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Numerical Modeling of a Landslide-Generated Tsunami Following a Potential Explosion of the Montserrat Volcano

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Abstract. The explosion of the Montserrat volcano (Caribbean Sea) could trigger a major landslide and lead to the generation of a tsunami in the Caribbean Sea. In the worst case scenario, the volume of material reaching the sea has been estimated at 80 millions of cubic meters. The sliding of this mass and the generation of the associated tsunami have been simulated numerically, assuming that the debris behave like a heavy fluid flowing into the sea. The numerical model solves the 3D Navier-Stokes equations for a mixture composed of rocks and water. The generated water waves is then propagated around the coast of Montserrat by means of a shallow water model. The numerical results show that the water heights above sea level are higher than 5 meters within a radius of 5 km of the source.

1. Introduction

Tsunamis are large water waves set in motion either by landslides, submarine volcanic explosions, or sea-bottom deformations associated with large submarine earthquakes. Tsunamis generated by collapses of the volcano edifice are scarce but generally more destructive than tsunamis of tectonic origin. The 1883 eruption of Krakatau (Indonesia) was one of the worst disasters. Similar disastrous events were the tsunami associated with the collapse of the Unzen volcano (Japan) in 1792 and the tsunamis following the collapse of the Santorin volcano (Greece) in 1620 BC. The 1883 tsunami in Indonesia seems to have been triggered by the collapse of half of the volcanic cone into the sea, in a giant avalanche similar to that at Mt. St. Helens in 1980 (Francis P., 1993). Several hundred kilometers of the coastlines in the Sunda Strait between Java and Sumatra were devastated by the tsunami (Nomanbhoy, N. and K. Satake, 1995). The tsunami with wave heights of 15 meters at the shoreline, killed more than 35,000 people. In 1792, an earthquake-triggered collapse of a dome on Unzen volcano, Japan, created an avalanche with a volume of 300 millions of m^3 (Francis, P., 1993). The resulting tsunami, with inundation heights of 6 to 10 meters at the shoreline, killed 15,000 people along the Shimabara Peninsula coastline and in the Ariake Sea. In 1620 BC, a catastrophic volcanic eruption took place on Thera, forming a spectacular caldera. At the same time, tsunamis ravaged coastal towns in the Aegean Sea and in the eastern Mediterranean Sea.

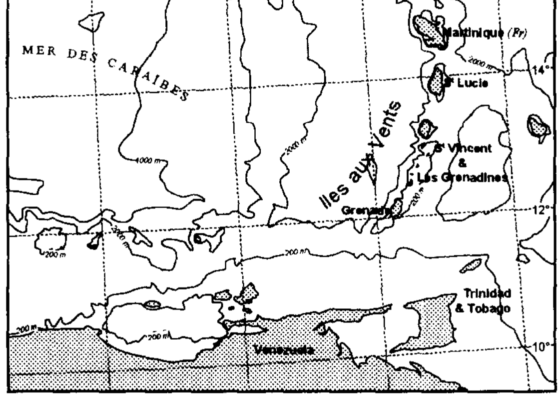

Fig.1. Map of the Caribbean Sea.

The eruption of Montserrat volcano (Figure 1) began in July 1995. The town of Plymouth (4000 inhabitants) is covered by ash and has been evacuated. A violent explosion of the Montserrat volcano might lead to major landslides and debris avalanches reaching the sea. The island

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of Montserrat belongs to the Antilles archipelago and is located 55 km north-west of Guadeloupe. In order not to increase the number of possible scenarios and taking into account the latest analysis, it has been selected a landslide of 80 millions of m^3 flowing down the Tar River valley located East of the volcano. This potential event may be considered as the worst-case scenario.

The objective of this paper is to simulate the hydraulic phenomena on the Montserrat coasts related to this subaerial landslide. First, the tsunami generation is calculated. Then, the generated water waves are propagated around Montserrat.

2. Numerical modeling of the subaerial landslide in Montserrat

The observation of subaerial landslides shows that a rocky mass as it slides down, behaves like a fluid : the materials deposit in fine and very long layers so that the base of the landslide is generally far away from the initial position. These observations account for the simulation of subaerial or submarine landslides by means of fluid mechanics models (Jiang and Leblond, 1993; Sousa and Voight, 1991). A three-dimensional Eulerian model solving the incompressible Navier-Stokes equations has been developed to study landslides on complex topography. The interaction of the debris flows with the sea is simulated by the same model, where water and the debris avalanches are considered as a mixture rather than two separate mediums. Thus, the problem consists in modeling the flow of only one fluid with variable density in time and space, as the solid -water interface are not to be dealt with. Details of the numerical techniques are described in the papers of Heinrich (1992) or Assier et al. (1997) concerning the simulation of two-dimensional submarine landslides. A rheology of the visco-plastic type has been introduced recently to model rockslides. For landslides of sedimentary types, diffusion of sediments in water can be also modeled.

The model used is based on the 3D hydrodynamics code of Torrey et al. (1987). The original code solves the Navier-Stokes 3D equations for an incompressible fluid with a water surface, using a finite difference method. The code is Eulerian and is used to calculate flows around fixed obstacles. The development of the mixture model has required re-writing the conservation equations of mass, momentum, mass transport and solving an additional diffusion equation which takes account of the concentration changes. The equations of this mixture model are written as follows :

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{v}) = 0 \qquad \text{(continuity equation)}$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}.\nabla \mathbf{v} = \mathbf{g} - \frac{\nabla p}{\rho} + \nabla.\boldsymbol{\tau} \qquad \text{(momentum equation)}$$

$$\frac{\partial F}{\partial t} + \nabla.F\mathbf{v} = 0 \qquad \text{(transport equation)}$$

$$\frac{\partial c}{\partial t} + \nabla.c\mathbf{v} = \nabla.\mathbf{J} \qquad \text{(diffusion equation)}$$

where **v** is the 3D fluid velocity vector of the mixture ; **g** is the gravity acceleration ; τ is the shear stress tensor ; c is the volume fraction of the sediment medium ; ρ is the mixture flow density ; F is the fractional volume of the cell occupied by the mixture and is used to calculate the interface water-air ; p is the pressure ; **J** is the diffusion flux. The volume fraction of the sediments c is normalized by the maximum solid packing. A unit value of c corresponds to a highly concentrated part of sediments and a 0 value of c indicates the water region. The modeling being eulerian, the resolution of the diffusion equation leads to the classical problem of numerical diffusion at the interface water-sediments. In order to suppress this numerical diffusion, a method has been developed based on a donor-acceptor technique. This technique is adapted from the one used by Torrey et al. (1987) for the convection of F. When no physical diffusion is calculated (J = 0), the convection of c from a donor cell to an empty downstream cell (c = 0) is carried out provided that the upstream donor cell is full (c = 1). This method allows one to follow the interface water-sediments without numerical diffusion.

For simplicity in this paper, the debris flows are treated as an homogeneous fluid of density 2 without rheology flowing down a frictionless slope and penetrating into water without diffusion. The bathymetry and topography have been also simplified : they are assumed to be uniform in the South-North direction, excepted for the Tar River valley that has been modeled by a U-shaped depression of 800 m wide orientated in the West-East direction. The flow of debris from the volcano to the sea has not been modeled. The debris are assumed to enter the sea at the initial instant with a 50 m high front impacting sea water with a velocity of 50 m/sec. The geometry of the slide and the topography are shown in Figure 2. The mean velocity of the debris flow (20m/sec) and the impact velocity of the front have been estimated from the observed and calculated velocities for the first Mt. St. Helens rockslide avalanche of 1980 (Sousa and Voight, 1995).

The 3D computational domain extends over 8 km from West to East and over 10 km from South to North (Figure 2).The maximum depth is 750 m. The mesh consists of 100x80 cells in the horizontal directions and 60 cells in the vertical direction. The minimum horizontal grid increment is 50 m in the area of the Tar River delta over an area of 2x2 km^2, the vertical grid increment is 5 m at the water surface and increases progressively upward and down to the bottom.

The numerical simulations show that the average velocity of the debris flows increases progressively from 20 m/sec at the initial instant to 30 m/sec one minute after the impact. The computed water surfaces are represented at instants 20 and 60 seconds after the impact (Figure 3). At 20 seconds, the water surface is composed of only one positive wave with an amplitude of 25 meters located at 1 km from the shoreline. At 60 seconds and due to geometrical dispersion, the maximum height of this crest is 15 meters at 2 km from the shore. It is followed by a trough of

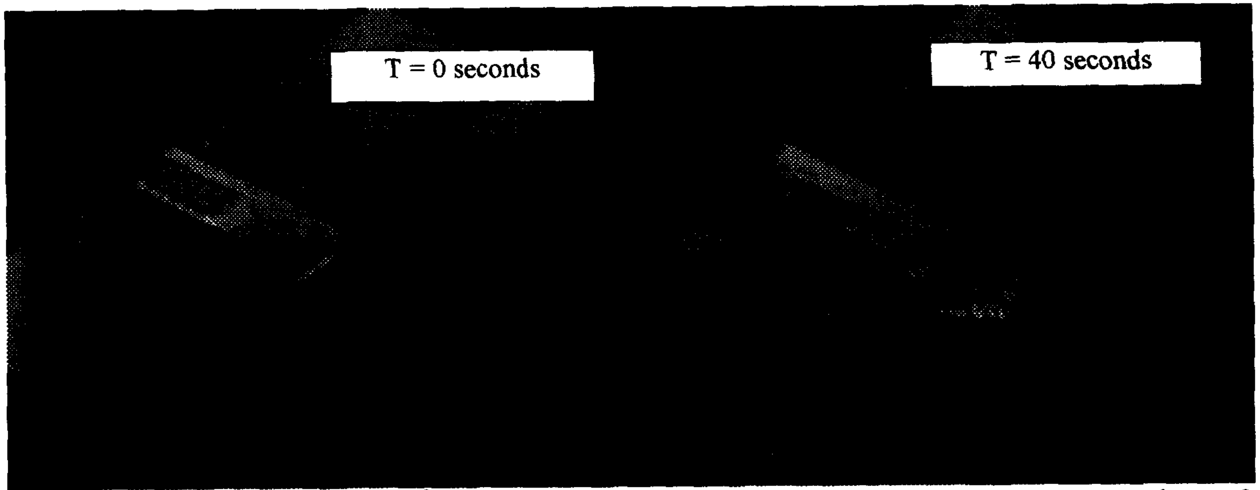

Fig. 2. Numerical simulation of a 80 millions m^3 subaerial landslide solving 3D Navier-Stokes equations for the sediments and water. Only the bathymetry and the sediments are represented on this figure. The debris flow down a U-shaped, West-East orientated valley of 800m wide. The computational domain extends over 8 km from West to East and 10 km from South to North. The vertical scale has been exaggerated.

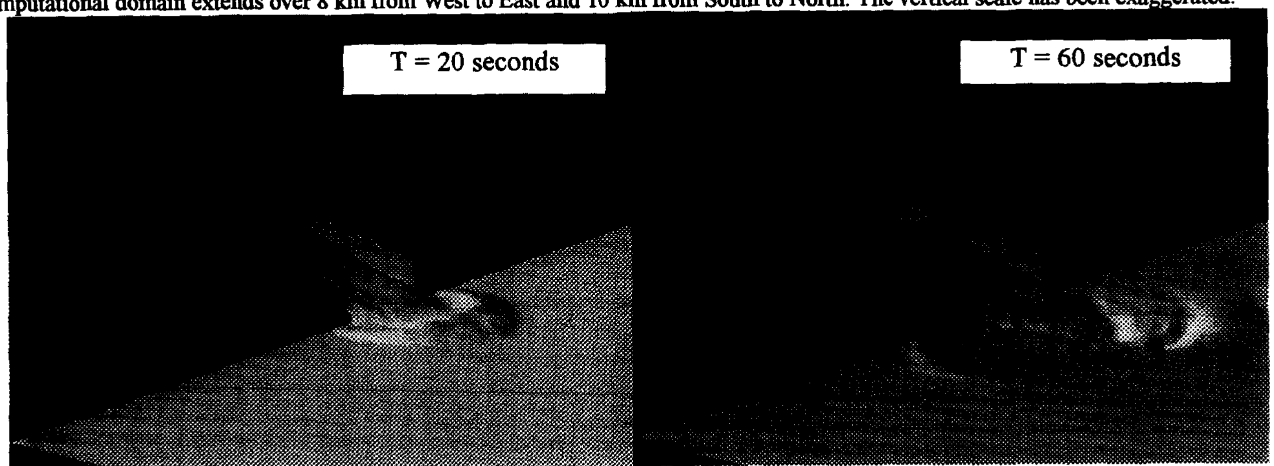

Fig. 3. Same simulation as in Figure 2. Computed water waves 20 and 60 seconds after the impact of sediments into the sea.

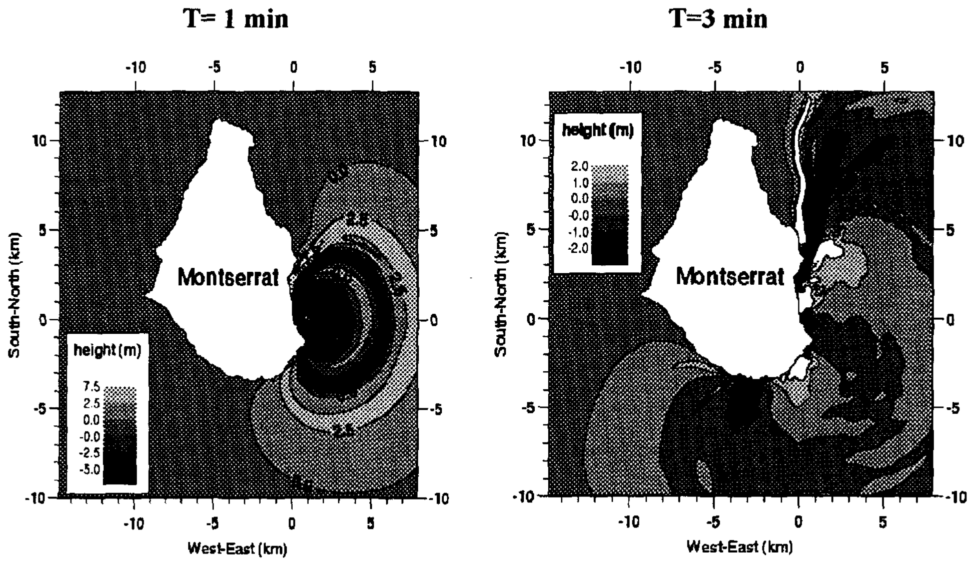

Fig. 4. Computed water waves 1 and 3 minutes after the wave generation. The grid increment is 100 meters. These maps have been calculated by a shallow water model for a landslide of 80 millions of m^3 flowing down the Tar River valley.

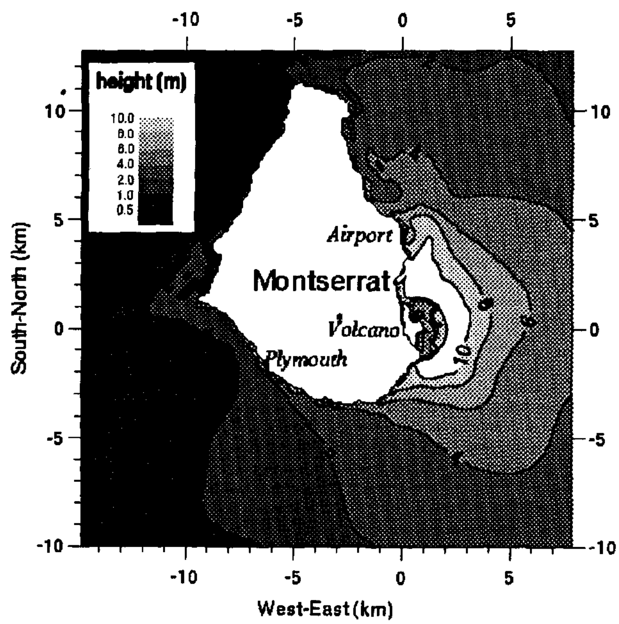

Fig. 5. Maximum computed water surface elevation reached during the tsunami propagation. The volcano is indicated by a star, the landslide is assumed to flow down Eastwards.

20 meters located 1 km from the shore. Later, the amplitudes of the following crests and troughs are smaller than a few meters. Most of the wave energy propagates in the open sea in a perpendicular direction to the slide. The period of the main wave, of about 2 minutes, is related to the landslide duration. This wave may be classified between the swell with maximum periods of 20 seconds and the tsunamis of tectonic origin, with periods ranging from 15 to 60 minutes.

3. Propagation of the tsunami along Montserrat coasts

Along the coasts of Montserrat, water depths are small compared to the wave lengths and rather short distances have to be covered. These two factors make frequency dispersion negligible. The shallow water model, taking into account significant non-linearities, is valid and has been used to simulate the propagation along Montserrat coasts. The equations are solved by a finite difference method, using an upwind scheme, iterative in time to limit the numerical oscillations due to non-linearities (Guibourg et al., 1997).

The model is initialized by interpolating, in the new domain, the water surface and the velocities originating from the generation model. Previously, the 3D velocity vectors field has been depth-averaged. The instant of this initialization has been selected 50 seconds after the impact of debris into water. Initializations at 40 and 60 seconds give similar results, showing that most of the energy has been transferred from the landslides to water waves approximately 40 seconds after the impact. The computed domain extends over 25 x25 km^2 with a grid space step of 100 meters. The topography close to the shore being not at our disposal, coastal inundation has not been simulated and complete reflection is computed at the shoreline. It has to be pointed out that the inundation heights are probably slightly larger than the calculated water heights close to the shoreline.

The water surfaces after a propagation time of 1 and 3 minutes are shown on Figure 4. The maximum water surface elevation reached during the tsunami propagation is shown in Figure 5. The generation area is affected by waves of 15 meters within a radius of 2 km centered at the Tar River mouth. The coastal area located within 5 km of the source is affected by waves higher than 5 meters. The airport is reached 3 minutes after the impact by a wave of 7 meters. The maximum sea level in the Plymouth area ranges from 2 to 3 meters. At the opposite of the source, the north-west coast is reached within 10 minutes by waves with amplitudes smaller than one meter.

4. Propagation of the tsunami in the Caribbean Sea

The islands closest to the East of Montserrat are Guadeloupe at 55 km to the SE and Antigua at 45 km to the NE of the source (Figure 1). The submarine slopes of the Caribbean islands are steep, so that local amplification of wave heights on the coasts is small. The other islands in the Caribbean Sea may be then considered as safe because of geometrical dispersion (the waves amplitudes decrease as a function of $1/\sqrt{r}$ where r is the radial distance from the source).

The maximum water depth between Montserrat and Guadeloupe or Antigua is about 1000 meters. Considering the wave lengths obtained in the second paragraph and the distance of propagation, the shallow water approximation is not any more valid. The initial wave length is approximately of the same order of magnitude as the depth, the initial wave hence swiftly disperses into a series of waves of various frequencies. Due to frequency dispersion, the amplitude of these short waves decrease as a function of 1/r (Murty, 1977). From this law and the results of the second paragraph, it can be calculated that wave heights off Guadeloupe or Antigua are about 50 cm. Considering the steep submarine slopes, it can be assessed that the maximum wave heights along these coasts probably do not exceed 2 meters above sea-level.

5. Conclusion

The tsunami generated by a potential major landslide on Montserrat has been simulated numerically. From this study, it can be inferred that only the South coast of Montserrat in the source area seems to be threatened by the hydraulic effects generated by a landslide of 80 millions of m^3.

The originality of this paper is to show a methodology for the study of such events. The results presented in this paper may be considered as preliminary, taking into account the simplifications of the landslide simulation. New simulations of the hydraulic source are planned to be carried out using a realistic topography and an accurate bathymetry in the source area. Furthermore, a Bingham model or a bi-viscous model based on the parameters of Sousa and Voight (1995) will be tested for the debris flows and the influence of friction will be studied.

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