Waves propagation and run-up by tsunami: earthquake of 1979 in Colombian Pacific

18

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Mathematical simulation or Numerical simulation

1 Introduction

PE

Tsunamis are phenomena ~~that~~ manifest are very harmful to the coast infrastructure and population. Math simulation can model important characteristics as the development of tsunamis ~~with time~~ and run-up (plausible inundation). ? The models use numerical solution of systems of partial differential equations, this solution represents the movement of water across ocean and its approaching onshore with local inundation effects in land.

PE/SC

In the modelling of tsunami, ~~the~~ waves propagation is affected by ~~an~~ irregular bathymetric data (~~the~~ seabed), ~~the~~ characteristics of event generator, (e.g., submarine earthquake), geomorphology aspects, complex coast shape, among others. The presence of these irregular terms can affect ~~the~~ mathematical and numerical analysis (?) of these systems, due to several discontinuities and loss of regularity in the solution, increasing complexity of efficient calculation of numerical solution.

The system of partial differential equations that model tsunami waves is a non-linear systems of conservation laws on two space dimensions. In this case, it can not be derived analytical solutions and it is mandatory to use numerical simulations to find approximate solutions. The discretization of the differential equation is implemented using highly specific and developed tools such as *ClawPack* [Clawpack Development Team(2017)], specifically *GeoClaw* (from University of Washington) and $STAV-2D$ [Canelas et al.(2012)Canelas, Ferreira, and Conde] (from Technical University of Lisbon).

Aim?

This work is ~~develops~~ developed as a case study of the tsunami model on the Pacific Ocean generated by the eathquake of 1979 with special interest in its effects over the mu-

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coast (?) led to on

nicipality of Tumaco (Nariño, Colombia), currently the second most important port of Colombia on the Pacific Ocean. The coast on the Pacific ocean in South America is exposed to the impact of near and far source tsunamis. In the recent history, ~~in~~ Colombia's case has been presented two major events that generated important tsunamis, those ~~in~~ 1906 and 1979. The last event ~~had some direct~~ reports ~~about~~ damages and other physical data of the earthquake ([Caicedo O. et al.(1996)Caicedo O., Martinelli, Meyer, and Reyna [Quiceno and Ortiz(2001)] and [Peralta et al.(2003)Peralta, Arellano, Leusson, and Quiñones]).

PE SC

The inundation model by tsunami is considered in this work as separate model in order to show the specific conditions in the area of interest. In the same way, the local effects of coast shape and geological characteristics (mainly presence of sediments) may affect the local inundation (run-up).

2 Conceptual model

FIRSTLY

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The mathematical simulation of tsunamis can advert most importants geophysical characteristics of waves propagation caused by a submarine earthquake and run-up (local inundation) over specifics coast zones, in order to establish realistic risk scenarios and consequently, design preventions or evacuations plans. This work will present two ~~sides~~: first, the mathematical modelling considerations, such as the equation systems, discretization squemes and numerical methods, techniques to computational efficiency and results interpretation. Second, the study case with tidal characteristics of the Pacific ocean, specific geomorphology conditions of the bay of Tumaco, Colombia, the earthquake of 1979 and the reports of affectation at that time. The tsunami modelling process is presented in Figure (1).

PARTS

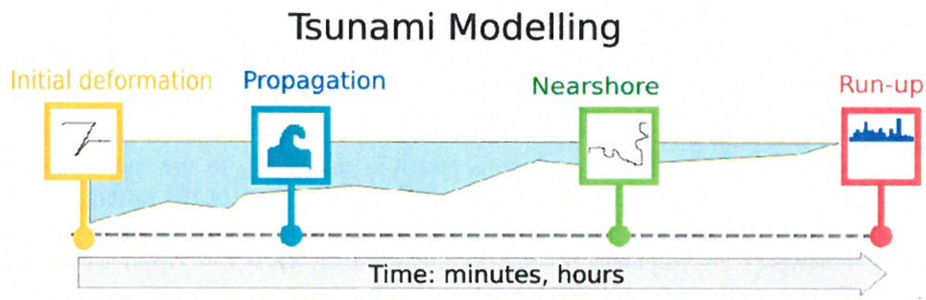

Fig. 1 General squeme in tsunami modelling

As a first step, the initial deformation is generated using the model proposed by Okada [Okada(1992)], where vertical component of the displacement in the surface is determined, getting the elastic dislocation model that show the seafloor deformation ~~by effect of this~~ seismic movement. This model use general characteristics of

DUE TO BY

fault plane, as location, dimensions, rupture angles and dislocation, generating a displacement of the body of water, starting the propagation. The mathematical simulation in propagation and run-up model is based in the Conservation Laws, because the amount of flow within the volume is conserved due to net effect of some intern sources. This amount is called flow and its expression is the result of mechanical and thermodinamical properties of the flow. The dynamics of the fluid is defined by the quantities of mass, momentum and energy. In general, ~~way a~~ conservation laws could be written,

SENTENCE IS NOT CLEAR!

$$\frac{\partial u(xt)}{\partial t} + \frac{\partial f(u(xt))}{\partial x} = 0,$$

where, u is a vector of conserved quantities (mass, momentum, energy) and the function $f(u)$ is called *flux function* to conservation laws system. See [LeVeque(1992)].

The system of conservation laws in two dimensions is presented as

$$u_t + f(u)_x + g(u)_y = 0.$$

Generally flow functions f and g are not linear functions of u. In this case, we can not derive exact solutions to this equation and hence it becomes necessary to use numeric methods to find approximate solutions.

In deep waters, during propagation the high of the wave increase several centimeters let show characteristics such as momentum, depths, speed and travel times. As the wave train approaches the coast, the height of the waves grows and its speed decreases facing geomorphological conditions as presence of sediments, small islands, cays and coast shape, so the flow is redirect in unpredictable ways. It is important notice that the ocean its huge, so the computational domain also, for that it is necessary to consider some alternatives that reduce the calculation complexity such as the use of different levels of geographical resolution.

SC/PE

Later, the run-up model must present numerical modelling as a oriented results to the authorities, since it allows the identification of safe areas where populations at risk can perform evacuations or get shelter. On the other hand, they warn of times of arrival and probable heights so that the authorities themselves can appropriately train communities, carry out territorial planning, develop early warning systems with the aim of reducing the impact of the disaster.

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3 Propagation and run-up models

The shallow waters equation system could presents most important elements in tsunami propagation. This system could be derivated of Navier-Stokes model and the mass and momentum conservation, presented in 2-D in a general way,

$$\frac{\partial U}{\partial t}+\frac{\partial}{\partial x}(M+M_d)+\frac{\partial}{\partial y}(N+N_d)=H \qquad (1)$$

are s

where U ~~is~~ variable vector, M, M_d, N and N_d are vectors of convective and diffusive flows in x and y directions respectively. H is friction vector and source term. It should be noted that these equations do not consider terms of dispersion of the Coriolis effect. The vectorial expressions U, M and N are:

$$U=\begin{bmatrix}h\\hu\\hv\end{bmatrix}\quad M=\begin{bmatrix}hu\\hu^2+\frac{gh^2}{2}\\huv\end{bmatrix}\quad N=\begin{bmatrix}hv\\huv\\hv^2+\frac{gh^2}{2}\end{bmatrix} \qquad (2)$$

where h is water depth, u and v the average speeds (over depth and time in turbulent flows) and g is the acceleration of the gravity. The corresponding expressions for diffusive flows M and N can be written:

$$M_d=\begin{bmatrix}0\\-\varepsilon h\frac{\partial u}{\partial x}\\-\varepsilon h\frac{\partial v}{\partial x}\end{bmatrix}\quad N_d=\begin{bmatrix}0\\-\varepsilon h\frac{\partial u}{\partial y}\\-\varepsilon h\frac{\partial v}{\partial y}\end{bmatrix} \qquad (3)$$

where ε is the kinetic viscosity coefficient. H is:

$$H=\begin{bmatrix}0\\gh(S_{ox}-S_{fx})\\gh(S_{oy}-S_{fy})\end{bmatrix} \qquad (4)$$

and S_{ox}, S_{oy} are the slopes of the seabed in the Cartesian directions. S_{fx}, S_{fy} are the friction of the seafloor, usually represented by ~~means of~~ empirical formulas. The most relevant considerations of the system are presented in Figure (2).

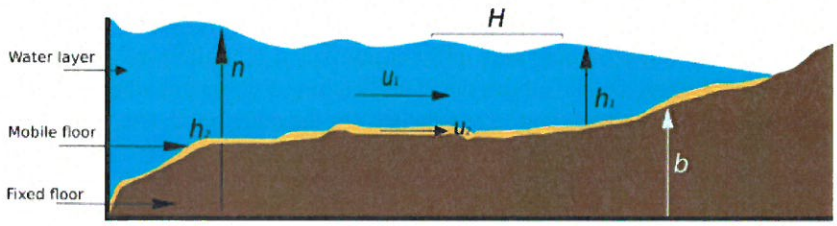

Fig. 2 General squeme Shallow waters with multiple layers

η does not appear in Fig 2!..

Where H is the wavelength, b is the depth of the seafloor, h the height of the body of water, η equal to $h+b$ and u the flow.

But wasn't "H the friction vector & source term"? Try to use diff symbols for diff quantities!

PE|SC

In our case, the problem of propagation nearshore presents more elements in consideration, particularly as multi-layer model where the water layer is presented h_1 such as the height of ~~the~~ body of water and u_1 the average flow in direction x_i. In the layer of mobil floor h_2 ~~such~~ as the height of the body of sediments and u_2 ~~the average flow~~ in x_i. In this case, the terms S_{ox}, S_{oy} and S_{fx}, S_{fy} ~~of the~~ Equation 4 indicate the normal flow between the seafloor and ~~the fluid column~~, the application of the Reynolds Transport Theorem to the total mass and momentum equations with sediment transport flow and deposited on the seabed, according to [Canelas et al.(2012)Canelas, Ferreira, and Conde] and [Canelas et al.(2013)Canelas, Murillo, and Ferreira] are:

a bit confusing Sox, Soy, Sfx, Sfy

mobile?

$$\partial_t h + \partial_x(hu) + \partial_y(hv) = -\partial_t b, \tag{5}$$

$$\partial_t(uh) + \partial_x(u^2h + \frac{1}{2}gh^2) + \partial_y(uvh) = -gh\partial_x b - \frac{1}{\rho_m}\partial_x hT_{xx} - \frac{1}{\rho_m}\partial_y hT_{xy} - \frac{\tau_{b,x}}{\rho_m}, \tag{6}$$

$$\partial_t(vh) + \partial_x(vuh) + \partial_y(v^2h + \frac{1}{2}gh^2) = -gh\partial_y b - \frac{1}{\rho_m}\partial_x hT_{yx} - \frac{1}{\rho_m}\partial_y hT_{yy} - \frac{\tau_{b,y}}{\rho_m}, \tag{7}$$

$$\partial_t(C_m h) + \partial_x(C_m hu) + \partial_y(C_m hv) = -(1-p)\frac{\partial b}{\partial t}, \tag{8}$$

?

$$\frac{\partial b}{\partial t} = \frac{q_s - q_s^*}{\wedge}(1-p)^{-1}, \tag{9}$$

where x and y are 2D coordenates, t is the time, h is height of the fluid, u and v are the average speeds, ρ_m is the density, C_m is the concentration, $\tau_{b,xi}$ is the slope of the bottom in direction x or y, T_{ij} the average depth of the turbulence. The term $\frac{\partial b}{\partial t}$ describes the morphology of the seabed, in detail, q_s is the discharge of solids, q_s^* ~~value of the capacity of~~q_s and $\wedge$ expresses integration in the time of net mass flow, indicated as volume per unit area.

??

For the momentum equations 6 and 7, according to [Conde et al.(2013)Conde, Baptista, Oliveira, and Ferreira] the following terms constitute the flow resistance, which are given by the slopes of the seabed:

$$\tau_b = C_f|u|^2\rho_m, \tag{10}$$

already defined

where ρ_m is the average flow density, C_f the coefficient of friction ~~described~~ for the case of debris flow by the derivative and T_{ij} the turbulence tensor [Ferreira et al.(2009)Ferreira, Franca, Leal, a described by

$$T_{ij} = \rho_w \nu_T \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{11}$$

where ρ_w is the density of water and ν_T is the viscosity of the turbulence. The discharge of the seabed is

$$q_s^* = C_c^* |u_c|^2 h_c, \tag{12}$$

where C_c^* is the average concentration of the layer, u_c the speed in the layer and h_c the thickness of the layer. See details [Canelas et al.(2013)Canelas, Murillo, and Ferreira].

3.1 Finite volume method

The idea of this method is based in divide the domain in intervals know as finite volume or cells, tracking an approximate solution of an integral on each of the cells. This values are an approximation of average value over an interval in a specific time.

A numeric solution of finite volume is a constant function to pieces Q_i^n that approximates the average value of the solution $q(x,t^n)$ in each cell of the grid $C_i = [x_{i-\frac{1}{2}}, x_{i+\frac{1}{2}}]$. A Finite volume method update the solution by the numerical difference of the fluxes in the cell boundary [Godunov(1959)]:

$$Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x}[F_{i+\frac{1}{2}}^n - F_{i-\frac{1}{2}}^n], \tag{13}$$

where

$$F_{i-\frac{1}{2}}^n \approx \frac{1}{\Delta t}\int_{t_n}^{t_{n+1}} f(q(x_{i-\frac{1}{2}},t))dt, \tag{14}$$

$F^n_{i+1/2}$?

and

$$Q_i^n \approx \frac{1}{\Delta t}\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} q(x,t^n)dx, \tag{15}$$

where it is assumed that the cells have fixed length Δx. and that the expression Q_i^{n+1} is a discrete representation of the Conservation Law in integral form [George and LeVeque(2006)] over each cell in the grid, obviating the source terms and using approximations in the averaged times of the flows at the borders. The essential properties of the finite volumen methods come from the approximation of the numerical fluxes $F_{i-\frac{1}{2}}^n$.

Some elements to take into account during the process of discretization in wave propagation, are the boundary conditions which are determined in each time step by the filling of adjacent cells; the Riemman problem is a problem of initial values that consist in a hyperbolic equation with a pieces constant. The solution to this problem generates a set of waves traveling at finite speeds. In the finite volume method these calculated waves and their velocities can be used to approximate a solution and update it in the next time step. Finally the ghost cells consists of incorporating two rows of artificial cells at the edges of the computational domain. The values of these cells are assigned at the beginning of each time step by copying the data from another side in the domain, until each edge is adjacent to another after executing.

What's the relationship of Riemmann problem w previous sentence?

Adaptative Mesh Refinement - AMR

The AMR algorithm to Conservation Laws, according to [Berger and LeVeque(1998)] uses a rectangular mesh that represents the study domain. The refinement is done on a subset of this domain and uses a rectangular mesh with smaller cells, which can be recursively nested until a level of accuracy is obtained. Generally, if a cell in the L level is detailed in x and y by integer pair R_L, then the time step is also redefined by the same factor, thus the time step R_L is taken on the refined mesh at the level $L+1$ for each cycle on the meshes at the L level. The radius of mesh $\Delta t/\Delta x$ and $\Delta t/\Delta y$ are the same for all meshes ensuring stability. Figure 3 show the refinement of the mesh according to the region of wave affectation. ??

At each time step, the error estimate based on the Richardson's extrapolation determines the region where the resolution of the solution is insufficient. The cells where the error is greater than the tolerance are marked for refinement and the area near these cells is also marked so that the characteristics of this region are considered in the next step of time. The boundary conditions for all cells are assigned using phantom cells, extending the computational domain in G cells for each direction. Applied to wave propagation, algorithms are used directly to update cell values and is particularly important in the proximity to the coasts, which is where the run-up process takes place.

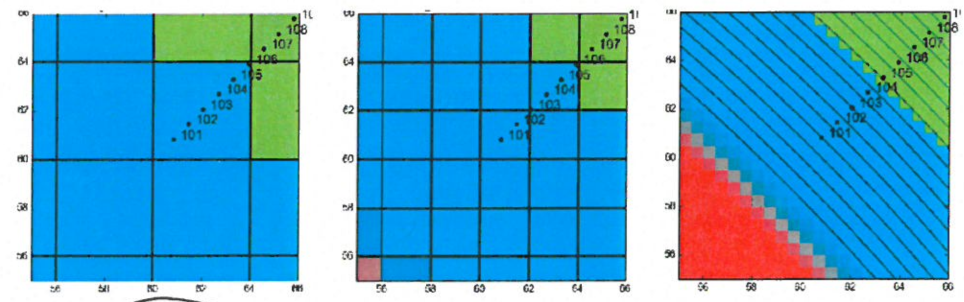

Fig. 3 Comportamiento AMR paso de tiempo n. Generado con GeoClaw.

Spanish

4 Characteristcs of Tumaco bay, Colombia

The Colombian Pacific is one of the most rainy areas in the world, characterized by the existence of multiple bodies of water that flow into the Pacific Ocean. In addition, the difference in tidal heights in this region varies between 2 and 4 meters everyday, which is called low tide and high tide. Especially the region of Tumaco, in the department of Nariño, has extensive rivers that flow into the bay of Tumaco.

it

Due to the intense rainfall, as well as the existence of large rainforest territories, bodies of water carry large amounts of sediment and solid material such as logs and vegetation. In [IGAC(2007)], is described the composition of the sandbanks from the area of El Faro de Tumaco to the islands of Tumaco and El Morro.

SC?

Tumaco is a population located on the Pacific coast in the department of Nariño, near the Ecuadorian border. Composed mainly by two islands called Tumaco and El Morro. In ~~the~~ Figure 4, it can be observed the differents islands and water bodies, as well as sandbanks or sediments observed mainly during periods of low sea.

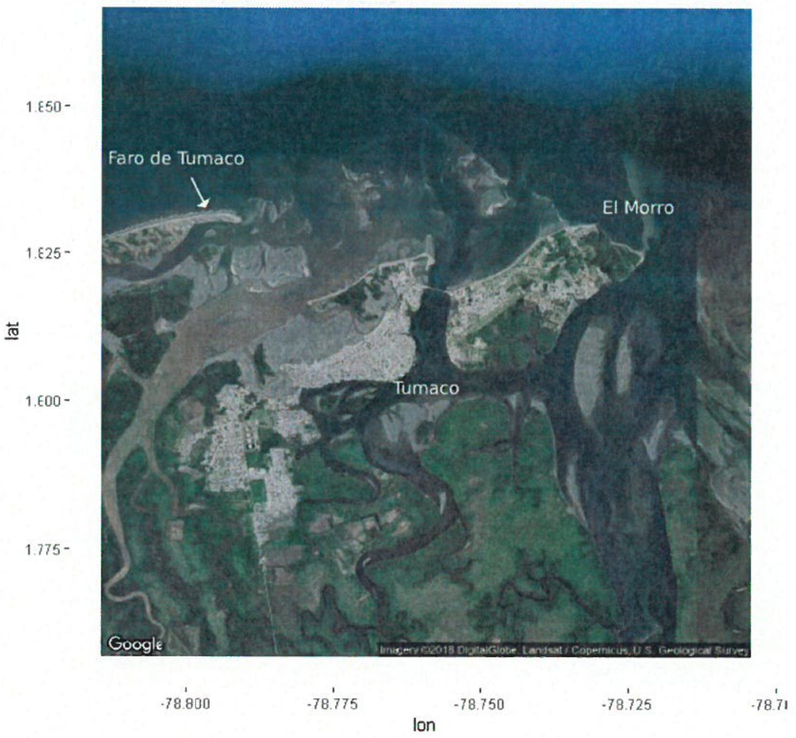

Fig. 4 Satellite image of Tumaco and El morro Islands. Coast of Nariño, Colombia. Credits: http://maps.google.com

5 Tsunami modelling stages

In the case of Tumaco, the impact of the sediments in the geomorphology of the bay is remarkable. Thus, it will be considered two cases in run-up step.

5.1 Initial deformation

The initial disturbance for the Tumaco model was the earthquake occurred in December 12, 1979 in low tide at the confluence of the Nazca and Suramericana plates, located approximately 120 km from the coast of Colombia. The parameters used in accordance with [Caicedo O. et al.(1996)Caicedo O., Martinelli, Meyer, and Reyna M.], are detailed in Table 1. This event was an earthquake with an epicenter at Latitude 3.2 degrees North and Longitude 79.6 degrees West. According to Okada's *GeoClaw* deformation model, an event with Moment Magnitude $M_w = 8,218$ is calculated. Figure 5 shows the initial deformation for three fault segments, the red star show the city of Tumaco and bathymetry - topography mode shows 30 seconds resolution of GEBCO [(IOC) and (IHO)(2015)].

Table 1 Earthquake Tumaco 1979 - Generation parameters

	North Segment	Center Segment	South Segment
Latitude	3.5 N	2.8 N	2.3 N
Longitude	79.28 W	79.7 W	80.01 W
Width	100 Km	100 Km	100 Km
Length	120 Km	64 Km	56 Km
Depth	0.5 Km	0.5 Km	0.5 Km
Strike	31g	31g	31g
Slip	1 m	5.9 m	1.75 m
Rake	90g	90g	90g
Dip	20	20	20

The local effects of the coast form give the conditions for the generation of shocks. The local inundation, can be affected by several elements, mainly by the effect of the bathymetry. However, for very specific geographical areas it is important to note other geological and coastal features that may be of interest for this study.

5.2 Propagation of waves in finite volumes

Taking as reference the first expression in 2D, written compactly:

$$\frac{\partial}{\partial t}q + \frac{\partial}{\partial x}f^1(q) + \frac{\partial}{\partial y}f^2(q) = \psi(q,x,y), \tag{16}$$

where

$$q = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \tag{17}$$

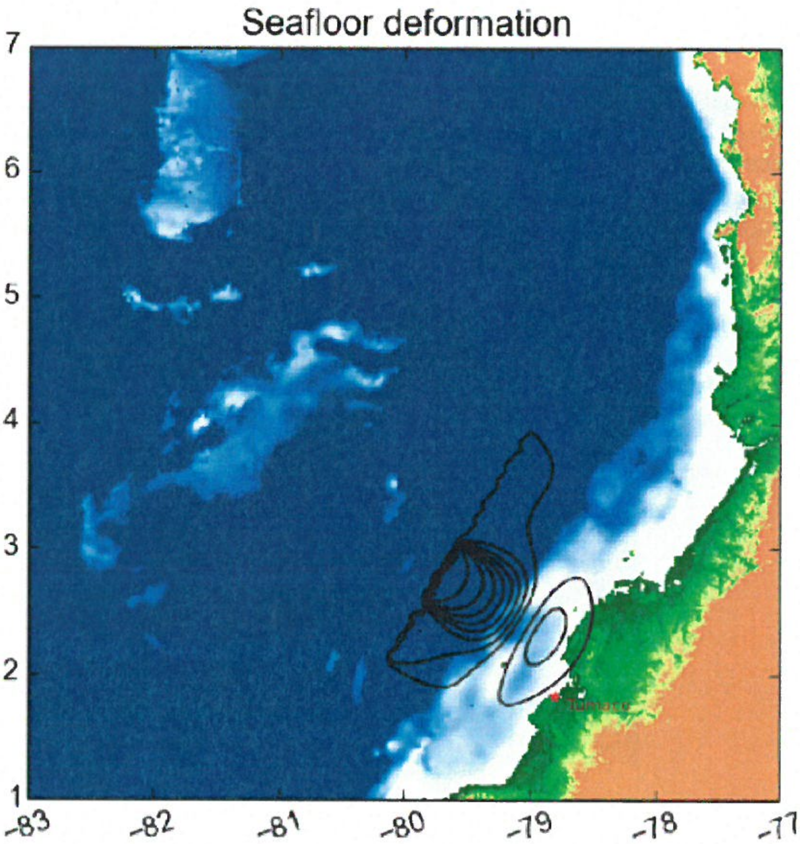

Fig. 5 bathymetry and topography Pacific ocean - GEBCO. Initial deformation $M_w = 8.218$. Axis X and Y is Longitude and Latitude.

Is H from Eq 4 ? or the wave length ?

and $f^1(q)$, $f^2(q)$ are the fluxes of q in directions x and y respectively, and $\psi(q,x,y)$ is a source term. From the point of view of the numerical method, the solution of Q^1_{ij} is an approximation to the average value of the solution of $q(x,y,t^n)$ in the cell:

$$Q^n_{ij} = \begin{bmatrix} H^n_{ij} \\ HU^n_{ij} \\ HV^n_{ij} \end{bmatrix} \approx \frac{1}{\lambda(C_{ij})} \int_{Cij} q(x,y,t^n)dxdy, \tag{18}$$

with rectangular cell C_{ij} and where λC_{ij} is the area in that cell. In the interface between C_{ij} and $C_{i-1,j}$ at time t^n.

SC ?
Sentence is incomplete!

For the development of the numerical model in propagation phase, is used the software *GeoClaw* which applied the high resolution algorithm for propagation waves of Leveque [Clawpack Development Team(2017)]: using the local solution of the problem of Riemman and updating the numeric solution at each step of time.

It's not clear what Cij stands for!

how does this algorithm work?

Using the Godunov scheme to solve Riemman using approximations, *GeoClaw* presents a numerically stable solution for high resolution conditions and computationally efficient with the use of adaptive refinement, allowing the generation of highly reliable results for tsunami propagation scenarios. The run-up, uses an absorbent boundary condition. A preliminary result of the propagation to the minute 15 after the earthquake is generated is in Figure 6.

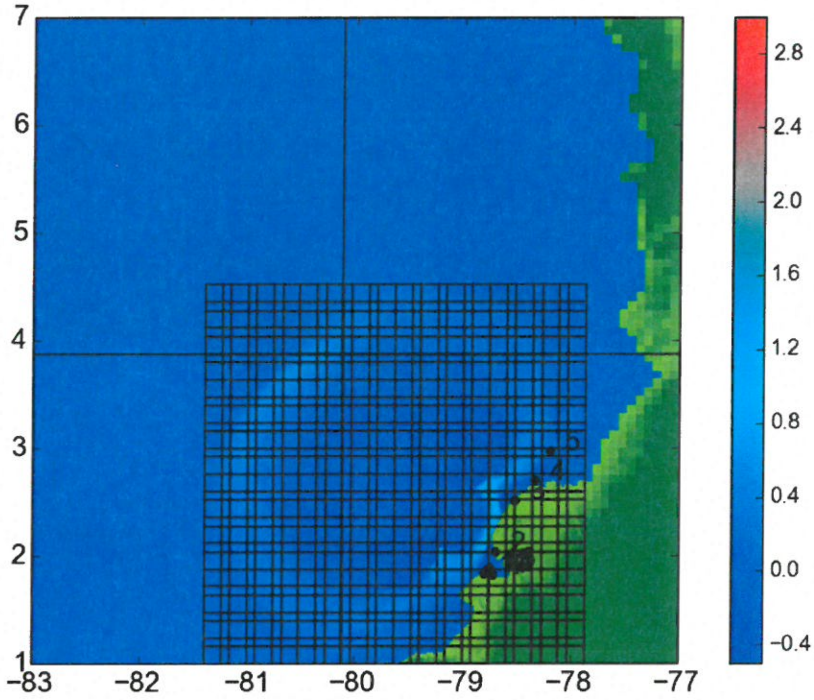

Fig. 6 Wave heights: Propagation of tsunami in Colombian's Pacific, Minute 15. Axis *X* and *Y* are Longitude and Latitude; the maximum heights (*Z*) in meters

5.3 Run-up models

In order to observe the local effects of tsunami in Tumaco, it is used bathymetry with resolution of 50 meters [Caicedo O. et al.(1996)Caicedo O., Martinelli, Meyer, and Reyna M.], which is showed in Figure 7.

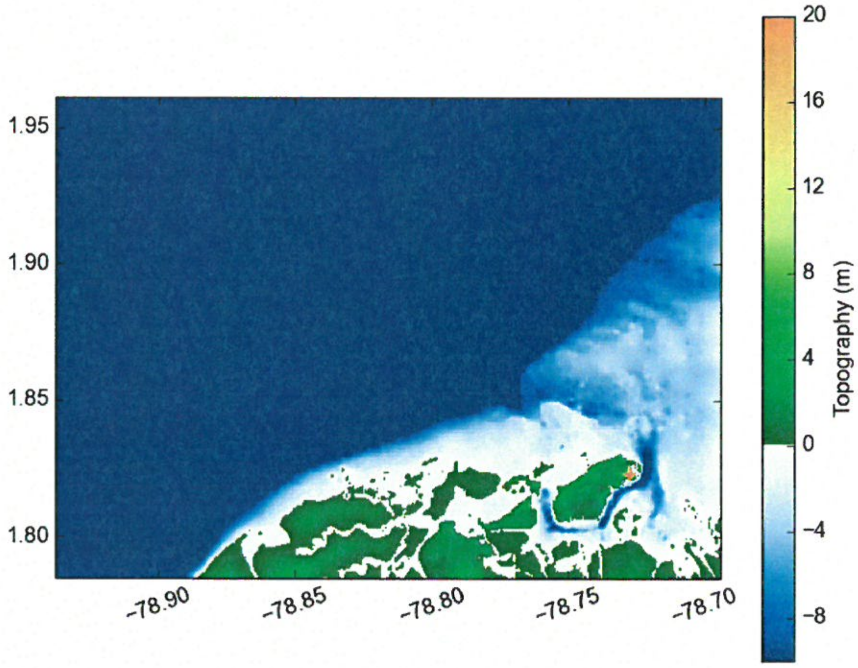

Fig. 7 Bathymetry and topography Tumaco bay. Axis X and Y is Longitude and Latitude

GeoCLAW

The problem of flooding refers to the case where h_{i-1} or hi is zero, or a dry state appears in a Riemman solution for t greater than zero. According to [George(2010)], given the difficulty of solving the Riemman problem accurately, Godunov schemes often make use of resolution methods developed for specific applications. Modeling inundation on highly variable topographies presents several complications, mainly due to the source terms. In realistic cases, it is very important to know the accurate inundation scenarios and where the Riemman problem actually reaches the coasts. This last source can be considered as a leap in topography, given as,

B? i,j?

$$[[B]] = B_{i,j} - Bi - 1, j, \tag{19}$$

in the same position for conserved variables. This results in a step in the flows for the time step:

$$f^1(Q^{n^+}_{i-1/2,j}(0^-)) \neq f^1(Q^{n^+}_{i-1/2,j}(0^+)), \tag{20}$$

not really clear!

which contributes to the effect of the final source. It has been seen that the source terms complicate the solution to the Riemman problem, one way to remedy this is to use the homogeneous equations and operate the effect of the source ~~soures~~ in a different time step. In general, this works well for most applications, but can cause serious errors in various situation. —> why?

SC/PÉ

In run-up models, a computational domain must contain wet cells ($H_{ij}^{n} > 0$) and dry cells ($H_{ij}^{n} = 0$), without specific reference in the numerical method to the movement of each other, simply where the wet cells are adjacent to the dry cells at any time step, carefully considering the Riemman problems for each.

Local inundation model is processing in GeoClaw...... ?? Sentence is incomplete!

STAV-2D

In a multi-layer model with a mobile layer (sediments), the fluxes for updating the conserved variables is calculated according to [Murillo and García-Navarro(2010)] and [Conde et al.(2013)Conde, Baptista, Oliveira, and Ferreira], thus

Si? h^{***}? ⊖? ΔE? T?

??

$$\begin{aligned} Si\,h_j^n = 0\,y\,h_j^{***} < 0\,then\,(\Delta E - T)_{ik}^{-} = (\Delta E - T)_k\,and\,(\Delta E - T)_{jk}^{-} = 0 \\ Si\,h_i^n = 0\,y\,h_i^{*} < 0\,then\,(\Delta E - T)_{jk}^{-} = (\Delta E - T)_k\,and\,(\Delta E - T)_{ik}^{-} = 0, \end{aligned} \tag{21}$$

In other case, the update is done over

$$\partial_t(U(V)) + \partial_x(F(U)) + \partial_y(G(U)) = H(U) \tag{22}$$

This restriction prevents the appearance of negative fluxes, assigning zero values in cells where the intermediate steps predict negative depth flows. In areas where h approaches zero, terms such as $u = uh = h$ generate possible errors, the speed is obtained with the formula,

$$u = \frac{uh\sqrt{2}h}{\sqrt{h^4 + max(h^4, \varepsilon)}}\,; \varepsilon = h_{min} max(1, \sqrt{2A}) \tag{23}$$

where h_{min} is a parametric mesh and A is the cell area.

The STAV-2D application implements in two dimensions an approximation of surface flows over complex boundaries and oceanic seabed. As discretization techniques it is based on the flow division vector scheme, incorporating a revised version of the Roe-Riemman solver [Canelas et al.(2013)Canelas, Murillo, and Ferreira], preserving the characteristics of the conservation equations in the sedimentary and water layers. STAV-2D specializes in modeling the effect of propagation on sedimentary valleys. For the case of several real scearios, such as the river beds or mouths of bodies of water on the sea, the soil is not a consistent surface, which causes that during the turbulence of the water, product of shocks like tsunami waves, additional effects of friction, fluid change, and the possible dragging of other mate-

PÉ/SC

rials are generated, modifying in some cases, the expected behavior of other models that do not consider these aspects. A preliminary result of the flood at the 43 minute after the earthquake was generated is in Figure 8

Discussão??

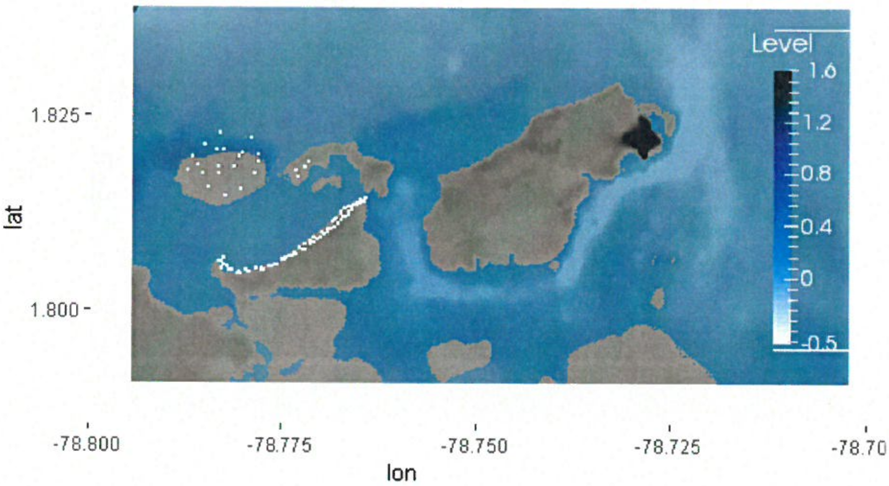

Fig. 8 Depths of the flow. Minute 43. STAV-2D. Tumaco's bay. Highs (z) in meters.

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