STUDY OF THE BATHYMETRIC INFLUENCE ON TSUNAMI PROPAGATION NEAR THE COAST OF ESMERALDAS BY TSUNAMI SIMULATION AND RAY TRACING ANALYSIS

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ABSTRACT

As a result of the subduction and other geological processes, there is the presence of some bathymetric features which significantly change the gradient of the seabed near Ecuador, such as the oceanic trench and the submarine Esmeraldas canyon. The main purpose of this study is to give a better understanding of how these alterations in the bathymetry affect the tsunami propagation by conducting ray tracing analysis and tsunami simulations using different bathymetry data sources of GEBCO, ETOPO and INOCAR, for local and distant events along the Pacific and the coast of Ecuador. In addition, we conducted tsunami propagation simulation using TUNAMI code with a nested grid system of six domains. We used general and high resolution bathymetric data and analyzed the results in all six domains. From the results of both analyses, we evaluated the consistency between the directivity of the rays and the wave's propagation for focusing areas such as Esmeraldas. We observed a faster propagation of the wave due to the particular bathymetric profile of the canyon in front of Esmeraldas, which made the first wave arrive at this city; with this result we confirmed the effect of local bathymetry along the tsunami path. This study can be used as a preliminary evaluation to determine the vulnerability of specific locations along the coast regarding the changes in the local bathymetry and topographic submarine features. Therefore, in the future we expect to conduct further analysis under other considerations not estimated in the present research.

Keywords: Tsunami simulation, ray tracing, bathymetry effect, propagation path, directivity.

1. INTRODUCTION

Ecuador is a country with high seismic risk; its geographical position is part of the "Ring of Fire" in the Pacific; therefore, it is vulnerable to threats not only from hydro-meteorological nature but also from the geological environment like earthquakes and tsunamis in most of its territory. Regarding tsunami studies, one of the most important topics to be discussed, is to know how the tsunami wave propagates from the source until it reaches the coast. In the case of Ecuador, which is located in front the subduction zone, there is always a possibility for the occurrence of a tsunami as a result from an earthquake, for this reason, this is a very important issue that should be considered. For a better understanding of the wave's propagation, Satake (1988) studied the effects of the bathymetry by the application of ray tracing to

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tsunami propagation, allowing to evaluate the directivity of the wave from a point source model along its propagation path. Ray tracing can also be used to determine focusing and defocusing areas by analyzing specific points of the coast where the rays concentrate or dissipate depending on the local bathymetry. In the same way, after the arrival of the first tsunami wave, it refracts back to the ocean or to other locations in the coast, which can also be estimated by ray tracing analysis. On the other hand, one of the advantages of this model is that ray paths are displayed in a short computational time; however, it has a strong sensibility for depth variations that depend on the bathymetry data used for the simulation, and for that reason it is necessary to understand the application of the model under different considerations. Since there are no other studies in Ecuador regarding the application of ray tracing to analyze the wave's directivity, this research can be considered as the first evaluation of this type for local populations along the coast. The current research focuses on the study of the bathymetry and its influence on the tsunami propagation since it affects the directivity and the wave direction. By this, focusing and defocusing areas can be determined as the support of tsunami risk management for vulnerable populations.

2. DATA

For this study, it was necessary to prepare the bathymetry data for both ray tracing and tsunami simulations. Since ray tracing code was set in MATLAB, we required to construct the spatial and depths matrix, for both far-distant and local events. For far-distant ray tracing simulations, we used original bathymetric data of 1 arc-min resolution from ETOPO1, that was resampled to 5 arc-min resolution for simulations with real bathymetry, and also replaced assuming a constant ocean depth of 5400 meters for simulations with constant depth. In the same way, for local ray tracing simulations, we used original 15 arc-sec and 1 arc-min grid resolution data from GEBCO and ETOPO1, respectively.

Table 1. Computational domain for the simulation of the TUNAMI model.

Domain	Longitude (deg)		Latitude (deg)		Spatial Resolution		Dimension		Connecting point
	Left	Right	Bottom	Top	Mts.	Arc-sec	IF	JF	ISL/JSL/IEL/JEL
1	-82.47	-78.51	-2.74	2.49	2430	81	181	238	....
2	-80.92	-78.69	0.33	2.01	810	37	307	229	72/141/173/216
3	-80.28	-78.94	0.57	1.63	270	9	553	433	89/34/272/177
4	-79.79	-79.56	0.95	1.11	90	3	295	193	202/156/299/219
5	-79.69	-79.6	0.97	1.06	30	1	358	355	127/20/245/137
6	-79.67	-79.65	0.98	1.01	10	0.33	187	391	93/42/154/171

On the other hand, for tsunami simulations, we constructed a nested grid system for six defined areas to compute the TUNAMI model from Tohoku University as shown in Table 1. This model considers the linear propagation for the first three grids, for that reason, we used 15 arc-sec resolution data from GEBCO for those areas; however, for non-linear propagation in grids 4 to 6, we used finer bathymetry with 10 meters spatial resolution from INOCAR, which was resampled according to the considerations of the TUNAMI model for the last three areas.

3. METHODOLOGY

3.1. Ray tracing simulation

According to the purpose of the current study, it was necessary to analyze how the bathymetry influences the way of propagation of the tsunami wave. Since it is known that the velocity of the tsunami is directly related to the water depth $\sqrt{gh}$, these changes of bathymetry will cause a variation in the propagation path from the source until it reaches the coast; for this reason, ray tracing methodology was used to analyze the bathymetric effect. Ray tracing is computed as a short wavelength approximation, which has a strong dependence on the water depth, being sensitive to the changed inhomogeneity. Considering the earth's sphericity, the governing equations (Satake, 1998) are as follows:

$$d\theta/dT = 1/nR * \cos\zeta, \tag{1}$$

$$d\varphi/dT = 1/nR \sin\theta * \sin\zeta, \tag{2}$$

$$d\zeta/dT = \sin\zeta/n^2R * \partial n/\partial\theta \quad + \quad \cos\zeta/n^2R \sin\theta * \partial n/\partial\varphi - \quad 1/nR * \sin\zeta \cot\theta, \tag{3}$$

where φ and θ are the longitude and the colatitude (in radians), respectively at the ray time defined as *T*, *n* is referred as the slowness ($1/\sqrt{gh}$), *R* corresponds to the earth's radius defined as 6371 km, and ζ is the direction of the ray measured counterclockwise from the south in radians in Eqs. (1) – (3). In order to solve the above equations, the Runge-Kutta 4th order method was used for the computation and the mid-point method for solving the integrations using interpolated velocities (Gusman et al., 2017).

Likewise, in order to execute the program, it is necessary to input five initial parameters: the time step and the maximum time of computation both in seconds, the ray azimuth interval in degrees and, X_O and *Yo* that are the point source longitude and latitude, respectively in decimal degrees. The program only works with positive values of bathymetry; if it is plotted inland or in a region of negative values, it does not show any propagation. In such cases, we needed to change the values of X_O and *Yo* to the nearest point on the coast to see the ray propagation. For this reason, it was important to check the data, especially if it came from different sources, since positive values are defined for the bathymetry and negative for topography data.

3.2. Tsunami simulation

In general, tsunami waves are mostly generated after an earthquake occurs, when the deformation of the seafloor causes a vertical displacement of a large volume of water. From this consideration, we considered the deformation as an initial condition of a tsunami source, and used the Okada's (1985) dislocation model to estimate the deformation of the seafloor by assumed fault parameters.

As previously mentioned, we used the TUNAMI code which was developed and modified by Tohoku University (Koshimura, 2018). Since for the non-linear simulation we needed to understand the behavior of the wave propagation in shallow waters, for practical use in the numerical modeling, it was necessary to consider the bottom friction terms, which are related to the interaction of the bottom. We expressed the shallow water theory for non-linear propagation (Koshimura, 2018) in Eqs. (4) – (6) with the bottom friction terms for Cartesian coordinate system as follows:

$$\frac{\partial\eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{4}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial\eta}{\partial x} + \frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} = 0 \tag{5}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + gD\frac{\partial\eta}{\partial y} + \frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2} = 0 \tag{6}$$

where n is the Manning coefficient, M and N are the discharge fluxes in x and y directions respectively, and D is the total depth $(=\eta + h)$ which is related to the water level η and the water depth h.

4. RESULTS AND DISCUSSION

For far-distant events, two different ray tracing simulations were conducted for each scenario in Alaska, Nicaragua and Chile, using both artificial bathymetries assuming a 5400 meters constant ocean depth and real bathymetry of 5 arc-min resolution data resampled from ETOPO1.

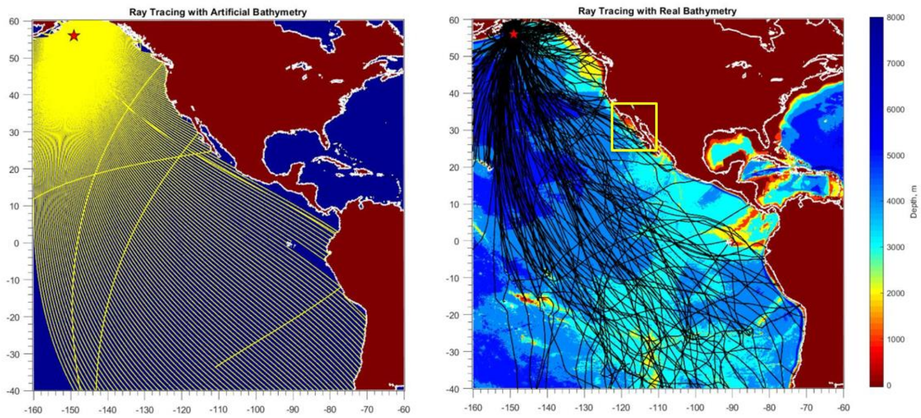

Figure 1. Ray tracing simulation from a point source located in Alaska.

As it can be appreciated in Figure 1, two simulations were conducted from the same point source in Alaska. The plot on the left shows the result using the 5400 meters constant depth, of where it indicates that all the west coast of the United States, Ecuador, Chile, and also the south part of the Colombia and Peru coasts were affected by the wave directivity. However, according to the plot on the right using real bathymetry, we could observe that the most affected area was California in North America, in contrary, Ecuador does not seem to have a significant effect compared with the results from the simulations using the artificial bathymetry.

In the same way, we conducted simulations for local events under different conditions. At first we considered two resolution bathymetries, obtaining some spatial variations regarding the propagation of the rays. Secondly, we evaluated the influence of the oceanic trench in the ray propagation. For this case we defined two sources at the same latitude but different longitude considering its position regarding the trench. Results showed that the trench acts as a barrier trapping and refracting the waves back to the ocean due to the point sources located near the coast and offshore the trench, respectively as shown in Figure 2.

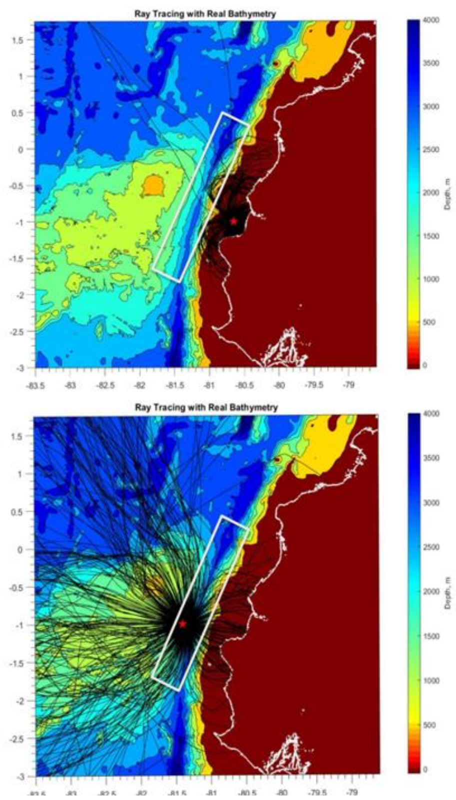

Figure 2. Ray tracing simulations from point sources located near the coast (top) and offshore the trench (bottom).

After evaluating how the trench influences the directivity of the wave, we conducted a deeper analysis for the most important and vulnerable cities along the coast, from 20 point sources distributed in three areas: north, central and southern Ecuador; considering their position respect to the oceanic trench, we also defined the worst-case scenarios for each area. From the previous results, we observed a particular trend of the rays focusing to the coast of Esmeraldas in the north area. For the next step, we did more ray tracing simulations considering the presence of the Esmeraldas canyon, obtaining the same trend from other point sources located in the north.

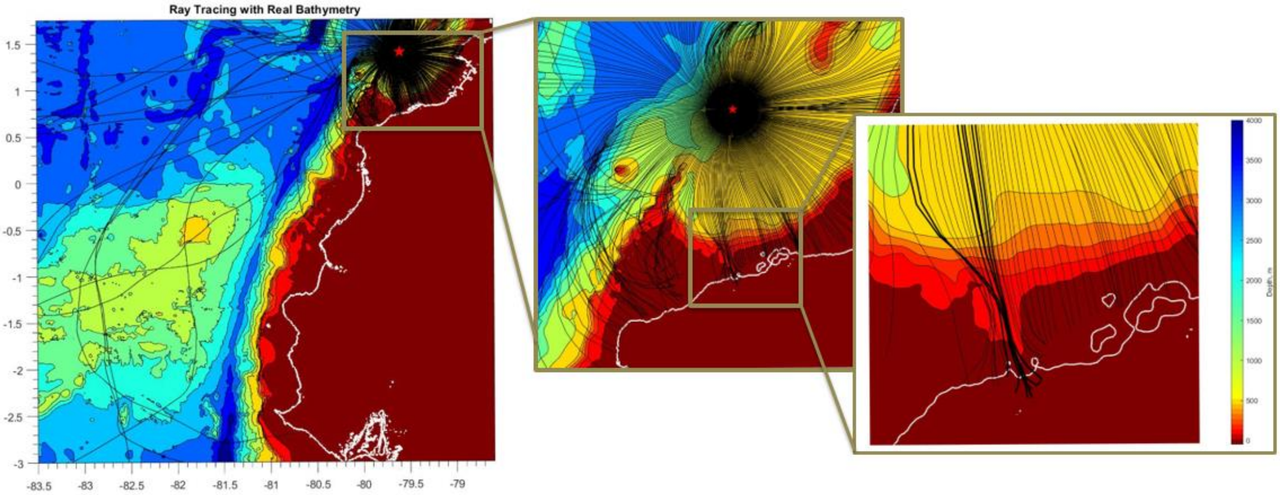

Figure 3. Ray tracing simulation from a point source in northern Ecuador.

As it can be seen in Figure 3, the rays follow a particular pattern; converging and propagating from the source following an explicit path arriving to the coast. From these results, we can confirm that the presence of the Esmeraldas canyon in front of Esmeraldas city considerably influenced the propagation of the tsunami regarding the wave's directivity.

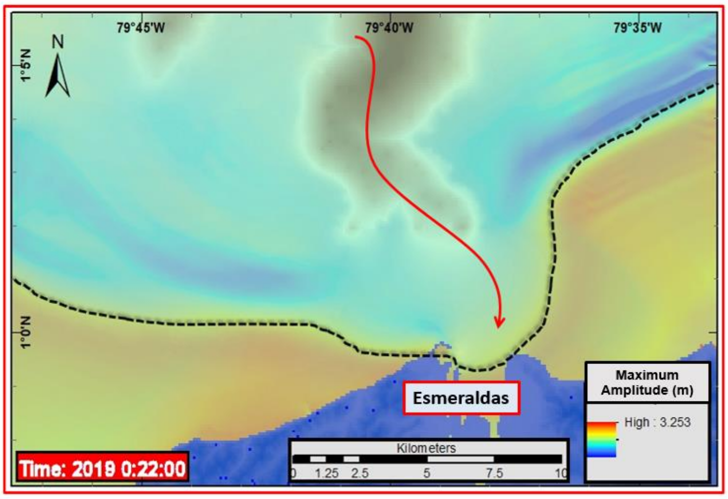

Figure 4. Snapshot obtained from TUNAMI simulation model after 22 minutes propagation in Domain 4 (See Table 1).

In order to have a better understanding of this process, we conducted tsunami simulation using the TUNAMI code with the six nested grids, as described in section 2. After the simulation, we obtained the outputs each minute for one-hour propagation, merging the bathymetric and the propagation layers in order to have a better appreciation of the tsunami wave along the Esmeraldas canyon. With all the previous analyses, we observed a consistency between both results of ray tracing and TUNAMI model simulations. From the results of ray tracing simulations, we appreciated how the wave's directivity changed its direction along the propagation path, as seen in Figure 3. In this way, we can define Esmeraldas as a focusing area against a tsunami event generated in the north due to its location in front of the canyon, which influences the wave to move faster and reach first to Esmeraldas compared to other points in the north region. From the results of TUNAMI simulation, and as previously discussed, the wave arrived first at Esmeraldas compared to the areas to the side. Due to the bathymetric profile of the canyon, the wave moves faster along the canyon which ends in front of Esmeraldas as appreciated in Figure 4. This particular trend makes this area more vulnerable compared to other neighboring populations, being one of the main reasons to continue performing tsunami studies in that area.

5. CONCLUSIONS

From the results of ray tracing simulations for far distant events, we concluded that there is a clear difference in the propagation of the wave's directivity between using artificial and real bathymetries, since then, we computed other simulations only considering real data. In the same way, for local simulations, we also observed that there are spatial variations from using bathymetry data at different resolutions.

From the results of local simulations, considering the presence of the oceanic trench, we could appreciate how the trench acts as a barrier regarding the position of the source, near the coast or offshore. From simulations located near the coast, we observed how the rays are trapped and refracted back to the coast, contrary from an event located offshore the trench, where most of the rays returned to the deep sea. According to these results, we can infer that an event generated near the coast may have more influence on coastal populations, compared with a source offshore the trench. Regarding this last consideration, we computed other simulations along the coast for three different areas, defining the worst scenarios for most important populations.

After the evaluation of the results from the north area, we observed a particular trend for Esmeraldas. Simulations from different point sources in the north showed the same tendency, rays focusing in a specific point in the coast following the shape of the Esmeraldas canyon. In that sense, we conducted tsunami simulation using the TUNAMI model for linear and non-linear propagation which considers the deformation of the seafloor. Results showed that there is a consistency between the ray tracing analysis and tsunami simulation; we observed how the velocity and the wavefront tend to move faster in the direction of the canyon reaching first to Esmeraldas compared to other areas.

Finally, from the evaluation of all simulations, we defined Esmeraldas as a focusing area from a source located in northern Ecuador; that is due to the presence of the Esmeraldas Canyon, which causes the tsunami wave to focus at this point, reaching first to this location in the north.

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REFERENCES

Gusman, A. R., Satake, K., Shinohara, M., Sakai, S. I., and Tanioka, Y., 2017, Pure and Applied Geophysics, 174(8), 2925-2943.

Koshimura, S., 2018, Lecture notes on Tsunami Hazard Assessment- Theory of Tsunami Propagation and Inundation Simulation, IISEE/BRI.

Okada, Y., 1985, Surface deformation due to shear and tensile faults in a half-space, Bulletin of the seismological society of America, 75.4, 1135-1154.

Satake, K., 1988, Effects of bathymetry on tsunami propagation: Application of ray tracing to tsunamis, Pure and Applied Geophysics, 126(1), 27-36.