Model analysis for tsunami generation by landslides

1 Introduction and scientific context

The CEA has been monitoring potential landslides on the underwater slopes of the Pacific atolls and associated tsunamis for several decades. Numerical simulation is a privileged tool for the analysis of these phenomena. While the source of seismic tsunamis is relatively well known, the knowledge of landslides is fraught with uncertainties about their sliding speed (whose duration varies from a few tens of seconds to several hours), the nature of the rocks or sediments involved and therefore their law of behaviour. Until now, the modelling of these phenomena has been carried out by the tool developed at the CEA, AVALANCHE. Sliding is treated as the flow of a fluid with a higher density than its environment, by choosing the thin film approximation. Similarly, wave generation and propagation modelling is based on the long wave hypothesis. These two hypotheses lead to a 2D treatment of the collapse and the associated waves. Technical progress now allows us to consider more accurate 3D modelling. The Summer School Project focuses on evaluating literature models in the early stages of wave generation.

The project is also of interest to the CENALT[1] which is responsible for monitoring strong earthquakes and tsunamis in France and is hosted by the CEA. Many recent tsunamis, following strong underwater earthquakes, have been exacerbated by the onset of tsunamigenic gravity instabilities. Modelling these tsunami generation processes is essential to better predict hazards and establish risk maps for coastal areas.

2 Goals of the project

The objective of the project is to make progress on the modelling of waves generated by underwater or sub-aerial landslides. For a supposedly known landslide, it is proposed to intercompare several two-dimensional models (or scale models) of wave propagation and compare the results with those calculated by a 3D multiphase fluid mechanics code. Until now, the possibility of modelling this phenomenon in 3D had been ruled out due to the prohibitive computing time. In recent years, several laboratories have chosen to solve Navier-Stokes 3D equations for two fluids: air and water. We propose here to use the widely distributed 3D code for the mechanics of OpenFoam[2] continuous media, which has about 250 users in France in different fields of activity. The open-source code developed in C++ is designed as an easily programmable

[1] Centre d'alerte aux tsunamis, `http://www.info-tsunami.fr`

[2] Open source Field Operation And Manipulation, `https://openfoam.org`

toolbox. The core of the project will be to determine whether the classic wave propagation models (Shallow-Water, Boussinesq, GreenNaghdi) are efficient for generating waves from a supposedly known landslide.

In particular, several types of bottom deformations and their influence on the wave generation. When the collapse is a granular avalanche, the deformation of the bottom can be modelled by a Gaussian function evolving over time. On the other hand, when collapse is a block fall, the deformation of the bottom can be discontinuous and create strong instabilities in scale models.

3 Methodology and tasks description

The models involved are well understood by the team of supervisors. The calculation codes simulating fluid dynamics will be provided for the project. First of all (see 3.1), the OpenFoam code will be modified to take into account a time variation of the background reflecting a landslide. The main part of the project will focus on the numerical comparison of the reaction of different wave propagation models to a forcing due to a time variation of the bathymetry (see 3.2). Depending on the results obtained, the wave generation will be corrected in reduced models (see 3.3) or to solve a reverse problem to estimate the deformation of the seabed according to the shape of the wave propagated offshore (see 3.4). Finally, we will seek to apply the results obtained to a recent real case (see 3.5).

3.1 Development of a 3D computational code

The first part of the project will be to develop in a version of OpenFoam bifluid (water and air) the possibility of deformation of the bottom. In this version, the OpenFoam code solves for the fluid equations the incompressible Navier-Stokes equations by a finite volume method, with a 3D geometry. This geometry is obtained using an adaptive mesher (AMR), available in the OPenFoam code.

The students will first learn how to launch and post-process a simulation from the existing tutorials (in particular the tutorials on dam failure and AMR technique). They will then implement the deformation of the bottom inducing a temporal deformation of the mesh and run simulations by adapting the tutorials to their own cases, described in 3.2.

3.2 Comparison of wave propagation models response to a landslide

Several models describe wave propagation with more or less approximations. In particular for real-world applications, non-linear reduced models are widely used: the Shallow-Water model, the Boussinesq model [3, 4] and the Green-Naghdi model [5]. While the differences between these models are well known with regard to wave propagation (dispersion relationship, soliton...), their response to forcing, in particular a temporal variation in bathymetry, has not been studied precisely in the literature. However, it is obvious that the energy transmitted to the fluid depends strongly on the model if the vertical velocity of the bottom is not negligible. The question then arises as to whether these models, even the most accurate ones, are relevant for wave generation or whether forcing by a variation in bathymetry should be supplemented by additional modelling.

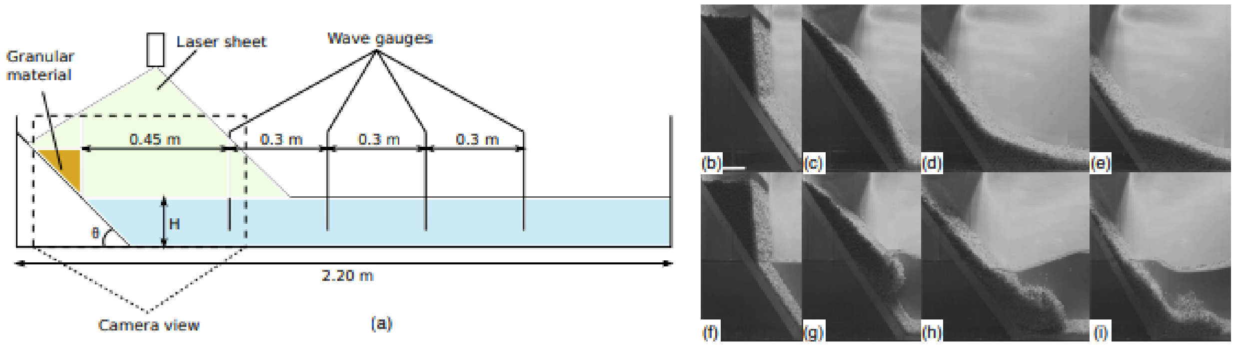

Figure 1: Viroulet et al's channel experiment [7]. The deformation of the granular flow and the generation of waves are recorded by a fast camera. The wave amplitude is measured by 4 probes near the slip.

Two comparisons will be carried out in monodimensional form (variations following the second horizontal coordinate are not considered). The Navier-Stokes bi-fluid model established in the first part (see 3.1) will be used as a reference. Comparison of the waves calculated near the slip will allow the different models to be evaluated.

The second comparison will be based on recent experiments by Viroulet et al. [7] in a basin, consisting of sliding a granular mass along an inclined plane and measuring the wave generated in the first moments (Fig. 1). The deformation of the bottom will be estimated from the flow photos taken during the experiments.

3.3 Correction of a wave produced by a variation in bathymetry

In this part, we will try to correct the energy transmitted to the fluid. This additional energy can be introduced in several ways. While it seems difficult to modify the potential energy of the fluid without violating mass conservation, a kinetic energy source term may be considered. However, it is generally difficult to work on the velocity without significantly changing the results and often making the numerical codes less robust. Another solution consists in estimating *a priori* an additional pressure term.

3.4 Inverse problem for source estimation

If the scale models are successful in representing wave generation, it will be investigated whether it is possible to recover the deformation of the bottom using tide gauge observations. The objective is to determine whether wave measurements can quantify and characterize underwater landslides (volumes, thicknesses and velocities). The idea is to quickly estimate the potential damage caused by these landslides, such as those observed on underwater communication cables, for example. To do this, an initial effort will be made to find a Gaussian-type generated variable with three degrees of freedom (elevation, standard deviation and travel speed). We will then try to improve this study by a composition of several Gaussian. Similar strategies have already been studied [1, 2].

Figure 2: Diagram of a volcanic collapse generating a tsunami (UNESCO). Eruption of the Krakatau a few minutes before the collapse of part of the volcanic cone.

3.5 Application to a real case

We propose to focus on a recent real event. It is a collapse of a hundred million cubic meters following the eruption of the Krakatau in the Sound Strait (Indonesia) on 22 December 2018 [6]. This collapse generated a tsunami that devastated tens of kilometres of coastline and killed several hundred people. From the known land displacement, we will compare the results of the different models near the source. The waves will then be propagated in the far field by the scale models, and our results will be compared with the tide gauges recorded in several ports surrounding the Krakatau region.

Considering the cost of the Navier-Stokes 3D model, the wave simulation by OpenFoam will be limited to the generation area.

References

[1] Cecioni, C., Romano, A., Bellotti, G., Risio, M., and de Girolamo, P., *Real-time inversion of tsunamis generated by landslides*, Nat. Hazards Earth Syst. Sci., 11, 2511-2520, 2011.

[2] Mulia, I. E., and Asano, T., *Initial tsunami source estimation by inversion with an intelligent selection of model parameters and time delays*, J. Geophys. Res. Oceans, 121, 441– 456, 2016

[3] Paris, A., Okal, E.A., Guérin, C., Heinrich, P., Schindele, P., *Numerical Modeling of the June 17, 2017 Landslide and Tsunami Events in Karrat Fjord, West Greenland*, Pure Appl. Geophys., 2019

[4] Paris, A., Heinrich, P. et al., *Numerical modeling of the December 22, 2018 Anak Krakatau landslide and the following tsunami in Sunda Strait, Indonesia* (Submitted) Proceedings, Meeting Oceans, June 2019.

[5] M. Parisot, *Entropy-satisfying scheme for a hierarchy of dispersive reduced models of free surface flow*, working paper or preprint, hal-01242128, Feb. 2018.

[6] Poupardin, A., Heinrich, P., Frère, A., Imbert, D., Hébert, H. and Flouzat M., *The 1979 Submarine Landslide-Generated Tsunami in Mururoa, French Polynesia*, Pure Appl. Geophys, 174, 3293–3311, 2017.

[7] Viroulet, S. Sauret, A., Kimmoun, O., *Tsunami generated by a granular collapse down a rough inclined plane*, EPL - Europhysics Letters, European Physical Society/EDP Sciences/Società Italiana di Fisica/IOP Publishing, 105, pp.34004, 2014