MODELING IMPACT OF EARTHQUAKE-GENERATED TSUNAMI ON THE CARIBBEAN SHORES OF PANAMA

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ABSTRACT

In this study, an earthquake-generated tsunami propagation and inundation analysis is performed by applying Delft3D software to the Caribbean side of the Panama. Five scenarios were established with different location and magnitude of earthquake after evaluating tsunamigenic zones and possible sources in the region. Two areas of interest were selected based on their industrial importance: one at the Colon and one at the Bahia Las Minas Bay both in about 57 kilometer northwest of the Panama City, Panama. The resulting tsunami waves were modelled with Delft3D after calibrating it for the 1991 tsunami triggered by Limon earthquake. Combination of 4 nested models with progressive improvement in the resolution starting from regional to site specific is used to model the impact of the tsunami scenarios on the two areas of interests. Model results are presented in the form of extreme water elevation maps, sequences of snapshots of water elevation during propagation of the tsunamis, and inundation maps of the studied low-lying coastal areas. This work features one of the first successful applications of a Delft3D model for the simulation of tsunami-induced coastal inundation in the Northern Panama. Model results showed that the maximum generated tsunami at the Colon and Bahia Las Minas areas would be in excess of 40 cm and 90 cm, respectively. It takes between 30 to 45 minutes for the tsunami to reach these regions.

Keywords: Earthquake, Tsunami, Flooding, Delft3D, Tsunamigenic.

1 INTRODUCTION

Tsunami is known as a series of water waves that propagate from the location of the tsunamigenic source (i.e. point of generation) toward the shore. Known tsunami sources are earthquakes, large landslides, volcanic activities and meteorite impacts. The most frequent cause of tsunamis is an earthquake and since it is impossible to forecast earthquakes, and hence it is impossible to forecast tsunamis (PNNL 2009). Not every event triggers tsunami, as it generate a tsunami only if disruption of the seabed takes place, which means that the center of the event is in relative limited depths beneath the seabed.

Tsunamis can be severely destructive to infrastructure, human life, and the economy located near the coast. In order to safely design any offshore or shoreline structure, it is essential to perform a tsunami hazard assessment. The objectives of the present study include the following:

(a) Establishment of tsunami scenarios and earthquake parameters through review of historical events.
(b) Developing hydrodynamic model to simulate the propagation of initial tsunami wave from source to the study area.
(c) Establishment of the high and low water levels and velocities at the study area.

2 PROJECT SITE

Study area encompasses large portion of the southern Caribbean Sea to cover the tsunami sources and enable the propagation of waves (Figure 1, left). However, the focus of the study is on the Bahia Las Minas (Bay) and Limon Bay (Colon), which their entrances are toward the Caribbean side of the Panama. The Bay (Figure 1, right) is a topographically complex, shallow-water, embayment whose margins were dominated at the time of this study by extensive mangrove forests, seagrass beds, and coral reefs. The Bay is approximately 5 km long and comprises of extremely shallow area at the upper side of the Bay. The width of this waterbody is 490 m from the mouth toward the site and decreases from there to a minimum of 130 m at the upstream of the Bay. Majority of the area surrounding the Bay is heavily vegetated with port Pilon located at the most upstream part of the Bay with residential areas. Colon is a natural harbor located at the north end of the Panama Canal,
west of the cities of Cristóbal and Colón. Ships waiting to enter the canal stay here, protected from storms by breakwaters. Strategic Liquid Natural Gas (LNG) terminals and power plants exist on the shores of this bay.

Figure 1. Location of Study Area in Regional Scale (left); Bahia Las Minas Bay (right).

3 HISTORICAL EVENTS

A tsunami can only be generated near a subduction zone (Sobolev and Babeyko 2005), which is a geological process that takes place at convergent boundaries of tectonic plates, where one plate moves under another. Tectonic boundaries of the region are dominantly oceanic and contain a diversity of interesting tectonic features such as all three of the dominant types of plate boundaries, multiple triple junctions, hotspots and more (García-Casco et al. 2011).

The seismic activity of Panama has been a topic of debate since the planning of the Panama Canal. Historically, the seismic activity has been relatively low and the seismic hazard includes large uncertainties. Panama is located on the Panama Microplate, which has a convergent boundary along North Panama Deformed Belt (NPDB) to the Caribbean plate. It is a medium-size plate that moves eastward at a speed of 2 cm/yr (NOAA 2015). Some studies (Camacho et al. 2010; Rockwell et al. 2010) show that the NPDB can be considered a subduction zone or at least an incipient subduction zone capable of creating more than 7 Mw earthquakes (Mw = moment magnitude). Lander et al. 2002 states that the area of Caribbean Sea is geologically active with common occurrences of earthquakes and volcanos. However, the majority of tsunamis are on the northern and eastern part of the Caribbean Sea and significantly away from the study area.

According to the tsunami catalogue of Central America (Molina 1997, Fernandez et al. 2000/2005, and NOAA 2015), 53 tsunamis are detected in Central America from 1539 to 2015. Where, 40 of those are from local sources and 13 from distant events, 41 affected the Pacific coast and 12 the Caribbean coast. Among the largest tsunamis are; 1882 with 7.9 Mw, 1916 with 7.5 Mw, and 1991 Lemon Earthquake with 7.6 Mw.

4 TSUNAMI SCENARIOS

Due to lack of data, the actual historical earthquakes that have affected Panama are difficult to model. Five hypothetical scenarios were established with a magnitude in the order of the largest historical earthquakes in the region (Mw of 7.5 to 8). It should be clarified that the magnitude of the largest historical earthquakes in the region, as presented in Section 3, range from 7.5 Mw (1916 event) to 7.9 Mw (1882 event).

The epicenter of the earthquake in the first scenario is located just off the coast of Costa Rica near Limon, and with a magnitude of 7.6 the earthquake resembles to some degree the 1991 Limon earthquake. The location of scenarios 2 to 4 is approximately 100km offshore from the Bocas del Toro Province. The location of Scenario 5 is about 100km offshore of Bahia Las Minas Bay. The epicenter of the earthquakes is shown in Figure 2. The strike angle of all scenarios is assumed to be along the NPDB. The magnitude and strike angle of the scenarios are given in Table 1.
**Table 1. List of Scenarios for Tsunami Wave Simulations**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Moment Magnitude (Mw)</th>
<th>Epicenter Location</th>
<th>Strike Angle [deg.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.6</td>
<td>E3</td>
<td>140</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>E1</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>7.8</td>
<td>E1</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>8.0</td>
<td>E1</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>7.8</td>
<td>E2</td>
<td>35</td>
</tr>
</tbody>
</table>

**Figure 2.** Epicenter of the Earthquakes Causing the Modelled Tsunamis.

5 NUMERICAL MODELING

Delft3D-Flow module solves the non-linear shallow water equations (conservation of mass and vertically-integrated momentum) on a series of dynamically-nested rectangular grids using an implicit time scheme. This numerical model was applied to initialize and propagate tsunami waves towards the Site. Regional and site-specific domains were connected using cascades of domains with decreasing grid size for the modelling of tsunamis as presented in Figure 3. The regional domain covered south of the Caribbean Sea and the bathymetry was based on General Bathymetric Chart of the Oceans (GEBCO) 2008 bathymetry data. Combination of recent hydrographic soundings, nautical charts, and GEBCO 2008 data are used to generate bathymetry for the site-specific domain.
Grid spacing is selected to ensure at least 20 to 30 grid points per tsunami wavelength and a courant number of less than 1 by setting the time steps to 6 seconds. Eddy viscosity has found to be insignificant parameter in such modeling and is set to the default value of 1. Bed resistance is specified by a Chezy number of 65. By try and error, the open boundaries are set far enough so that the tsunami waves reach the boundary of the nested domain before reaching to the open boundaries. This is a necessary step as the waves get reflected from open boundaries to the model domain and distort the results.

The initialization of the tsunamis was given as an initial displacement of the surface elevation due to displacement of the seabed. The Delft3D Tsunami tool was applied to create this initial displacement of the surface elevation applying widely used method of Okada’s Double couple (Okada 1985).

Tsunami model is calibrated for a location near the Colon, Panama for the 1991 tsunamnic, which is very close to the Scenario 1 of this study. Model results show that the maximum water level during Scenario 1 is 0.2m, which matches well with the available calibration value of 0.21m.

6 CONCLUSIONS

The evolution of the tsunami from the regional model for Scenario 4 is presented in Figure 4. It shows how the tsunami wave is propagating and increasing in height due to shoaling as it approaches the coast. It takes approximately 30 minutes for the tsunami to get to the bay in Scenario 4. This time increases to 45 minutes in other scenarios. The maximum surface elevation values at the Site (P1) and entrance (P2) points are given in Table 2. During the analysis, care was taken to make sure that the model is extended enough to cover the spread zone of the tsunami.

In general, the maximum water level increases linearly from Scenario 1 to Scenario 5. A maximum water level of 128cm is generated inside the bay at P1 location during Scenario 5. This is reasonable, as the epicenter of Scenario 5 is located approximately 100km north of the bay entrance and there is no structure or breakwater to dampen the tsunami waves. The shoaling and funneling phenomenon occurs from entrance of the bay through the intake and discharge location due to change in bathymetry and width. Tsunami scenarios generate depth averaged velocities ranged from 0.28m/s to 1.58m/s inside the bay.
Figure 4: Regional Model: Evolution of Tsunami Wave, 5, 10, 20, and 30 Minutes after Earthquake of Magnitude 8 (Scenario 4).

Table 2. Maximum/Minimum Water Levels and Velocities Caused by Tsunami

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Project Site Location (P1)</th>
<th>Bay Entrance (P2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WL&lt;sub&gt;max&lt;/sub&gt; (m)</td>
<td>WL&lt;sub&gt;min&lt;/sub&gt; (m)</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
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<td>-0.78</td>
</tr>
<tr>
<td>5</td>
<td>1.28</td>
<td>-1.71</td>
</tr>
</tbody>
</table>

REFERENCES


GEBCO One Minute Grid, November 2008
https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_one_minute_grid/.


