The Puerto Rico Tsunami Warning and Mitigation Program

A. Mercado-Irizarry†‡; C. von Hillebrandt‡ and V. Huerfano‡

†Dept. of Marine Sciences, University of Puerto Rico, Mayaguez, 00681-9013, Puerto Rico amercado@uprm.edu
‡ Puerto Rico Seismic Network, Department of Geology, University of Puerto Rico, Mayaguez, 00680 victor@midas.uprm.edu
christa@midas.uprm.edu

ABSTRACT


A recent compendium of the history of tsunamis in the Caribbean reports that since 1498 there have been 91 tsunamis in the Caribbean region. In fact, in the Caribbean Sea region we have all of the potential tsunami-generating sources: submarine earthquakes, subaerial or submarine landslides, and underwater explosions. Past and recent studies support the interpretation that Puerto Rico and the northern Virgin Islands sit within a broad zone of deformation between two larger plates: the North American to the north and the Caribbean to the south. Offshore faults along which major earthquakes can occur have been identified in the boundary zone of the North American and Caribbean plates. The landslide-tsunami threat for the island comes from the existence of the Puerto Rico Trench just north of the island, along which there is evidence of a large slump, with a potential volume of approximately 900-1500 km³. The Puerto Rico Tsunami Warning and Mitigation Program was funded by the USA Federal Emergency Management Agency and the University of Puerto Rico with the purpose of addressing the tsunami threat and concern in the island. It consisted of six tasks: 1) preparation of tsunami flood maps for the island; 2) education about this "forgotten hazard"; 3) local (Puerto Rico) and regional (Caribbean) seismic wave form analysis for rapid determination of earthquake source parameters; 4) development of tsunami warning and advisories protocols; 5) preparation of a PC-Windows based Atlantic and Caribbean Historical Tsunami Database; and 6) participation in the meetings of the USA National Tsunami Hazard Mitigation Program.

INTRODUCTION

LANDER et al. (2002) reported that since 1498 there have been 91 “tsunamis” in the Caribbean region. Among them, Lander et al. has verified that twenty-seven are true, verifiable tsunamis and nine additional wave events are considered to be very likely true tsunamis. In fact, in the Caribbean Sea region we have all of the potential tsunami-generating sources: submarine earthquakes, subaerial or submarine landslides, and underwater explosions. According to JANSMA and MATTIOLI (2003), Puerto Rico and the northern Virgin Islands sit within a broad zone of deformation between two larger plates: the North American to the north and the Caribbean to the south. This separate microplate moves approximately 15 mm/yr relative to North America and 3 mm/yr relative to the Caribbean. Offshore faults along which major earthquakes can occur have been identified in the boundary zone of the North American and Caribbean plates. The landslide-tsunami threat for the island comes from the existence of the Puerto Rico Trench just north of the island, along which there is evidence of a large slump, with a potential volume of approximately 900-1500 km³ (SCHWAB et al., 1993; GRINDLAY, 1998) and many other smaller ones (ten BRINK and SMITH, 2003).

It is not strange then that the northeastern corner of the Caribbean, the region encompassing the islands of Hispaniola, Puerto Rico, and the United States and British Virgin Islands, has experienced three destructive tsunamis in the last 136 years: 1867, 1918, and 1946. All three tsunamis affected the island of Puerto Rico, with the one in 1918 doing great damage along the west coast of the island (MERCADO and MCCANN, 1998). This “forgotten hazard” has led state and federal agencies to sponsor a number of workshops and projects with the purpose of evaluating the magnitude of this threat. The University of Puerto Rico Sea Grant College Program and the Puerto Rico State Emergency Management Agency sponsored a Caribbean Tsunami Workshop in 1997 and a series of studies (MCCANN and MERCADO, 1997; MCCANN, 1998; GRINDLAY, 1998; MERCADO, 2001; LYNETT and LIU, 2002; MERCADO, 2002) that set the stage for the Puerto Rico Tsunami Warning and Mitigation Program (PRTWMP). The two years long PRTWMP was funded by the USA Federal Emergency Management Agency and the University of Puerto Rico. It consisted of six tasks: 1) preparation of tsunami flood maps for the whole island; 2) education about this "forgotten hazard" in the Caribbean (including a video, tsunami drills, workshops and the installation of tsunami warning signs along beaches); 3) local (Puerto Rico) and regional (Caribbean) seismic wave form analysis for rapid determination of earthquake source parameters; 4) development of a tsunami warning and advisories protocol for Puerto Rico and the Caribbean region; 5) preparation of a PC-Windows based Atlantic and Caribbean Historical Tsunami Database; and 6) participation in the meetings of the USA National Tsunami Hazard Mitigation Program.

It is the purpose of this presentation to summarize the most important results from each task and the impact it has had in raising the awareness about this latent coastal hazard.

PROGRAM TASKS

Task 1: Tsunami Flood Maps

For the preparation of the tsunami flood maps we first had to characterize the system of local faults. For this, data recorded by the Puerto Rico Seismic Network (PRSN) was used. This included obtaining the basic parameters that control the tsunami tectonic generation: quake moment (Mo), fault dimensions and rupture geometry. Significant progress in the understanding of the geologic and tectonic environment of the Puerto Rico region has been made during the past years. Details of the seismogenic zones are being identified and the concept of a block for Puerto Rico and the Virgin islands has been established. However, there remain a number of fundamental questions. The two most important ones are the relationship between the seismicity and the geologic structures and the stress regime in relation to the
tectonic processes in the Local Zone of Puerto Rico (LZPR). The northeastern Caribbean region, encompassing Hispaniola on the west and the Leeward Islands on the east (which defines our LZPR), was divided into 12 subregions according to major tectonic features, seismic distribution and stress pattern: 19° Faults, Anegada Passage, Eastern Dominican Republic, Leeward Islands, Mona Passage (identified as McCann's faults), Mona Canyon, Muertos Trough, North Platform, North Puerto Rico Trench, Puerto Rico West to Southeast, Septentrional and Sombrero (see Figure 1). The seismicity associated with faults in the LZPR are currently located using Geiger's method (LAY and WALLACE, 1995), that is a linearization of the travel time equation in a first order Taylor series that relates the difference between the observed and theoretical travel times to unknown adjustments in the hypocentral coordinates through the partial derivatives of travel time with respect to unknowns. There are some techmics available to improve the quake locations with the goal of identifying structural details, such as the location of active planes, into well defined focus. But in general, all methods show a diffuse picture of seismicity. A very important observation is that the spatial distribution of smaller earthquakes delineates areas in which larger earthquakes are likely to occur (KAFFKA and LEVIN, 2000), but this requires a very reliable earthquake location method to delineate fault systems. Based in the hypothesis that any quake that occurs is due to the fracture along a specific fault, and that multiple and successive quakes delineate the fault plane, HUERFANO (2003) proposed a complete set of faults using two methods. The first is based on the composite focal mechanism analysis while the second is based on geometrical analysis of hypocenters stratified by magnitude.

Earthquake location programs like PR-HYPO, the one used in the PRSN, need a realistic crustal model. HUERFANO and BATAILLE (1994) proposed a flat homogeneous P-wave model for Puerto Rico and from Wadatti plots the Vp/Vs ratio (P wave to S wave velocity ratio) was determined. The complete PRSN seismic catalogue was recompiled with this model so that all solutions are based on the same methodology. A criteria used to determine the data quality is the network stability. Time history analysis indicates that from 1992 to present the data obtained by the PRSN remains mostly stable as evidenced by the number of readings and location errors. During the time period from January 1987 to June 2002, 4422 microseismic records from the PRSN catalogue with quality A, B and C (local scale) were selected to determine the seismic potential in the LZPR. Quality factors are based on the number of readings, rms, hypocentral errors and azimuthal coverage (gap). These factors allow us to identify reliable solutions inside a specific region.

Based on the offshore seismic distribution of shallow earthquakes (depth less than 50 km) and mapping of known fault systems, the 12 sub-regions were proposed, each one defined by specific stress parameters. Each region was previously analyzed by classic seismological methods like the Gutenberg and Richter b-value, Wells and Coppersmith relationships, composite stress patterns and the hypo-centering algorithm (HUERFANO, 2003). The Puerto Rico Trench (PRT) was subdivided into eastern and western sections due to intrinsic differences in seismicity and tectonics. Finally we characterized 238 spatially linear potential faults, each one generating their hypothetical earthquake. These sources were considered as local (relative to Puerto Rico) and it was found that the linear faults generate bigger tsunamis compared with the 102 spatially nonlinear or segmented faults which were also considered (HUERFANO, 2003).

Based on the 340 potential faults determined under the methodology described above, a simulation was made of each one of them using the Japanese non-linear shallow water tsunami TIME model. Three nested grids were used, starting with the outer grid with a cell size of 27 arc seconds, followed by the intermediate grid with cell size of 9 arc seconds, and the inner grid with a resolution of 3 arc seconds. The region covered by Figure 1 shows the extent of the lower resolution grid, while the two rectangles show the location of the intermediate and higher resolution grids. It is in the higher resolution grid that the model is run in its non-linear mode, allowing for the computation of coastal flooding. The induced sea bottom deformation was determined for each one of the potential faults using the MANSHINA and SMYLIE (1971) method. For nearshore bathymetry, recently acquired SHOALS bathymetry was used.
for deeper shelf waters National Ocean Survey data was used, and for deep water we used the latest SANDWELL and SMITH (1997) bathymetry. For topography use was made of the USGS Digital Elevation Model data for the island, with a resolution of 30 meters. The tsunami model and the data have been shown to provide good estimates of the observed runup due to the 1918 Puerto Rico tsunami (MERCADO and McCANN, 1998). This reference can also be consulted for further details about the modeling aspects.

Adopting a standard hazard mitigation approach of preparing for the worst, the maximum flooding, irrespective of time of occurrence, at each computational cell for each scenario, was saved. Next, the maximum of the maximums (MOM) was obtained at each computational cell by going through each one of the 340 runs and picking out the maximum among all the runs. The maps prepared are based on the MOM. As in the simulation of the 1918 tsunami, a constant Manning coefficient of 0.025 was utilized.

The inland limits of the flood was overlaid on top of topographic maps and recently acquired IKONOS 1-m resolution color photos and made available through paper copies, CD's, and the Internet (http://poseidon.uprm.edu).

**Task 2: Education**

Together with the preparation of the tsunami flood maps, the educational phase of the project is the most important one. Caribbean tsunamis (with the exception of the 1755 Lisbon earthquake) have all been local events. As such there is not much a tsunami warning system can do, and by having citizens with knowledge about this hazard is the only way we can insure that the risk is minimized. For this purpose workshops were given throughout the island, in which representatives of various government agencies participated. This was accompanied by the distribution of a Spanish language tsunami video to all schools, government agencies, and interested citizens. Newspaper, radio and TV shows were contacted in order to reach the widest audience possible. Two tsunami drills were carried out at two public schools. Tsunami warning signs were prepared to be placed at all coastal areas which, according to the flood maps, are potentially vulnerable. For these, the internationally accepted figure and message for tsunamis was used. Finally, a WEB page was developed (http://poseidon.uprm.edu).

**Task 3: Local and Regional Seismic Waveform Analysis**

With the goal of establishing a Caribbean Tsunami Warning System for Puerto Rico, local and regional seismic waveform analysis algorithms were adapted to the Caribbean region. At-risk regions need real-time determination of earthquake source information to assess the nature of the hazard in order to optimize emergency response. In 1998 FEMA and the University of Puerto Rico funded a project to upgrade the instrumentation of the Puerto Rico Seismic Network (PRSN) of the Department of Geology of the University of Puerto Rico at Mayaguez. As part of this project, 9 digital telemetered broadband stations were installed on the main island of Puerto Rico and offshore islands. The digital waveforms are recorded and saved at the facilities of the PRSN. Also, since 1998 the PRSN operates the data center for the Middle-America Seismograph Consortium (MIDAS). Currently available methodologies for the routine computation of earthquake source parameters were
modified and adopted for use in the Caribbean region based on
regionally and locally-recorded seismic waveforms.
An analysis of digital broadband waveforms from the Puerto
Rico Seismic Network (PRSN) for local analysis and the
Incorporated Research Institutions for Seismology (IRIS)
Digital Management Information Center for regional analysis
is carried out to provide earthquake-faulting information in
near-realtime. If possible, PRSN data will be supplemented
with realtime broadband waveforms recorded by Global
Seismograph Network (GSN) stations in the Caribbean and data
submitted to the MIDAS.Data Center.

For the regional analysis, the techniques developed by
Ammon, Randall and Owens (RANDALL et al., 1995) were
implemented to perform a regional moment-tensor inversion
using all three components (vertical, transverse, and radial)
available from the digital seismograph stations. An analogous
methodology, now based on ZAKHARIN and et al. (2001) was
adapted for local analysis. In both methods, an inversion
scheme is applied to identify the focal mechanism that best
reproduces the seismic waveforms observed at regional and
local distances (less than 12 degrees). For regional analysis
theoretical waveforms are computed by applying a reflection-
matrix technique that uses a prescribed crustal-velocity model.
For local analysis theoretical waveforms are computed by
applying the BOUCHON (1991) method that uses a prescribed
crustal-velocity model. Prior to inversion, the observed records
are deconvolved to remove the instrument response.

The application of these moment-tensor inversion methods in
a semi-automatic manner should provide source parameters in
near-realtime for earthquakes in Puerto Rico and the
Caribbean.

We have also adapted to the Caribbean region the “Earlybird”
system developed and used in the West Coast and
Alaska Tsunami Warning Center. This package provides rapid
earthquake location and magnitude and will provide the
moment-tensor solution. As part of this the PRSN has acquired a
display system, composed of 9 PC monitors under one CPU,
allowing the acquisition and display of waveforms, earthquake
location on a local and regional basis and iterative waveform
analysis, all on separate displays.

These activities are in harmony with the long term plans of
NOAA to establish a Caribbean Tsunami Warning Center at
Mayaguez.

Task 4: Warning Messages and Protocol

Once a felt earthquake has been characterized in terms of
magnitude, location and faulting mechanism and its
tsunamigenic potential has been determined, this information
needs to reach the affected communities as fast as possible.
Warning protocols need to be developed at the municipal, state,
and federal levels, and also within the rest of the Caribbean
community. The key agencies in the Pacific states for warning
messages and emergency response coordination are the
National Oceanographic and Atmospheric Administration
(Pacific Tsunami Warning Center, West Coast and Alaska
Tsunami Warning Center and the National Weather Service
Field Office, NWS), the USGS regional seismic networks, and
state and local emergency response agencies. A similar setup
will be established in Puerto Rico and the US Virgin Islands, and
will include the Puerto Rico Seismic Network (PRSN) of the
University of Puerto Rico, NWS, and the Puerto Rico State
Emergency Response Agency. This will also involve the
participation of Puerto Rico’s Warning Coordination
Meteorologist - WCM - in the regular Tsunami Warning
Coordination Meteorologists Training Workshops held on the
West coast; the Pacific states WCM’s have now included
tsunamis as part of their coastal hazard community
preparedness activities. The WCM’s have been designated as
the point of contact between the States and NOAA.

For this purpose, a “Tsunami Protocol Meeting” was held at the
Mayaguez Campus of the University Puerto Rico during the
15-16th of January 2003. The objective of this meeting was to
set the groundwork for a tsunami warning system capable of
rapid dissemination of information throughout the Caribbean
on potentially tsunamigenic events in Puerto Rico and the
Virgin Islands.

Task 5: Development of a Caribbean Historical
Tsunami Database (CHTDB)

A comprehensive earthquake and tsunami database,
Historical Tsunami Database for the Atlantic has been
developed containing the written history of earthquakes and
tsunamis that have occurred in the Atlantic Ocean, including
the Caribbean Sea. The database includes all of the earthquake
information available, while the tsunami information is based on
the comprehensive compilation by LANDER et al. (2002).

This database contains a PC-based Graphical User Interface
for ease of visualization, and it was developed under contract at
the Novosibirsk Tsunami Laboratory, Russia. The whole
package is contained on CD, but it can also be run on-line at
http://omzg.ssc.ru/tsubas/. Figure 2 shows a plot of the
tsunami runup and earthquake data available for the Caribbean
region. A bar is shown at each location where runups have been
measured and the bar height is proportional to the runup
elevation. The same information can also be listed as a table for
printing.

Task 6: Participation in the USA National
Tsunami Warning and Mitigation Program

At the national level there is a National Tsunami Hazard
Mitigation Program (NTHMP), which presently includes the
states of Washington, Alaska, Oregon, California, and Hawaii.
This program is sponsored by FEMA, NOAA, USGS, and state
co-sharing. During the PRTWMP we were able to attend
various meetings and workshops sponsored by the NTHMP and
we hope to be able to become a member in the near future.

CONCLUSIONS

Based on the amount of feedback obtained from relevant
government agencies (for example, Education Department,
Puerto Rico Planning Board), private industries, civic
organizations, and the public in general, we can conclude that
we have reached our most important goal of raising the
government and public awareness of this forgotten hazard.

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