XVIII^{èmes} Journées Nationales Génie Côtier – Génie Civil
Anglet, 2024
DOI:10.5150/jngcgc.2024.093 *© Editions Paralia CFL*
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Navier-Stokes simulation of landslide generated waves : methodological difficulties associated to real events

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Abstract:
This study outlines the numerical method applied for the computation of an actual event of tsunami generated by submarine landslide : the 1979 Mururoa oceanic atoll flank collapse as described in POUPARDIN *et al.,* (2017). The model (Multiphase InterFoam) solves the Navier-Stokes equations for three phases (slide, water, air) using the VOF method. This preliminary work aims at highlighting the methodological difficulties related to this type of computations. The main one is the mesh which has to adjust to a complex bathymetry, while being perfectly flat at the ocean surface and refined in specific areas (close to the free surface and along the slide path). On these aspects, we give the first recommendations based on our investigations using two different mesh generators. We also show encouraging preliminary results on the event itself.

Keywords:
Numerical modeling, Fluid mechanics models, OpenFOAM, Landslide, Tsunami generation, Water waves.

1. Introduction

Many tsunamis, consecutive or not to strong earthquakes, are generated or accentuated by the triggering of sub-aerial or submarine land collapses. This is the case of several historical tsunamis (Nice, 1564, 1979; Ligure Sea, 1887; Polynesia 1979; Papua, 1998; Java, 2012; Greenland, 2017; Anak Krakatau, 2018) that have impacted several kilometers of near or distant coasts. In this context, the scientific community faces the challenge of accurately simulating potential landslide tsunamis to estimate the inundation heights at the coast.

The objective of this work is to propose in a near future realistic and accurate 3D simulations of such events with a Navier-Stokes multiphase model. This implies solving a few difficulties which are actually not really reported in the literature simply because such studies are rare. Indeed, most of the time, Navier-Stokes simulations of waves generated by landslides are restricted to idealized configurations (e.g., ROMANO *et al.*, 2023, PARIS *et al.*, 2021). A few exceptions exist (ABADIE *et al.*, 2012 and 2020, RAUTER *et al.*, 2022), but they did not try to come up with a general procedure in order to ensure the accuracy of the results.

In the following, we tried to identify the difficulties related to such computations. Beyond the computational load which is significant, several bottlenecks can also be listed :

i) the mesh has to respect strong constraints (conformation to complex bathymetry/topography features and horizontality of the ocean surface).

ii) the choice of the slide rheological law (for a real case study the slide material may be more or less known).

iii) procedure for transferring the results from the 3D simulations into a 2D depth-averaged "tsunami" code as initial or boundary condition (this transfer is required for computation time).

The idea of this work is also to provide guidelines for a generic model commonly used by the scientific community and freely available. Here we choose the model OpenFOAM owing to the large community of developers involved.

We conducted our investigations on a real past event, chosen for its complexity. The case is the 1979 Mururoa atoll flank collapse and its associated tsunami (POUPARDIN *et al.*, 2017). It is particularly challenging due to the presence of a reef flat. In fact, the mesh size must take into account both the water surface (z=0m) and the reef flat (z=1m), which is complex when the mesh size is greater than 1m. The underwater landslide that occurred at Mururoa is related to an oceanic atoll flank collapse including limestone deposits with a volume of ~ 80 Mm^3. Direct observations of the landslide-generated tsunami for this historical event are available on the north shore of Fangataufa, which is 40 km south of Mururoa, and on the south coast of Mururoa. Inundation rose to a height of 5-7 meters on the Mururoa reef flat.

The objective of this study is therefore double : first, to propose general guidelines for the modeling of real cases of landslide generated tsunamis and second, demonstrate the relevance of these guidelines on a specific case.

2. Numerical model

In this work, as previously mentioned, we use the open-source code OpenFOAM and in particular the *multiphaseInterFoam* solver. This solver is based on the volume of fluid (VOF) method to deal with the interfaces. Three phases are used (air, water, sediment) and considered as Newtonian fluids, in these preliminary results. Domain decomposition and MPI parallelization is performed to allow for high-resolution simulations with a large number of grid cells.

2.1 Governing equations

The general set of solved governing equations are mass and momentum equations, expressed as:

$$\nabla \cdot U = 0 \tag{1}$$

$$\rho \frac{\partial U}{\partial t} + \rho U \cdot \nabla U = -\nabla P + \rho g + \nabla \cdot [\mu(\nabla U + (\nabla U)^T)] \tag{2}$$

where U, P are the velocity and pressure of the flow, respectively, and g is the gravitational acceleration. ρ is the density in kg/m^3 and μ the dynamic viscosity in Pa.s. The Finite Volume Method (FVM), which is based on an unstructured mesh with arbitrary continuous polyhedral cells, is used to discretize these equations spatially. Furthermore, the pressure-velocity coupling is fully solved for each time step using the PIMPLE algorithm, which combines the PISO (Pressure Implicit with Splitting of Operator) (ISSA, 1986) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) (FERZIGER & PERIC, 1999) algorithms. After that, the pressure and velocity field are adjusted many times to meet the continuity equation requirements and to converge. These linear equations are solved by the linear solver Geometric-Algebraic Multi-Grid (GAMG). In addition, the gradient operators are subjected to Gaussian interpolation and time-derivatives are discretized using the implicit Euler scheme.

A self-adjusting time step Δt is used to improve the numerical model accuracy and stability. This latter is modified in accordance with the specified maximum Courant Number Co at the start of each subsequent time loop (COURANT *et al.*, 1967). The Courant Number is defined as follows: $Co = \frac{\Delta t}{\Delta x}|U|$ where Δt is the maximum time step, Δx is the cell size and $|U|$ is the velocity magnitude. The maximum Courant number value should be below 1 throughout the whole domain.

2.2 Free surface treatment

The VOF method is a fixed-grid approach based on the one-fluid model and considers that the various immiscible fluids (or 'phases') can be described as a single fluid whose local physical properties, namely density and viscosity, vary in space and time depending on the volume fraction C_i of each phase i (YOUNGS, 1982; HIRT & NICHOLS, 1981). The volume fraction of each fluid intrinsically obeys $\sum_{i=0}^{n} C_i = 1$ where n is the number of phases. In this study $1 \leq n \leq 3$. Typically, $C_i = 1$ in grid cells filled only with fluid i, and $0 < C_i < 1$ in grid cells cross-cut by an interface. The transport of the volume fractions is expressed as :

$$\frac{\partial C_i}{\partial t} + U \cdot \nabla C_i = -\nabla \cdot (U_r C_r) \tag{3}$$

The term $-\nabla \cdot (U_r C_r)$ is artificially added to Eq. (3) to reduce the effects of numerical smearing of the interface, where $C_r = C_l \cdot (1 - C_l)$, and U_r is designated by BERBEROVIĆ (2009) as a “compression velocity”.

2.3 Numerical setup

A 2D cross-section of the southern flank of Mururoa at the site of the landslide is modeled. Future simulations will be conducted in 3D, but for the identification and solving the difficulties, 2D simulations eases the process. The domain is 15 km long and 3 km high. The slide is located near the surface (see Figure 1). A simulation of 120 s is performed with a maximum Courant number of 0.1. As previously mentioned, the slide is considered as a Newtonian fluid. Here, the entire mass is assumed to suddenly lose its equilibrium and turn into a dense flow. Slide density and (kinematic) viscosity are : $\rho = 1500$ kg.m-3 et $\nu = 6.67$x10-4 m2.s-1.

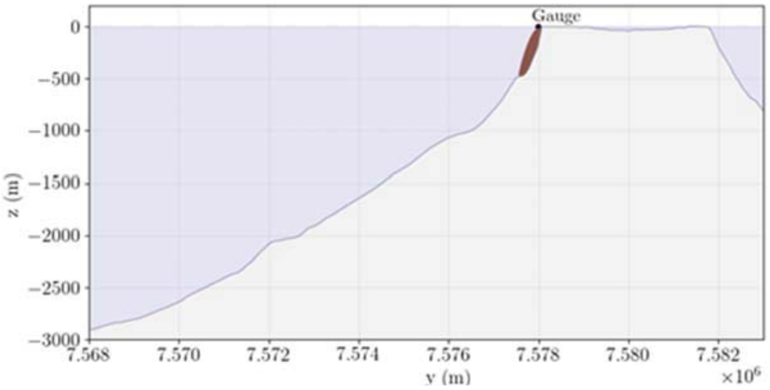


Figure 1. 2D numerical setup: slide is in brown, water in blue and bathymetry in grey. Only the surface of the bathymetry is taken into account in the modeling.

3. Numerical results and discussion

There are two easy-to-use mesh generators in OpenFOAM: *snappyHexMesh* and *cfMesh*. *SnappyHexMesh* consists of 1) the creation of the background mesh using the blockMesh utility (or any other hexahedral mesh generator), 2) extraction of features on the surfaces, 3) closes the mesh following the bathymetry. The advantage is that a horizontal line can be imposed at the water surface and the mesh is almost horizontal everywhere (except at the reef flat). Conversely, in order to create its mesh, *cfMesh* begins with the bathymetry. The mesh is not horizontal in the interface zone, but it exactly follows the bathymetry. Unfortunately, mesh sizes smaller than 5 m for *snappyHexMesh* and 20 m for *cfMesh* cause calculation divergence. No solution has yet been found to this problem.

Several numerical wave gauges will be used for cross-comparison between our computations. The observation data described in POUPARDIN et al. (2017) will also be confronted to our simulations.

3.1 Water surface elevation in the absence of sliding

On Figure 2, we compare the water surface elevations obtained using different mesh sizes with *snappyHexMesh* (50, 20 and 10 m, blue lines) and *cfMesh* (50, 20 m, green lines) without any slide. In all cases, the simulations generate spurious oscillations at the water surface whereas this water surface should remain unchanged (i.e., flat) without the slide. Decreasing cell size reduces the amplitude of oscillations. For the same size mesh, *snappyHexMesh* produces less oscillations than *cfMesh* (blue and green continued lines), maybe due to the fact that an horizontal mesh line is imposed at the interface.

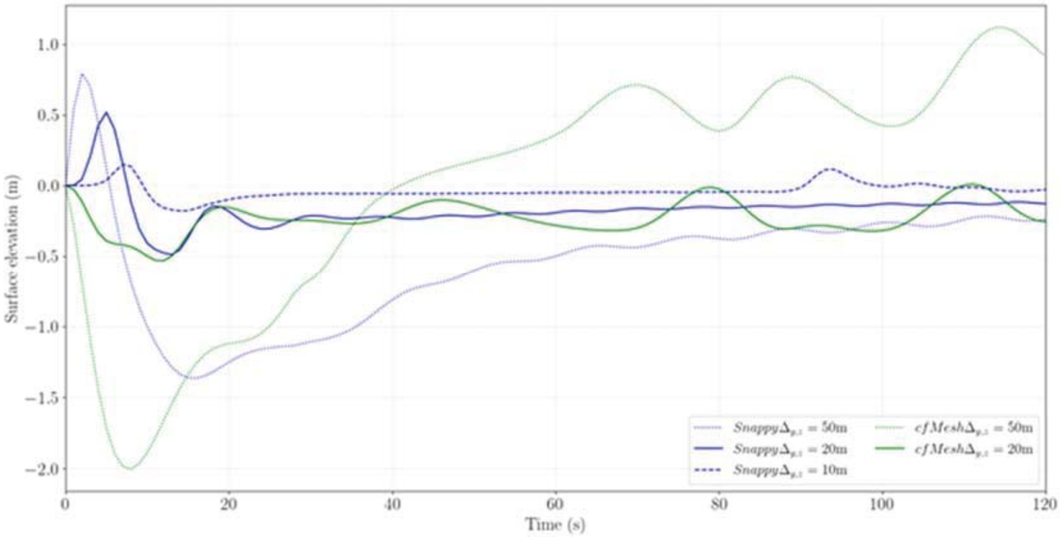


Figure 2. Surface elevation over time at gage position y = 7.57798 x 10^6 m, for two meshers and various size of meshes: snappyHexMesh (50, 20, 10 m, blue lines) and cfMesh (50, 20, green lines).

3.2 Phase volume fraction initialization in the absence of sliding

The VOF method fills cells with a phase volume fraction between 0 and 1. In OpenFOAM, at initialization, cells are generally filled with 0 or 1 everywhere, but not intermediate values. Here, we test filling the cells at the interface according to the actual quantity of water or air in the cell (partial volume fraction). Surface water elevations for *snappyHexMesh* and *cfMesh* meshes are presented in Figure 3. Partial volume fraction initialization (solid line, *0≤□≤1*) leads to a flatter interface for both meshmakers, and even more for *cfMesh* (1 m vs 10 m for full initialization). For *snappyHexMesh,* the gain is reduced, probably for the same reasons as in the previous section: the imposed horizontal line at the interface.

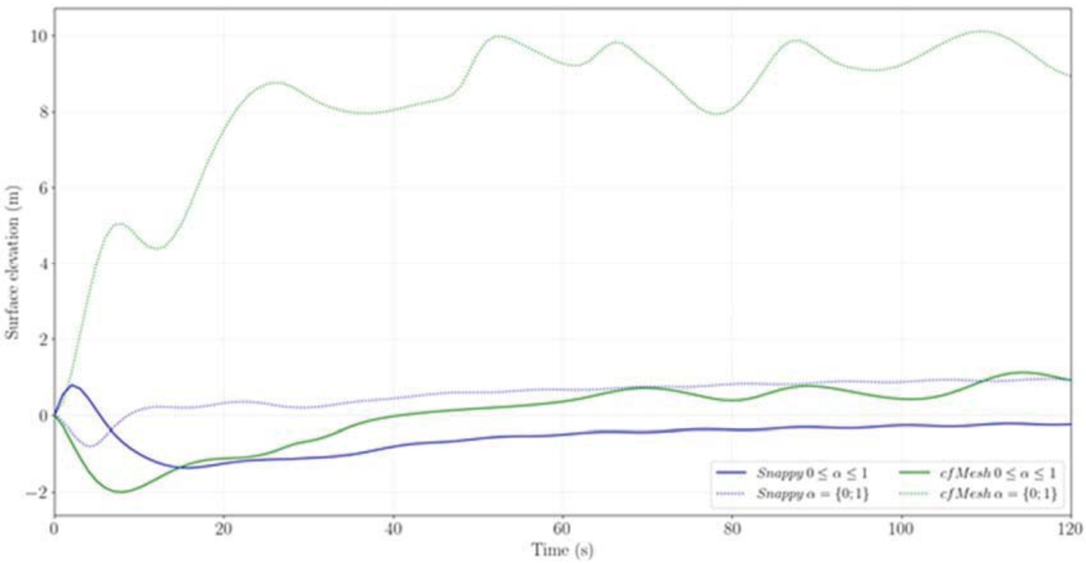


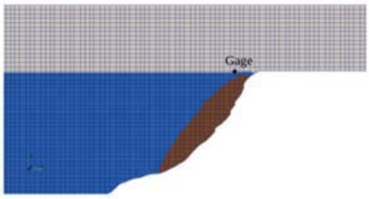
Figure 3. Surface elevation over time at gage position y = 7.57798 x 106 m, influence of the initialization of α: partial (0≤α≤1) or full (α=0 or α=1) for 2 meshers (snappyHexMesh and cfMesh) without any slide.

3.3 <u>Comparison with real observations</u>

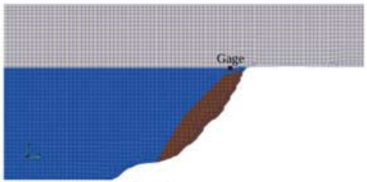
In this section, we compare our 2D simulations with the water surface elevation observed at a specific point (coordinates x;y = 706304;7.57798x10^6 m) during the 1979 Mururoa event (POUPARDIN et al., 2017). The slide volume and location are the same as in the reference paper. Here, we compare the two meshes provided by the two studied meshers with a cell size of 20 m (see Figure 4 a), b)). The difference is that, along the bathymetry, *snappyHexMesh* generates triangles whereas *cfMesh* produces squares.

Figure 4 c) shows the surface elevation water over time. Results for *snappyHexMesh* and *cfMesh* are similar at the beginning (until time ~ 10s) but show a slight discrepancy afterward. These differences may be explained by the different discretizations of the bathymetry and/or by the spurious oscillations at the water surface due to inaccurate initialization. Nevertheless, the order of magnitude is similar to that of the data, at least for the first dip. In comparison with the Avalanche results (the shallow water model used in POUPARDIN *et al.*, 2017), our results do not show the first bump which may be characteristic of the error introduced by the shallow water approximation.

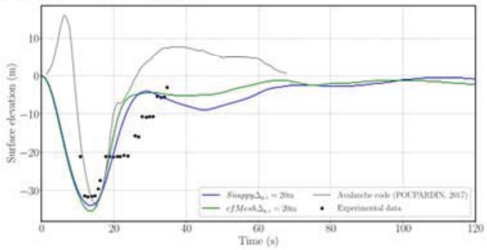
Finally, Figure 4 d) presents snapshots of the slide and the water surface over time. The shape of both slides becomes very different after a certain time. We should determine whether this difference is critical or not for the wave formation (it will not be if the generation is over). In addition, a more realistic rheology (e.g., ROMANO et al., 2023) could likely improve this wrong behavior. These investigations are left for future works.



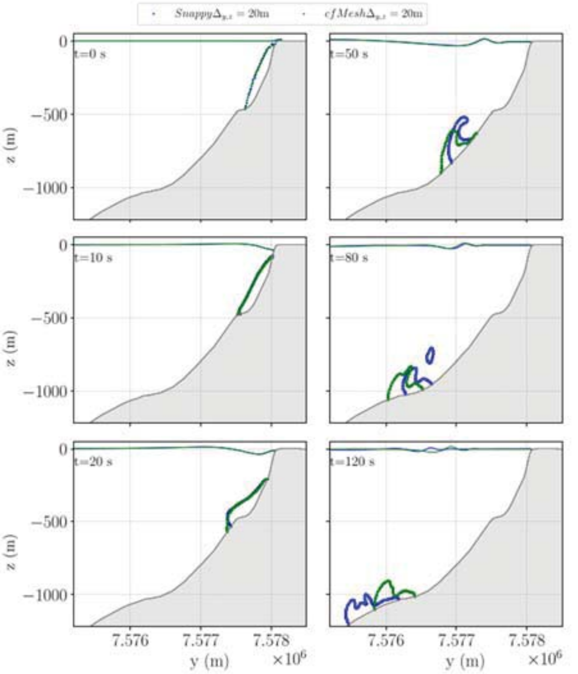
a) Mesh generated with snappyHexMesh



b) Mesh generated with cfMesh



c) Surface elevation overtime for meshes at gage y = 7.57798x10^{6} m. Comparison with experimental data and Avalanche code



d) Snapshots of the water surface and slide deformation for various time step

Figure 4. Simulations of the 1979 Mururoa event with 20 m grid meshes produced by snappyHexMesh and cfMesh.

4. Conclusions

OpenFOAM packages have been used in the present work to simulate a real tsunami generated by a landslide in 2D. The first aspect of the work was methodological. We tested two meshers: *snappyHexMesh* and *cfMesh.*

We show that : i) reducing cell size helps to reduce the amplitude of spurious oscillations at the water surface and ii) initializing the VOF method with a volume fraction proportional to the height of the water in the cell helps preventing spurious water surface deformation, especially for meshes generated with *cfMesh*.

We then provided preliminary results regarding a real event (POUPARDIN et al, 2017). The order of magnitude obtained for the water surface is that of the observation data. These initial results obtained with 20m cells are, in a way, encouraging for both types of mesh. Nevertheless, so far, the mesh size cannot be further reduced, since it implies, for the time being, the divergence of calculations. Further investigations are therefore required to elucidate this point as well as improving further the slide rheology.

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