TSUNAMI CHARACTERISTICS OF OUTER-RISE EARTHQUAKES ALONG THE PACIFIC COAST OF NICARAGUA
- A CASE STUDY FOR THE 2016 NICARAGUA EVENT-

Amilcar Cabrera* **Supervisor: Yuichiro TANIOKA****
MEE16718

ABSTRACT

Nicaragua outer-rise earthquake characteristics were defined by the analysis of the oceanic lithosphere characteristics and the local seismicity, considering INETER and CMT catalogs; establishing a distance range of occurrence for the outer-rise earthquakes, a range of depth and a range of the most common dip angle for these events. The Mw 6.9 outer-rise earthquake occurred in 2016 surrounding the subduction zone of Nicaragua may be triggered by the interplate Mw 7.3 earthquake occurred in 2012 in the same area. An analysis of the 2016 Nicaragua outer-rise earthquake was carried out by tsunami simulation, considering linear dispersion; taking as input parameters, the values for hypocenter location and focal mechanism given from CMT solution. The best fault model for the earthquake and the slip amount were found by comparing the simulated tsunami signal and observed tsunami signal at the DART32411 buoy. Under the consideration that interplate events can trigger huge outer-rise events, we performed a tsunami simulation considering a tsunami triggered by an outer-rise event with Mw 8.4 located in the same area as the 1992 Nicaragua events. GEBCO bathymetry of 30 arc-minutes and SRTM of 3 arc-seconds were used to perform the tsunami inundation. The comparison between inundation measures obtained by simulation and measures surveyed in 1992 shows that an outer-rise event with this magnitude could cause a similar effect to the last devastated tsunami earthquake in 1992. Since outer-rise events represent a real tsunami hazard for the Pacific coast of Nicaragua, the study of these earthquakes must be considered for the disaster prevention policies and countermeasure processes.

Keywords: Outer-rise Earthquake Characteristics, Linear Dispersion, Tsunami Simulation.

1. INTRODUCTION

The Nicaraguan Institute of Territorial Studies (INETER) is the governmental institution in charge of the monitoring system for natural phenomena that affect the country. The seismic network was strengthened after the tsunami earthquake that affected the Pacific coast of Nicaragua in September 1992, and in parallel, the Tsunami Early Warning System was implemented. Due to the high seismicity in the subduction zone and the imminent tsunami hazard, INETER must be able to generate its own Tsunami Early Warning Bulletins for Nicaragua and even Central America. Currently, there is the headquarters of the Central America Tsunami Advisory Center (CATAC- Project) in Nicaragua which was established with the support of JICA. The main aim of this project is to establish a strong tsunami monitoring system and also to generate early warnings for the Central American countries.

---

*Nicaraguan Institute of Territorial Studies (INETER), General Direction of Geology and Geophysics, Nicaragua.
**Professor, Hokkaido University, Faculty of Science, Institute of Seismology and Volcanology, Japan.

The last tsunami warning issued by INETER was in November 2016, triggered by a large earthquake with Mw 6.9, located outer-rise of the Middle America Trench. Fortunately, no damage was reported. Near the epicenter of the 2016 event, the large El Salvador-Nicaragua earthquake with Mw 7.3 previously occurred at the plate interface as an underthrust event.

2. DATA

2.1. Characterization of Nicaraguan outer-rise earthquakes

We used the Global CMT catalog since 1976 until now and the INETER catalog since 1975 until now to characterize the outer-rise event occurred in front of the Pacific coast of Nicaragua.

2.2 Case study of the 2016 Nicaragua outer-rise earthquake

The source parameters for this event were taken from CMT, this information is shown in Table 1.

Table 1. CMT solution for the 2016 Nicaragua outer-rise event with normal faulting.

Hypocenter			Magnitude	Seismic moment	Focal Mechanism		
Longitude	Latitude	Depth	Mw	Mo	Strike	Dip	Rake
-89.2º	11.83º	12 km	6.9	3.16E+19 Nm	127º	50º	-89º

The tsunami simulation was carried out using a GEBCO bathymetry data with 30 arc-seconds. We also used observed tsunami waveform data of DART buoy. Figure 1 shows the tsunami signal recorded by the DART32411 buoy.

Two more tsunami records were reported by the PTWC tsunami bulletin, one corresponding to the Acajutla tide gauge and another corresponding to the La Libertad tide gauge, both located close to the Pacific coast of El Salvador. Nevertheless, the signals recorded were severely affected by the environmental noise.

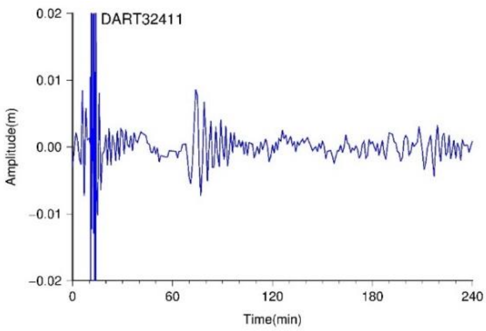

Figure 1. Recorded tsunami signal at the DART32411 buoy.

2.3. Run-up simulation due to a large outer-rise earthquake

The tsunami run-up simulation was performed from the worst scenario using a fine bathymetry grid composed by GEBCO 30 arc-seconds and the SRTM terrain model of 3 arc-seconds provided by Earthdata home page.

3. METHODOLOGY

3.1. Characteristics of outer-rise earthquakes of Nicaragua

The distance limit from the trench where the Nicaraguan outer-rise events can be occurred is determined using the earthquake catalogs from CMT and INETER. The common dip angle of the normal fault outer-rise earthquakes is also determined from the CMT catalog.

3.2. Case study for the 2016 Nicaragua outer-rise earthquake

The tsunami signal of this event recorded by the DART32411 buoy was used to compare three types of tsunami simulations in order to find the best fault parameters that reproduced the observed signal.

3.2.1. Tsunami simulation considering shallow water theory

We used Blaser et al. (2010) scaling law for normal faulting, to estimate the fault model of this event. The corresponding equations for the calculation of the fault dimensions are presented by Eqs. (1) and (2).

$$\log_{10} L = -1.61 + 0.46Mw \tag{1}$$

$$\log_{10} W = -1.08 + 0.34Mw \tag{2}$$

where L (km) is the length (km) of the fault, W is the width, and Mw is the moment magnitude of the earthquake (Blaser et al., 2010).

We performed tsunami simulations using the Tohoku University's Numerical Analysis Model for Investigation of Near Field Tsunamis version 2 (TUNAMI-N2) modified by Dr. Fujii (Fujii, 2016-2017). The program calculates the sea floor deformation using Okada formulation (Okada, 1985).

3.2.2. Tsunami simulation considering Imamura number

Due to the distance between the source and the DART buoy (around 600 km), the tsunami wave could be affected by dispersion. For that case, Imamura et al. (1990) defined a condition under which dispersive wave can be simulated through finite difference computation. This condition is expressed by Eq. (3).

$$\frac{\Delta x}{2d}\sqrt{1 - c_0^2\left(\frac{\Delta t}{\Delta x}\right)^2} = 1 \tag{3}$$

where Δt is the grid interval, Δx is the grid size, d represents the ocean depth and C_0 is the phase velocity.

3.2.3. Tsunami simulation considering Linear dispersion

Assuming the recorded signal is affected by dispersion, we performed a simulation using Linear Boussinesq equations with Coriolis force (Goto et al, 1988). This simulation was carried out using Yamanaka code and a grid resolution of 30 arc-seconds considering spherical coordinates.

3.3. Tsunami inundation due to outer-rise normal faulting

Once described the outer-rise characteristics in front of Nicaragua, we performed a tsunami simulation assuming one hypothetical outer-rise earthquake in the same area as the historical 1992 Nicaragua Tsunami earthquake. For this case we assumed a huge earthquake with Mw 8.4 corresponding to the biggest outer-rise earthquake recorded in the world, such as the Great 1933 Sanriku-oki earthquake (Uchida et al., 2016).

The simulation was performed using TUNAMI-N2 code modified by Prof. Yanagisawa from Tohoku-gakuin University (Yanagisawa, 2016-2017). This code considers nonlinear shallow water equations for the tsunami inundation.

4. RESULTS AND DISCUSSION

4.1. Nicaragua outer-rise characteristics

From previous studies of the global seismicity in oceanic lithosphere surrounding the subduction zone (Craig et al., 2014; Jackson et al., 2008 and Muller et al., 2008), we established a maximum depth for earthquakes occurrence of 30 km for the outer-rise Nicaraguan region.

In order to describe the seismic behavior around the subduction zone, we made an earthquakes classification taking the trench as a parameter for division. Using the focal mechanism classification diagram of Kaverina (Kaverina et al., 1996), we obtained a detailed classification of these events. From Figure 2, the domain of normal faulting for the southwest part of the trench and the thrust faulting domain for the northeast part of the trench are evident.

Another important result is the estimation of the more frequent dip angle for these events. Through the analysis of the seismicity, we obtained a high earthquakes frequency between 0 to 60 km of distance from the trench; and a most frequent dip angle in a range from 35 to 55 degrees for normal faulting.

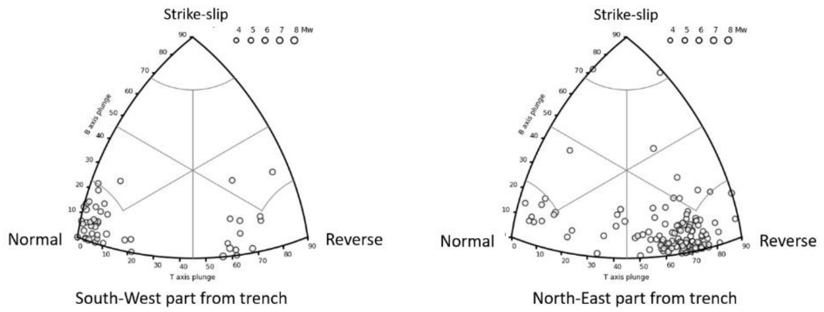

Figure 2. Kaverina diagram classification for the earthquakes surrounding the subduction zone in front of Nicaragua. Data taken from global CMT catalog since 1975 until now.

4.2. The 2016 Nicaragua earthquake

From Blaser's relationship, we obtained a fault model of 36.6 km length and 18.4 km width for a 6.9 Mw (CMT solution). Initially, we performed a tsunami simulation using TUNAMI code, considering non-linear shallow water theory and assuming a slip amount of 1 meter. Figure 3 shows the result of this simulation.

From Figure3 we can see, non-linear shallow water theory cannot explain the observed tsunami waveform. Searching for a way to explain the behavior in the observed signal, we took into consideration Imamura Number and we performed a tsunami simulation under the following parameters: Δt = 3 seconds, Δx = 3 minutes and d = 3 km in average. The result of this simulation is shown in Figure 4.

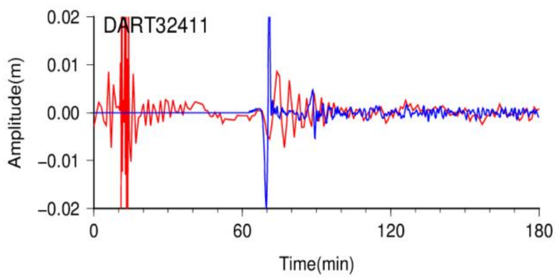

Figure 3. Waveform comparison between observed data (red line) and simulated data (blue line).

Assuming that the waveform was affected by dispersion (shown with Imamura Number simulation in Figure 4), we performed a tsunami simulation considering linear dispersion. The result of the simulation is shown in Figure 5.

It is evident that this simulation can explain the observed signal; however, in Figure 5 we can observe some differences in the first arrival and also the maximum amplitude. In order to reduce that difference of the seismic moment, we decided to look for an improved fault model taking into consideration Blaser's model uncertainty (Blaser et al., 2010).

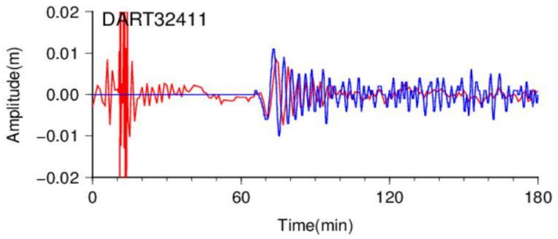

Figure 4. Waveform obtained using Imamura Number parameters. Blue line is the simulated signal and the red line is the observed signal.

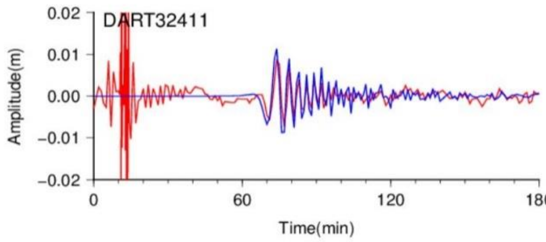

Figure 5. Waveform obtained considering linear dispersion. Blue line is the simulated signal and the red line is the observed signal.

.

We established L=2W as a search criteria. The range of search for L was set from 20 km to 60 km as maximum with an increment of 10 km. We also compared all the times the resulting seismic moment with the seismic moment given by global CMT. Figure 6 shows the results of this search.

The best fault model that reduces the differences between the previously simulated results and the given results corresponds to 30 km length and 15 km width, with a slip amount of 1.05 m and a seismic moment of 3.16E+19 Nm. Figure 7 shows the agreement between the observed waveform and the simulated waveform considering the new improved fault model.

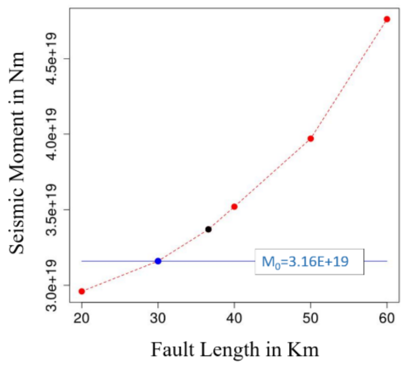

Figure 6. Search of best fault model comparing the seismic moment obtained by simulations with the CMT solution (blue line).

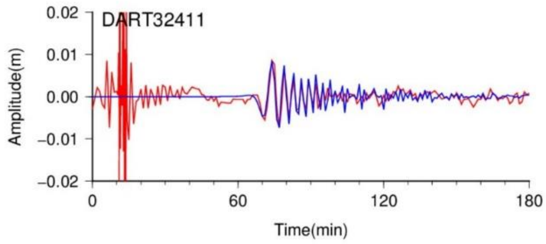

Figure 7. Tsunami waveform comparison; red line represents the observed signal, and blue line is the simulated signal obtained with the improved fault model.

4.3. A hypothetical outer-rise earthquake scenario for Nicaragua

Large interplate earthquakes can trigger outer-rise events (Christensen and Ruff, 1988; Wartman et al., 2009). Off Nicaragua, the 2016 outer-rise earthquake was triggered by the 2012 interplate earthquake. Following this assumption, we set a hypothetical outer-rise earthquake scenario triggered by the 1992 Nicaragua event for this case we set a magnitude Mw of 8.4.

We compare the inundation obtained by simulation and the inundation values surveyed for the 1992 Nicaragua tsunami earthquake (Abe et al.,1993). From figure 8, the result of this comparison shown a huge outer-rise earthquake with magnitude Mw 8.4 could produce a similar

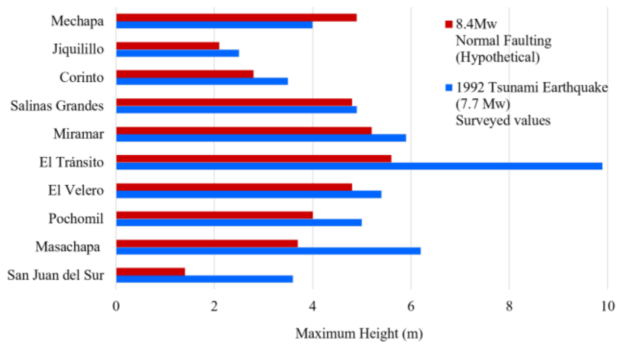

Figure 8. Comparison between inundation values simulated (red bars) and the inundation values surveyed by Abe et al. (1993).

inundation to the last devastating tsunami. converting large outer-rise events in a real tsunamigenic hazard for the county.

5. CONCLUSIONS

Outer-rise earthquakes are predominant normal faulting, occurring at a distance of 0 – 60 km from the trench in the southwest part of it, with a maximum occurrence depth of 30 km approximately. The predominant dip angle of these earthquakes corresponds to a range from 35 – 55 degrees.

A long distance between the source and the DART buoy affected the tsunami signal of the 2016 Nicaragua events. Therefore, linear Boussinesq equations which include a dispersion term are needed to be solved in the tsunami simulation in order to model the observed signal.

We found the best fault model for this event, corresponding to 30 km length and 15 km width, considering the Blaser relationship. The slip amount was estimated as 1.05 m by amplitude comparisons between observed and simulated waveforms.

A huge outer-rise normal faulting could produce devastating damage along the Pacific coast of Nicaragua, indicating this type of events is a real tsunami hazard to be considered in disaster prevention policies and countermeasure processes.

ACKNOWLEDGEMENTS

I want to express my deep gratitude to my supervisor Dr. Yuichiro TANIOKA for his advice, support, motivation, and encouragement to fulfill successfully the goals proposed during this process.

REFERENCES

Abe, K., Tsuji, Y., Imamura, F., Katao, H., Iio, Y., and Estrada, F., 1993, 1992, Bull. Earthq. Res. Inst. Tokyo Univ., 68, 23-70.

Blaser, L., Krüger, F., Ohrnberger, M., and Scherbaum, F., 2010, Bull. of the Seism. Soc. Am, 100(6), 2914-2926.

Christensen, D. H., and Ruff, L. J., 1988, J. Geophys. Res., Solid Earth, 93(B11), 13421-13444.

Craig, T. J., Copley, A., and Jackson, J., 2014, Geophysical Journal International, 197(1), 63-89.

Fujii, Y., 2016-2017, Lecture note on tsunami simulation, IISEE/BRI.

Goto, C., Imamura, F., and Shuto, N., 1988, Study on numerical simulation of the transoceanic propagation of tsunami, Part, 1, 515-526.

Imamura, F. Shuto, N., and Goto, C., 1990, J. Seismol. Soc. Jpn., 43, 389-402.

Jackson, J., McKenzie, D. A. N., Priestley, K., and Emmerson, B., 2008, Journal of the Geological Society, 165(2), 453-465.

Kaverina, A. N., Lander, A. V., and Prozorov, A. G., 1996, Geophys. J. Int., 125(1), 249-265.

Müller, R. D., Sdrolias, M., Gaina, C., and Roest, W. R., 2008, Geochemistry, Geophysics, Geosystems, 9(4).

Okada, Y., 1985, Bull. of the Seism. Soc. Am., 75(4), 1135-1154.

Uchida, N., Kirby, S. H., Umino, N., Hino, R., and Kazakami, T., 2016, Geophysical Journal International, 206(3), 1619-1633.

Wartman, J. M., Kita, S., Kirby, S. H., and Choy, G. L., 2009, In AGU Fall Meeting Abstracts.

Yanagisawa, H., 2016-2017, Lecture note on numerical simulation of tsunami inundation and its application, IISEE/BRI.