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ASSESSING POTENTIAL TSUNAMI HAZARDS IN COLOMBIA

S. Koshimura[(1)], E. Mas[(2)], B. Adriano[(3)], M. Puentes[(4)], R. Sanchez[(5)], H. Giraldo-Gómez[(6)], D. López[(7)]

[(1)] *Professor, International Research Institute of Disaster Science, Tohoku Univ., Japan, koshimura@irides.tohoku.ac.jp*
[(2)] *Assistant Professor, International Research Institute of Disaster Science, Tohoku Univ., Japan, mas@irides.tohoku.ac.jp*
[(3)] *Post-doctoral Researcher, International Research Institute of Disaster Science, Tohoku Univ., Japan, adriano@irides.tohoku.ac.jp*
[(4)] *Director, Dirección General Marítima (DIMAR), Colombia, mpuentes@dimar.mil.co*
[(5)] *Researcher, Dirección General Marítima (DIMAR), Colombia, rsanchez@dimar.mil.co*
[(6)] *Director, Sede Tumaco, Universidad Nacional de Colombia, Colombia, hgiraldog@unal.edu.co*
[(7)] *Sub-director, National Unit for Disaster Risk Management (UNGRD), Colombia, diego.pena@gestiondelriesgo.gov.co*

Abstract

An international project was launched between Japan and Colombia, focusing on the application of state of the art technologies to strengthen research and response to seismic, volcanic and tsunami events, and enhance risk management in Colombia. This project so-called SATREPS ; the Science and Technology Research Partnership for Sustainable Development started in 2008 jointly sponsored by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA). Under the leadership of Prof. Hiroyuki Kumagai, Nagoya University, 9 universities and research institutes joined the project both from Japan and Colombia and the project consists of 6 sub-teams ; earthquake, crustal deformation, volcano, strong motion, disaster information and tsunamis.

We aim to report the overview of "tsunami" research group. Four institutes from Japan and four institutes (DIMAR, Universidad Nacional de Colombia, SGC, and UNGRD) join the team to accomplish the goal of "developing tsunami damage estimation and mitigation technologies in Colombia". This paper reports the preliminary outcomes throughout the project mainly focusing on tsunami propagation features and tsunami impacts along Pacific and the Caribbean coasts of Colombia with recent advances of tsunami inundation modeling.

Keywords: tsunami hazard, tsunami numerical modeling, Colombia

1. Introduction

An international project is underway between Japan and Colombia. The project focuses on the application of state of the art technologies to strengthen research and response to seismic, volcanic and tsunami events, and enhance risk management in Colombia. This project was launched in July 2015 as so-called SATREPS ; the Science and Technology Research Partnership for Sustainable Development started in 2008 jointly sponsored by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA).
Under the leadership of Prof. Hiroyuki Kumagai, Nagoya University, 9 universities and research institutes joined the project both from Japan and Colombia and the project consists of 6 sub-teams ; earthquake, crustal deformation, volcano, strong motion, disaster information and tsunamis (www.eps.nagoya-u.ac.jp/~aterra/).

We aim to report the overview of "tsunami" research group. Four institutes from Japan and four institutes (DIMAR, Universidad Nacional de Colombia, SGC, and UNGRD) join the team to accomplish the goal of "developing tsunami damage estimation and mitigation technologies in Colombia". To accomplish the goal, we are working on five topics ; 1) Review of the past tsunami events in Colombia and constructing potential tsunami source scenarios, 2) Study on tsunami propagation/inundation characteristics on the Colombia coast using tsunami numerical models, 3) Tsunami risk assessment along the Colombia coast, 4) Mapping tsunami inundation and loss estimation, 5) Enhancing tsunami risk awareness and evacuation plan. The research fields are planned in both Pacific and the Caribbean coasts; Tumaco, Buenaventura, and Cartagena. Especially Tumaco city, which is located on the Pacific coast of Colombia was affected by the past event (the 1979 great Tumaco earthquake[1], 200 people were killed by the tsunami) and is believed to be the most vulnerable area for potential earthquakes and tsunamis.

This paper reports the preliminary outcomes throughout the project mainly focusing on tsunami propagation features and tsunami impacts along Pacific and the Caribbean coasts of Colombia with recent advances of tsunami inundation modeling.

2. SATREPS Tsunami project

The goal of the project is to develop tsunami damage estimation and mitigation technologies for Colombia by conducting collaborative studies between Japan and Colombia sides. To accomplish the goal of the SATREPS tsunami project, we set 5 topics (plus one) as listed below;

[1] Transfer of tsunami numerical modeling technique
[2] Verification of tsunami numerical model and tsunami source study
[3] Tsunami risk assessment along the Colombian coast
[4] Mapping tsunami inundation
[5] Enhancing tsunami risk awareness and evacuation plan
[6] Bathymetric survey & Updating simulation

The core technology is the numerical modeling technique and mapping. Recently, it becomes quite general to model tsunami propagation and inundation by numerical models with modern computing power. Tohoku University provides a source code of tsunami numerical model based on the non-linear shallow water theory as activities of TIME (Tsunami Inundation Model Exchange) project. However, there is a concern about its use. As the numerical modeling technique becomes general, this powerful tool tends to be used without any understanding of physical aspects of tsunami as water waves.

When we perform the numerical modeling of tsunami inundation, it is general a set of the non-linear shallow water equations (1) to (3) are discretized by the Staggered Leap-frog finite difference scheme [2] with bottom friction in the form of Manning's formula *n* according to the land use condition.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) = -gD\frac{\partial \eta}{\partial x} - \frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} \qquad (2)$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)=-gD\frac{\partial \eta}{\partial y}-\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2} \qquad (3)$$

where,

$$M=\int_{-h}^{\eta} udz$$

$$N=\int_{-h}^{\eta} vdz$$

$$D=\eta+h$$

M and N are the discharge flux of x and y direction respectively, η is the water level and h is the water depth above the mean sea level. We applied the Staggrered leap– frog scheme for discretization of the governing equations, to have developed TUNAMI-code (Tohoku University's Numerical Analysis Model for Investigation of Tsunami). The transfer of TUNAMI-code was carried out in October, 2015, with the participants of Colombia scientists and engineers (Fig. 1).

Fig. 1 – SATREPS Colombia Tsunami group members (October, 2015).

3. Case studies of past earthquake tsunamis in Colombia

Pacific coast of Ecuador and Colombia lie on the convergent of the Nazca Plate subducting beneath the South American Plate along the Colombia–Ecuador Trench. The Nazca Plate is moving to the east at a convergence rate of 58 mm per year [3, 4]. It is believed that the north Ecuador–south Colombia (NESC) margin has three tectonic segments (the Manglares, Tumaco, and Patia segments), with different tectonic and structural patterns [5, 6]. In 1906 a 500 to 600 km long segment of the plate interface ruptured, to have caused a Mw 8.8 earthquake (the rupture was occurred in all four segments) and a trans-Pacific tsunami. Following the 1906 earthquake, there have been three megathrust events in 1942 (Ms 7.9); 1958 (Ms 7.8); and 1979 (Ms 7.7 in the NESC margin [1].

The earthquake of Ms 7.7 occurred at 07:59:4.3 (UT) on 12 December 1979. The epicenter of the earthquake was in the ocean at (1.584N, 79.386W) [the U.S. National Earthquake Service (NEIS), 1980]. The 1979 earthquake resulted in a tsunami that devastated six of the coastal villages along Colombia's southwest Pacific coast and caused hundreds of dead or missing. The tsunami was measured along the coast from 2-5 meters destroyed many of these coastal villages. It was reported that many people, who survived the earthquake running outside of their houses were washed-away a few minutes later by the large tsunami hit.

Our first attempt in the project is to perform the numerical simulation to reproduce the 1979 Tumaco earthquake tsunami. With the fault parameters shown in Table 1, we calculated the coseismic deformation as shown in Fig.2 [7].

One example of the case studies is shown in Fig. 3 as the maximum tsunami height distribution. According to the survey report by Pararas-Carayannis (1980), the hardest hit of all the coastal villages was the fishing village of San Juan [8]. The tsunami completely flooded the island to devastate everything in the process of penetration. 161 deaths and 38 missing were reported from San Juan. Pararas-Carayannis (1980) also mentioned about the eyewitness accounts that 3 to 4 waves were observed, the first wave arriving approximately 10 minutes after the main shock. The water receded initially to about 3 meters below the tide level at that moment. The first wave arrived minutes later. The third wave was the largest, and San Juan Island was approximately 5 meters above the level of the tide, and was at its lowest at that time. The tsunami was also observed in Ecuador coast. The record was obtained at the port of Esmeraldas in Ecuador, and it was confirmed that the sea surface was continuously oscillated in the port 3 to 4 times, though no damage was reported.

Looking at the longshore tsunami height distribution shown in Fig. 3, the results are consistent with the reported above. The tsunami energy was mainly concentrated along the coast of Esmeraldas, Ecuador to San Juan, Colombia.

Table 1 – Fault parameters of the 1979 great Tumaco earthquake.

Mw	**L (km)**	**W (km)**	**Epicenter**		**Depth (km)**	**Focal Mechanism (Strike, Dip, Rake)**			**Slip (m)**
8.1	184	76	1.598N	79.358W	20	30	16	118	2.5

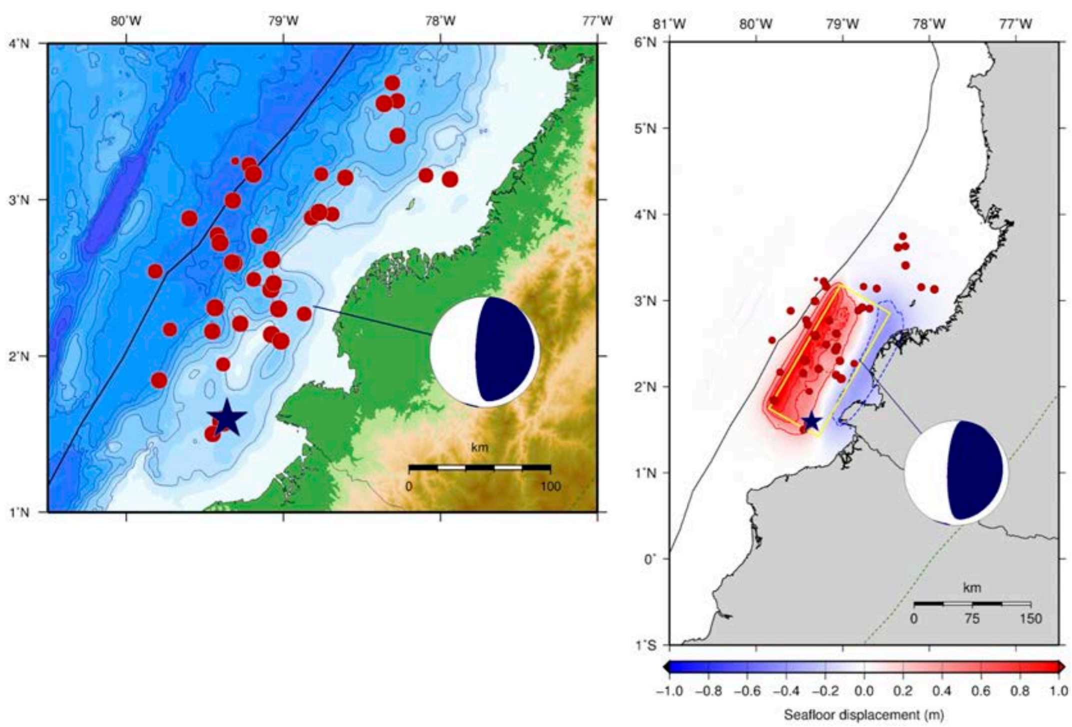

Fig. 2 – Tsunami source model for the 1979 great Tumaco earthquake. Left: Mainshock and aftershocks of the 1979 earthquake. Right : Sea floor deformation computed by Okada (1985) formula, assuming a thrust fault rupture of Mw 8.1 (Table 1).

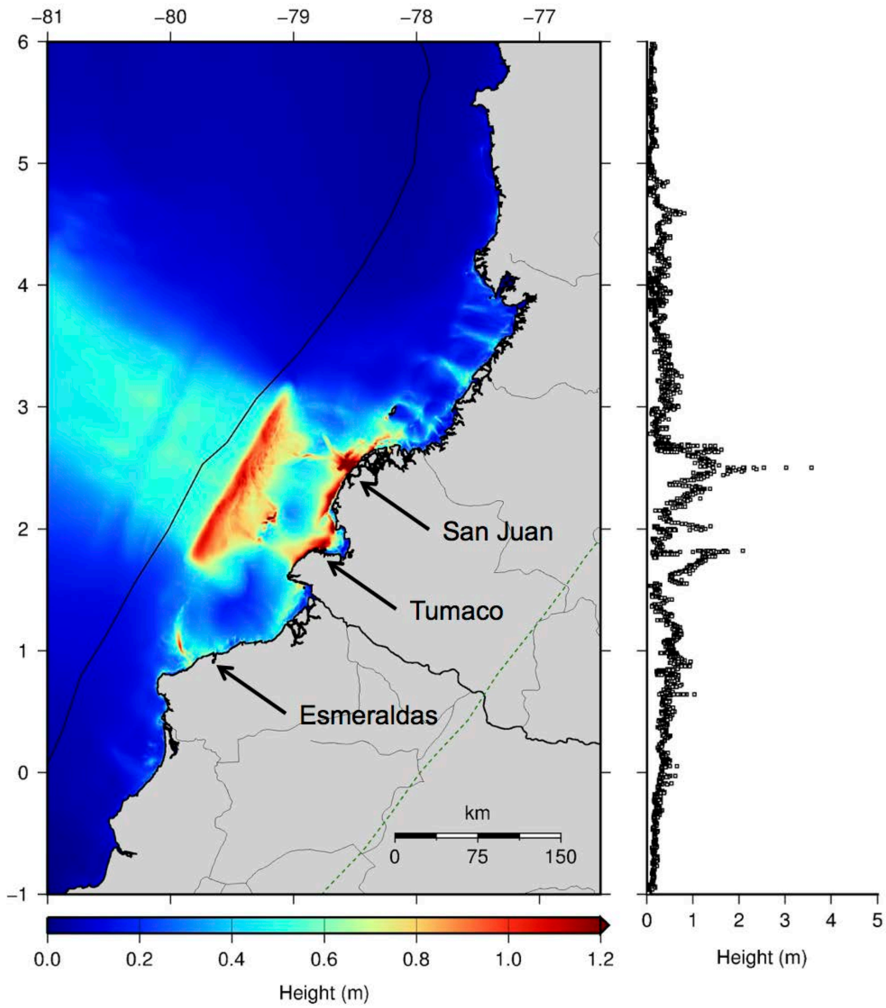

Fig. 3 – Computed maximum tsunami height of the 1979 great Tumaco earthquake.

Further analysis has been performed by Adriano et al. (2017) using tsunami waveform inversion [10]. The results imply that that the 1979 tsunami source was about 250 km long, extending from the epicenter to northeast.

4. Case Study, Analysis of the 2016 Ecuador Earthquake Tsunami

The tsunami model is applied to analyzing the recent events. A magnitude of 7.8 earthquake occurred at the coastal region of Ecuador (South America) on Saturday, April 16, 2016 at 23:58 UTC. This earthquake was occurred near the boundary of the Nazca and South American plates. The main part of the fault rupture was likely in the shallow crust, consequently generated local tsunamis propagating to the coast of Ecuador and Colombia. Fig. 4 shows the preliminary result of tsunami waveform inversion. Red and blue lines indicate the observed tsunami waveforms at tide gauge stations and synthetic tsunami waveform, respectively. Solid lines show the time windows used for inversion. As a result, the possible tsunami source model was obtained as Fig. 5, that implies Mw=7.78.

The estimated fault slip distribution shows that the large slip of 4 m was occurred at the epicenter of the mainshock and is consistent with the results of seismic waveform inversions with finite fault model [11]. In this event, the observed tsunami was small and no significant impact was reported. Through the case studies of recent and past events, the modeling efforts are increasing the capability of Colombia's tsunami risk studies.

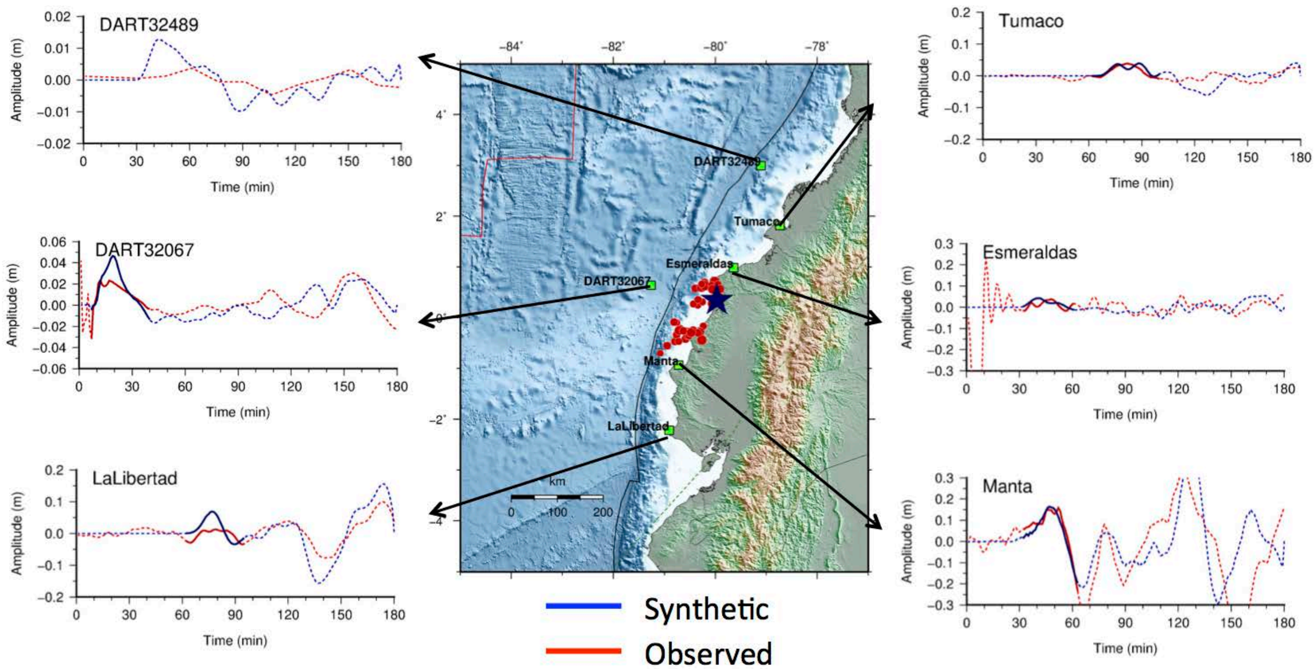

Fig. 4 – Preliminary result of tsunami waveform inversion of the 2016 Ecuador earthquake.

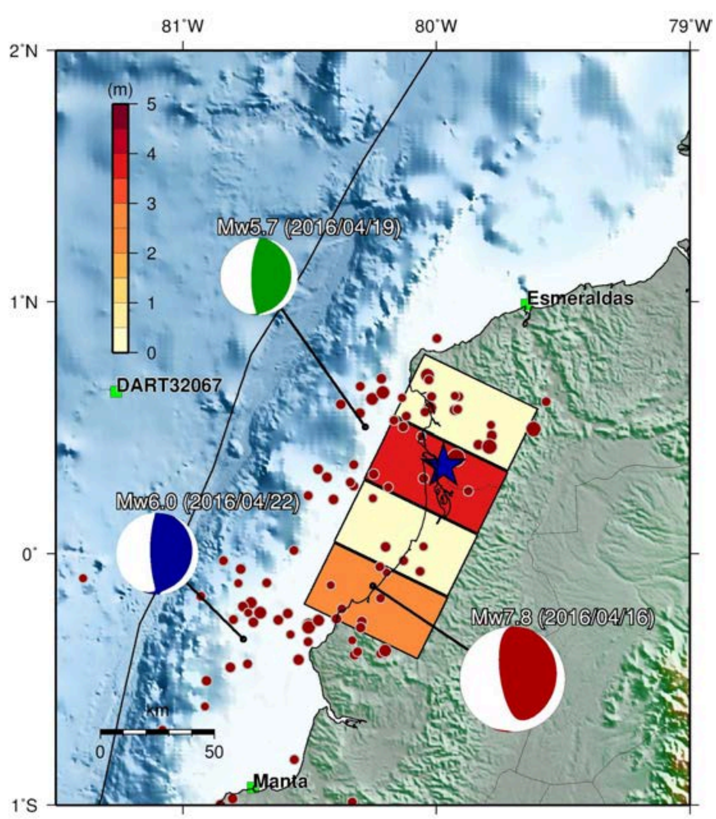

Fig. 5 – Tsunami source model of the 2016 Ecuador earthquake. The red circles indicate the centroids of main and aftershocks greater than Mw5.7.

5. Summary

SATREPS Colombia project was launched in October, 2015. First we conducted the technology transfer to share the tsunami numerical model between Japan and Colombia as a standard model to assess potential tsunami risks in Colombia. This year, we conducted some case studies of the past events, such as the 1979 great Tumaco earthquake tsunami including conventional tsunami propagation modelling and application of tsunami inversion analysis. The model was also applied to the recent event ; the 2016 Ecuador earthquake of Mw 7.8. The results are consistent with the result of earthquake source inversion analysis. We are now moving onto running more simulations to assess the tsunami risks in Colombia, mapping tsunami inundation and updating tsunami hazard maps, enhancing tsunami risk awareness and evacuation plan [12].

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