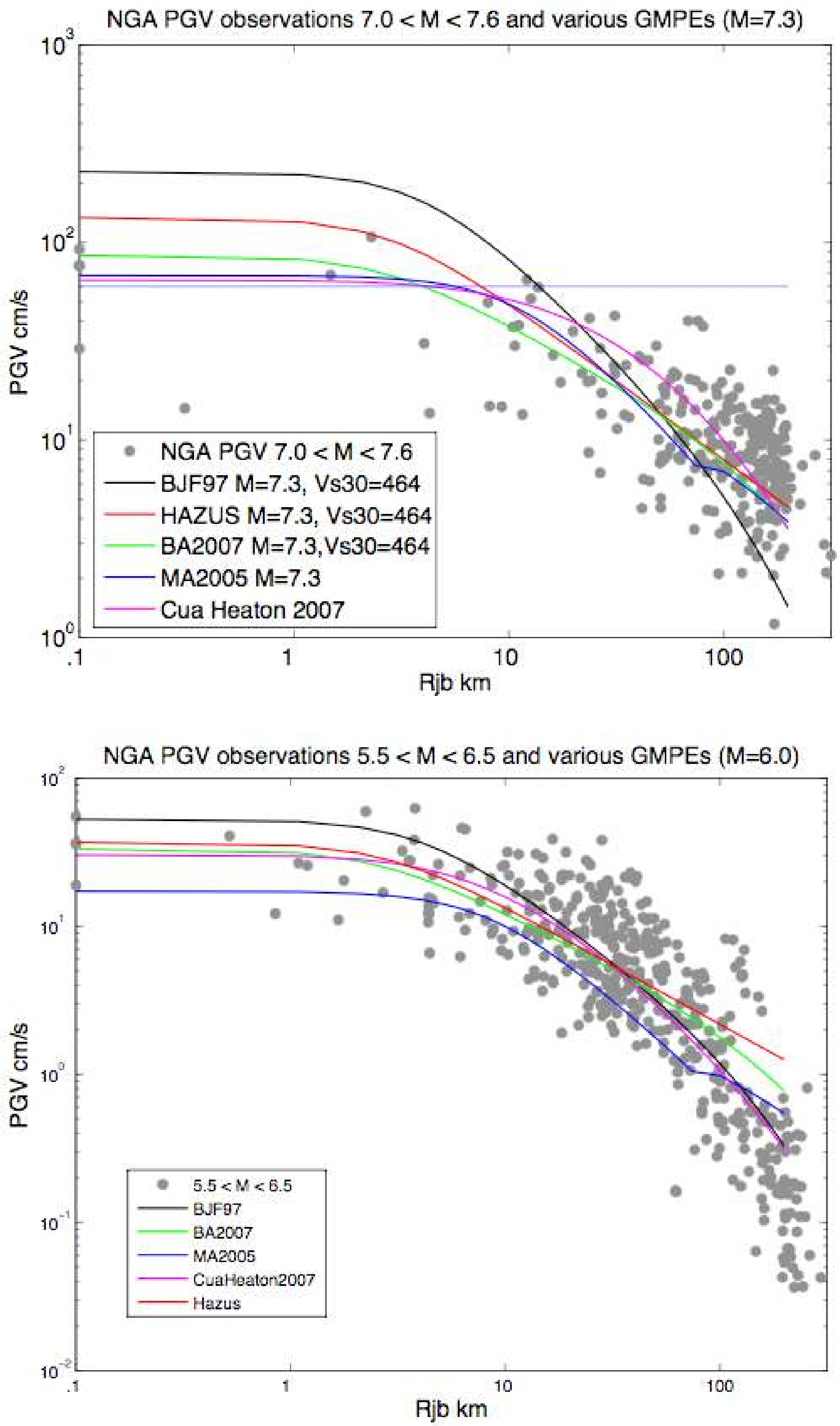


Figure 4: Observed PGV values from the Next Generation Attenuation (Power et al, 2008) strong motion dataset and median ground motion levels for various ground motion prediction equations considered for use in the scenarios.

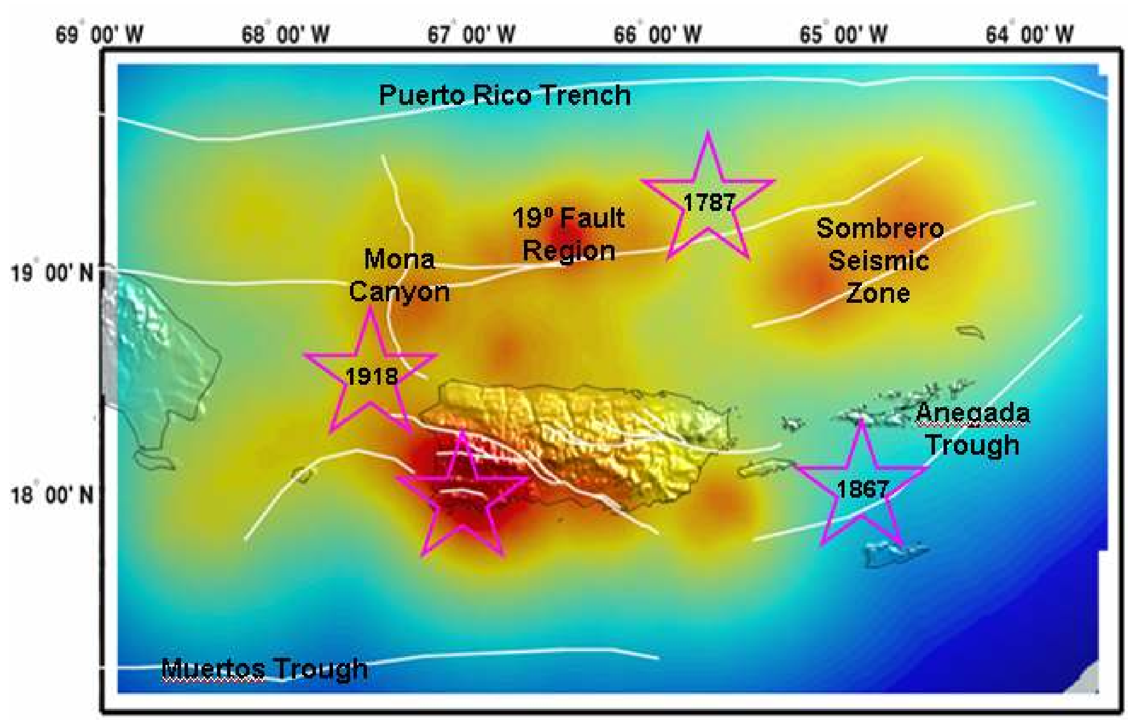
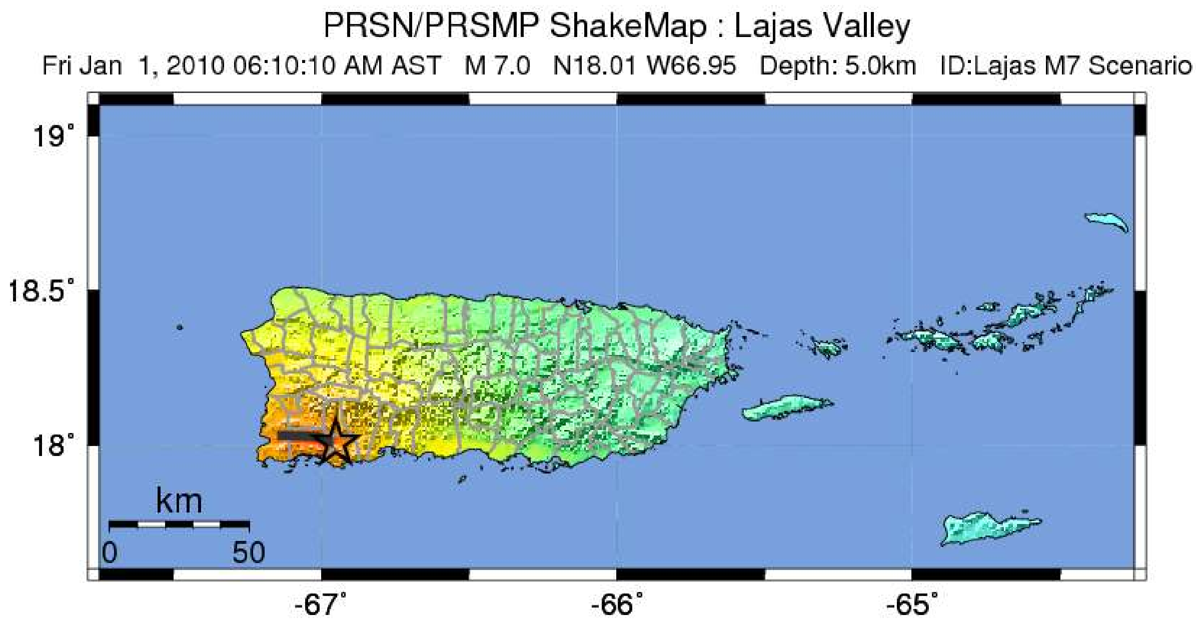
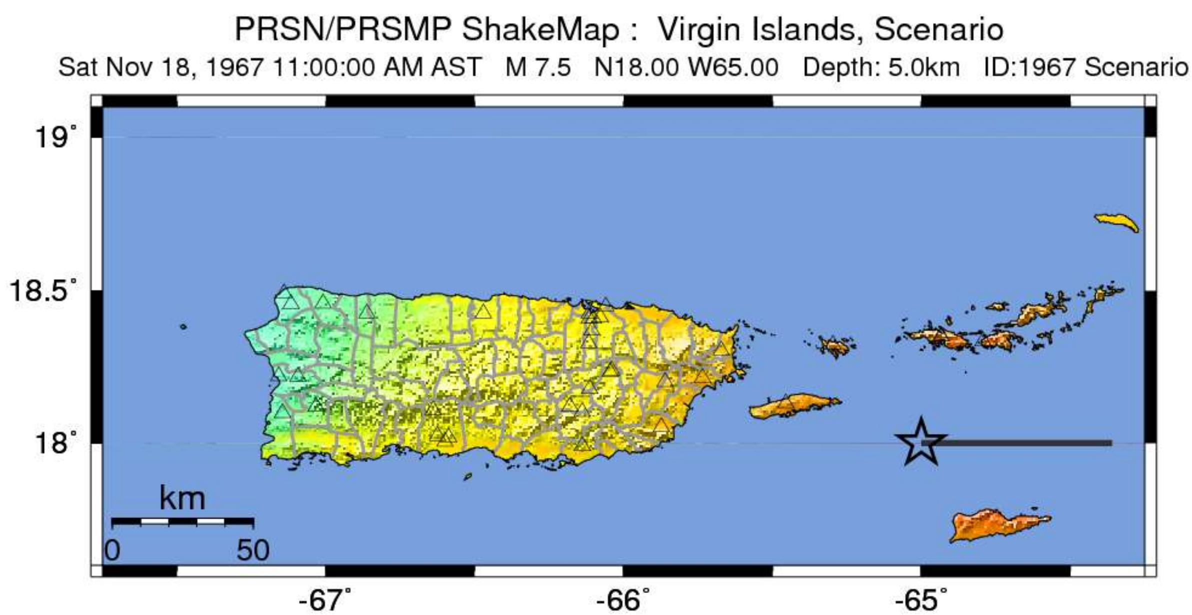


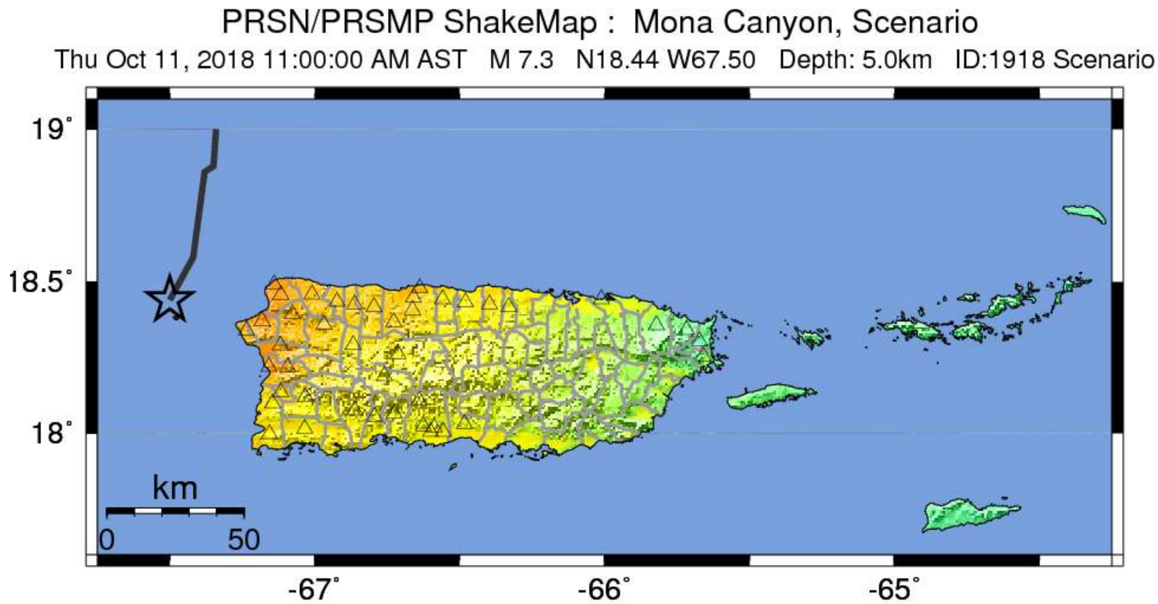
Figure 5. Earthquake density map (modified from Clinton et al, 2007) showing fault zones contributing to seismic hazard in Puerto Rico and the ShakeMap scenarios calculated as part of this project.

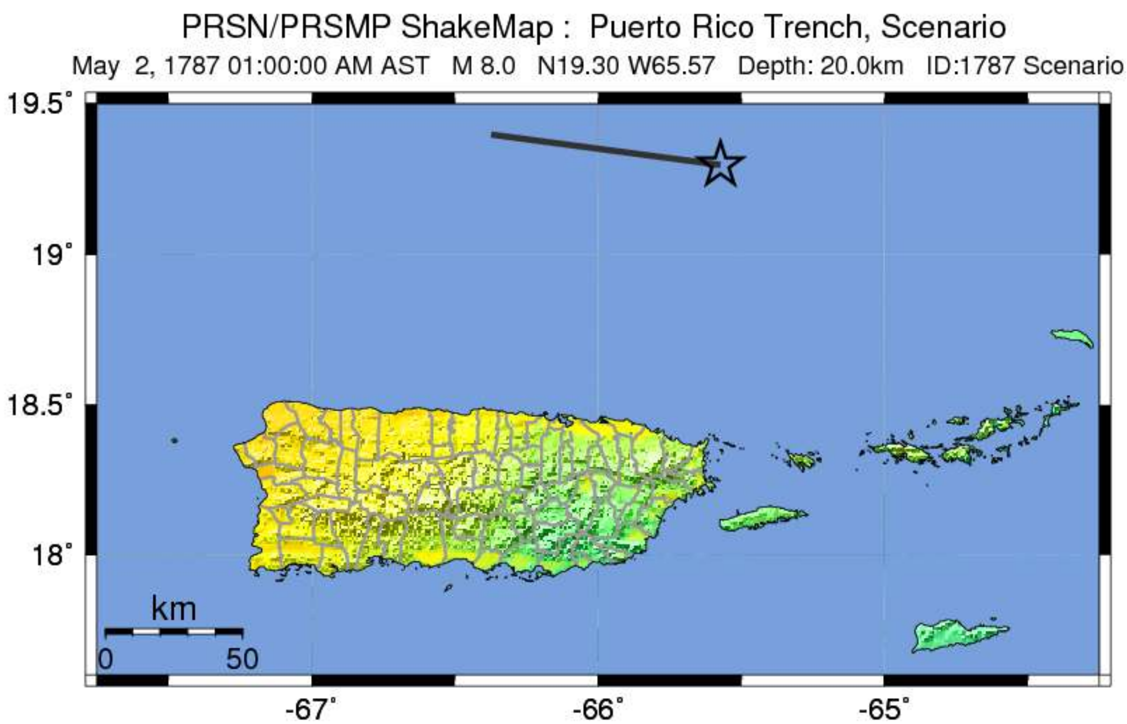




PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	***<.17***	***.17-1.4***	***1.4-3.9***	***3.9-9.2***	***9.2-18***	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	***16-31***	***31-60***	***60-116***	***>116***
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6.a. ShakeMap scenarios for the Lajas Valley (top) and the Virgin Islands earthquakes (bottom)





PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6.b. ShakeMap scenarios for the Mona Canyon (top) and the Puerto Rico Trench earthquakes (bottom)

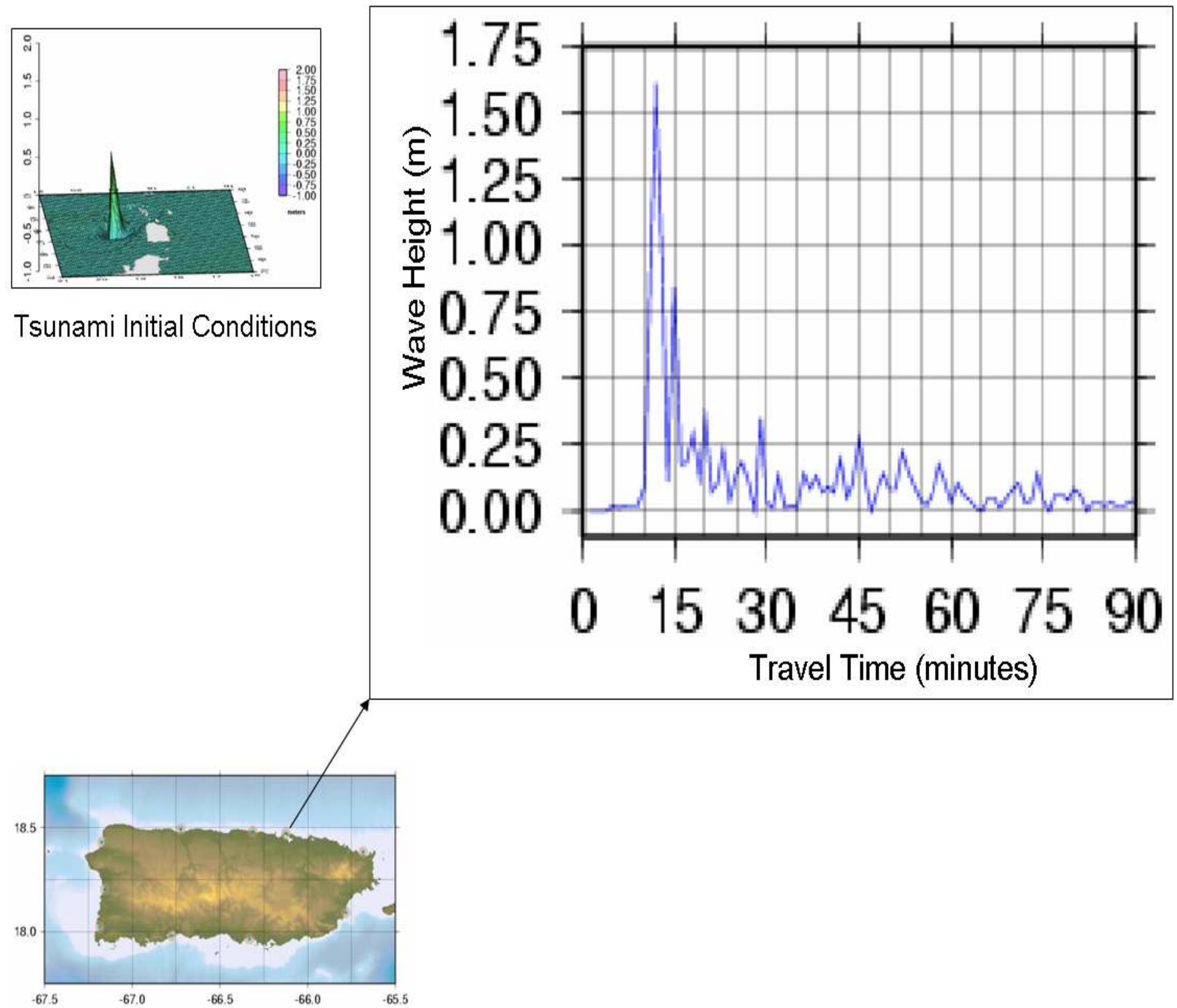


Figure 7: Predicted waveheights Lat: 18.4719 and Lon: -661247 (San Juan Bay) from the 1787 Puerto Rico trench scenario. Top-left frame shows the tsunami initial conditions.

Mapas de movimiento fuerte generados en la RSPR

. Automático (Teórico)

:s el primer mapa que se genera en la RSPR. A tan) segundos después de ocurrido un temblor en el ı de responsabilidad (AOR) de la RSPR, que luye a Puerto Rico y las Islas Vírgenes. La RSPR ɜrminará la magnitud y la localización del sismo. Ea vez revisada esta información y con la ayuda de estudios científicos previos de geología, geofísica e ingeniería, se puede estimar de manera teórica la distribución de la intensidad y los valores de aceleración y velocidad de movimiento del suelo en toda la región. Este mapa será colocado en la página electrónica de la RSPR.

2. Instrumental

La RSPR y el Programa de Movimiento Fuerte de Puerto Rico (PMFPR) operan una red de sismómetros y acelerómetros en Puerto Rico y en las Islas Vírgenes. Estos instrumentos tienen la capacidad de detectar y medir el movimiento del suelo generado por temblores y de manera casi instantánea reportar esos valores al centro de acopio de la RSPR, localizado en el Recinto de Mayagüez de la Universidad de Puerto Rico. Tan pronto el sismo es localizado, y a medida que nueva información llega de las estaciones, el personal de la RSPR actualiza el mapa automático de movimiento fuerte, de tal manera que se pueda saber con mayor exactitud la distribución de la intensidad y movimientos reales del suelo a lo largo de todo PR/IV. Esta información estará disponible a la comunidad y a las agencias de manejo de emergencias. En la figura 2, se ilustra el mapa de movimiento fuerte para el temblor del 30 de abril de 2007 a las 11:27 PM, que con una magnitud de 4.1 en la Escala Richter fue sentido en todo Puerto Rico.

Mapas de intensidad por Internet (CIIM)

Gracias a los adelantos en las comunicaciones, en especial a los servicios de Internet, tan pronto ocurre un temblor, el público puede ayudar a la RSPR a generar los mapas de intensidad con tan solo reportar lo que sintieron durante el sismo. Brindando sólo la Zona de Código Postal y el nombre del pueblo en dónde se encontraba cuando sintió el temblor, las personas pueden responder unas preguntas básicas y así ser partícipes en la actualización automática del mapa de intensidad. La figura 3 ilustra el CIIM obtenido para el sismo sentido el 3 de junio de 2006.

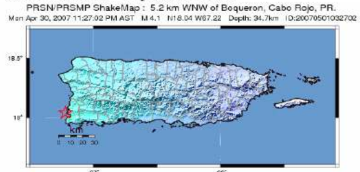


Figura 2. Mapa de movimiento fuerte para el sismo sentido en la Región de Puerto Rico el día 30 de abril de 2007.

Figura 3. Con 11 respuestas de 9 Zonas de Código Postal diferentes se generó el CIIM para el sismo sentido el 3 de junio de 2006.

RED SÍSMICA DE PUERTO RICO
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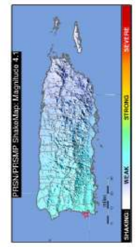
2007/06/15

Departamento de Geología / Geology Department

Universidad de Puerto Rico
Recinto Universitario de Mayagüez
Red Sísmica de Puerto Rico
Puerto Rico Seismic Network, University of Puerto Rico, Mayagüez Campus

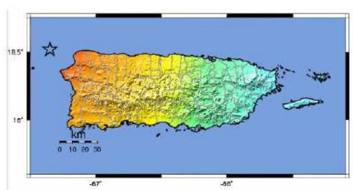


Mapas de Movimiento Fuerte para Puerto Rico e Islas Vírgenes

¿Qué son los Mapas de Movimiento Fuerte?

Los mapas de movimiento fuerte o "Shakemaps" (SM) ilustran la manera cómo se distribuye el movimiento de la superficie de la tierra en la zona cercana al epicentro de un temblor. Estos mapas son representativos de los efectos, desde leves a severos, ocasionados en una región específica por un determinado sismo. La escala de medición es similar a la escala de Intensidad Mercalli Modificada. Se han desarrollado diferentes métodos para generar los SM. En la Red Sísmica de Puerto Rico (RSPR) se utiliza, en primer lugar, la información de la localización del temblor y su magnitud. A medida que se recibe nueva información, el SM se actualiza de manera tal, que a pocos minutos de ocurrido el temblor ya se tiene una idea concreta de los efectos ocasionados por el mismo.

La información contenida en los SM es de vital importancia para las agencias de emergencias ya que les brinda una idea más clara de las zonas afectadas por el temblor. En la figura 1 se ilustra el mapa de movimiento fuerte recreado para el terremoto que ocurrió en el Cañón de la Mona el 11 de octubre de 1918 y que afectó la zona oeste de Puerto Rico.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figura 1. Mapa de movimiento fuerte para el temblor que afectó a Puerto Rico el 11 de octubre de 1918.

INTENSIDAD	Aceleración (%g)	Velocidad (cm/s)	Movimiento Sentido	Daños Estimados
I	< 0.17	< 0.1	Ninguno	Ninguno
II-III	0.17 - 1.4	0.1 - 1.1	Debil	Ninguno
IV	1.4 - 3.9	1.1 - 3.4	Ligero	Ninguno
V	3.9 - 9.2	3.4 - 8.1	Moderado	Minimos
VI	9.2 - 18	8.1 - 16	Fuerte	Leves
VII	18 - 34	16 - 31	Muy Fuerte	Moderados
VIII	34 - 65	31 - 60	Severo	Moderados/Severos
IX	65 - 124	60 - 116	Violento	Severos
X+	> 124	> 116	Extremo	Muy Severos

Tabla 1. Descripción de los colores en los mapa de movimiento fuerte generados por la RSPR.

¿Cómo interpretar los mapas de movimiento fuerte?

Cada uno de los colores presentes en los SM representa un nivel específico de movimiento del suelo. También se identifica cada color con un valor de aceleración (%g) y velocidad (cm/s), determinado en el sitio específico, mediante medición directa por los sismómetros y acelerómetros o calculado mediante ecuaciones matemáticas. La escala varía desde el color blanco (Intensidad I) que significa que el sismo no se sintió y que no hubo ningún daño, hasta el color rojo (Intensidad X o mayor) que significa movimiento extremo con daños muy severos (Tabla 1).

¿Por qué es importante generar los mapas de movimiento fuerte?

Inmediatamente después de ocurrido un temblor, las personas quieren saber en dónde ocurrió, cuán grande fue y si ha ocurrido algún daño. Las agencias de manejo de emergencias necesitan saber de manera rápida y exacta los efectos que pudieron ocurrir debido al terremoto, con el fin de movilizar ayuda a las zonas afectadas para así minimizar los daños y agilizar la recuperación. Las redes sísmicas modernas, como la RSPR, pueden determinar en cuestión de segundos en dónde ocurrió el sismo y su magnitud, pero es sólo con la generación de los SM que se puede saber cómo se movió el suelo en Puerto Rico y en las Islas Vírgenes (PR/IV).

Figure 8. Spanish ShakeMap flyer

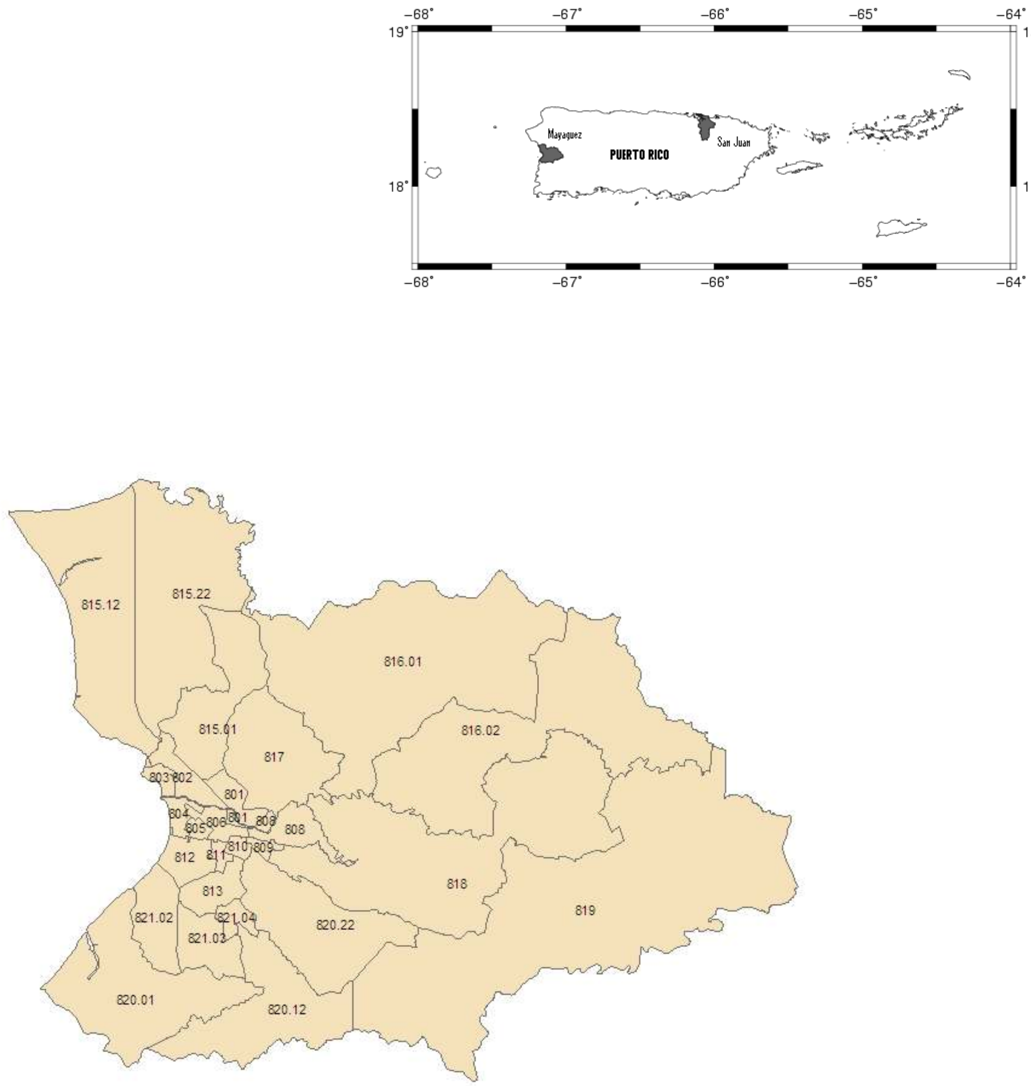


Figure 9: Census track of the city of Mayagüez

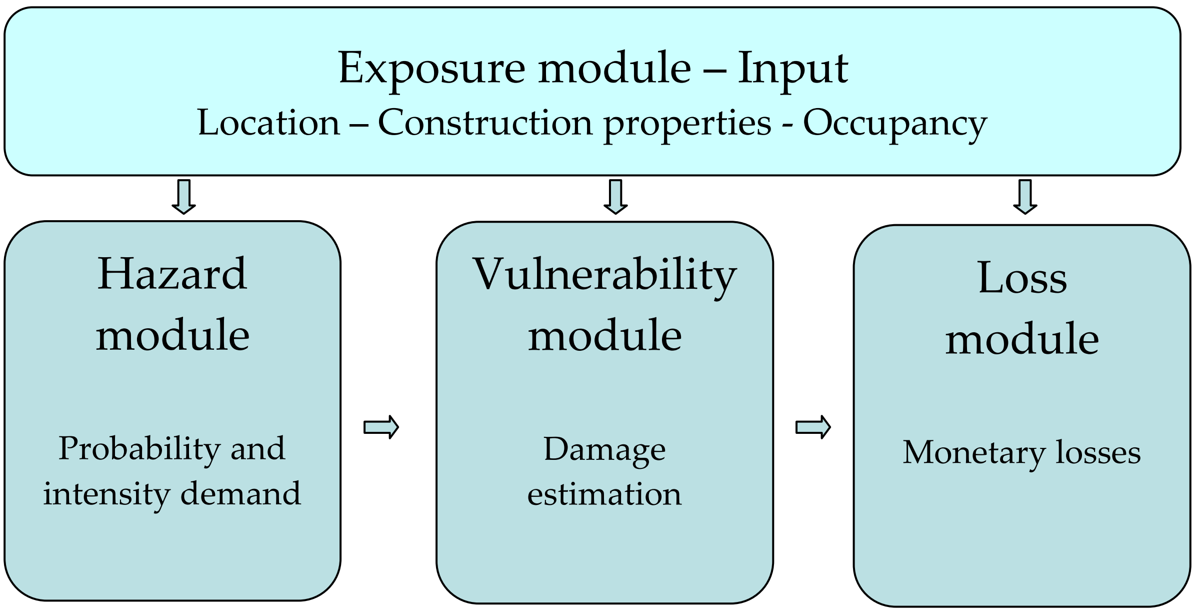


Figure 10: Catastrophe model modules of INSOL.

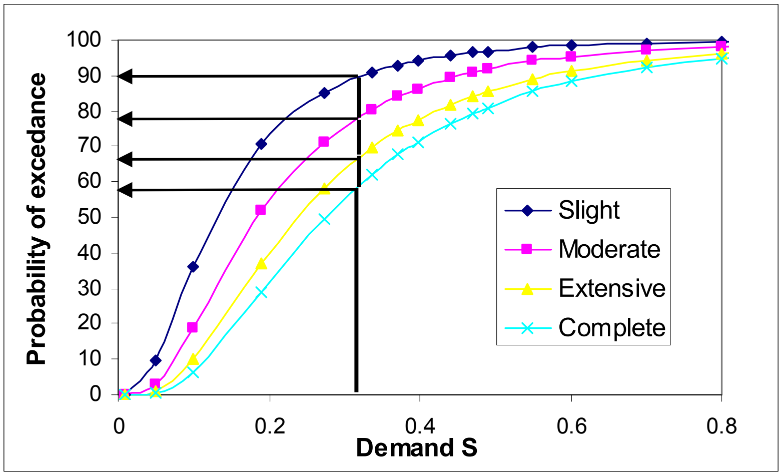


Figure 11: Example of fragility curves

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