Title: Modeling tsunamigenic landslides with shallow flow equations.

Authors: David George and Richard Iverson

Abstract:

A submarine landslide can directly generate a destructive tsunami through the vertical displacement of the water column caused by the changing seafloor profile. Therefore, modeling the mobilization and dynamics of submarine landslides can provide the initiation mechanisms for tsunami modeling. Accurate modeling of the landslide dynamics is therefore important in predicting the potential destructive capacity of a resulting tsunami. However, modeling landslides accurately has traditionally proven to be very difficult due to the complicated granular-fluid interactions, affecting the stress and mobility of the flowing mixture. Dynamic landslide models have typically fallen into two categories: three-dimensional fluid models and depth-averaged two-dimensional models. Three-dimensional models typically treat the landslide material as a homogeneous incompressible fluid with a specified rheology. More recently, depth-averaged models have gained in popularity due to the fact that more complicated and physically accurate friction laws for multiple phases can be adopted while still maintaining a computationally tractable problem. Depth-averaged models, or shallow flow models, are based on the assumption, used for many environmental surface flows including tsunamis, that the depth of the flow is small relative to the characteristic horizontal length scales in the flow. We will present a two-phase depth-averaged landslide model and accompanying software that we are developing. The model is unique in that the pore-fluid pressure , volume fractions and granular dilatency coevolve through dynamic coupling. The feedback between these quantities plays a dominant role in mediating the evolving stress in a landslide. Additionally, this allows us to model the potential mobilization of sediment masses determined to be vulnerable to failure. We plan to eventually couple the model to our tsunami model and other tsunami models.

Modeling tsunamigenic landslides with shallow-flow equations.

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Outline

- Intro to landslide modeling
- Depth-averaged models and software
- Our model for debris flows and validation
- Conclusions

Landslide Modeling

Two categories of landslide modeling:

- Slope stability modeling
  - Analyze entire regions (requires field data)
  - Determine vulnerable areas
  - Determine failure masses/surfaces → probabilistic
- Flow modeling
  - Determine motion and runout
  - Requires complicated physics models
  - Requires data for physical parameters → probabilistic

Landslide Modeling

Traditionally there is a disconnect between slope-stability and flow modeling

- Two-types of modeling are based on very different physical underpinnings
- slope-stability often based on geotechnical engineering principles
- Flow modeling from the field of computational fluid dynamics

Traditional flow models have a 'dirty secret'

- Initiation begins far from equilibrium
- Transition from small instability to unstable flow is ignored
- → the most critical transition stages are missed

Landslide Modeling

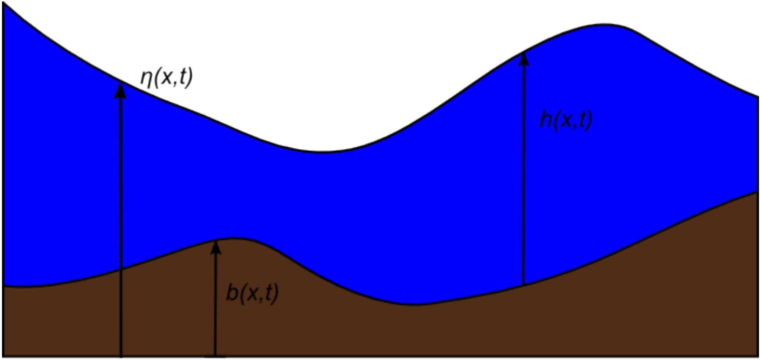
The important reality of landslide initiation:

- A failure mass is necessarily very close to equilibrium (at first!)
- Early shear results from a small local perturbation to stability
- Motion results in feedback between pore-fluid pressure and granular dilation/consolidation
- Feedback determines how failure progresses
- Flow can creep, stabilize, stick-slip or “explode”
- Result determines whether a large landslide occurs, or simply a “slump”

Our goal is to model these early stages, the transition from stability to instability

Depth-averaged flow equations

Flow between a fixed bottom $b(x, y)$ with a free surface $\eta(x, y, t)$:



Depth-averaged flow equations

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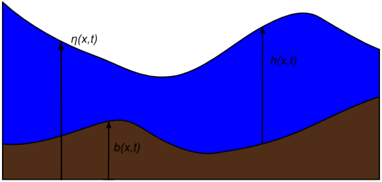
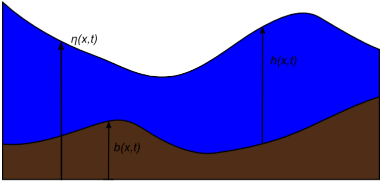


Starting with full equations:

$$\begin{aligned} \rho_t + \nabla \cdot \rho\vec{U} &= 0, \\ \left(\rho\vec{U}\right)_t + \nabla \cdot \left[\rho\vec{U}\vec{U}^T + \sigma\right] - \rho\vec{g} &= 0. \end{aligned}$$

Depth-averaged flow equations

Flow between a fixed bottom $b(x,y)$ with a free surface $\eta(x,y,t)$:



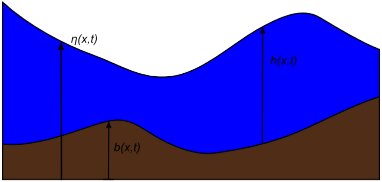
Integrate from $b(x,y)$ to $\eta(x,y,t)$:

$$\int_b^\eta \left[\rho_t + \nabla \cdot \rho\vec{U}\right]\, dz = 0,$$

$$\int_b^\eta \left[\left(\rho\vec{U}\right)_t + \nabla \cdot \left[\rho\vec{U}\vec{U}^T + \sigma\right] - \rho\vec{g}\right]\, dz = 0.$$

Depth-averaged flow equations

Flow between a fixed bottom $b(x, y)$ with a free surface $\eta(x, y, t)$:



Making assumptions about the flow ($\vec{U}$) and (σ) and using B.C.'s gives a system in 2D for h, hu and hv. (Equations for other depth averaged variables might be added as well. *.e.g.* pressure.)

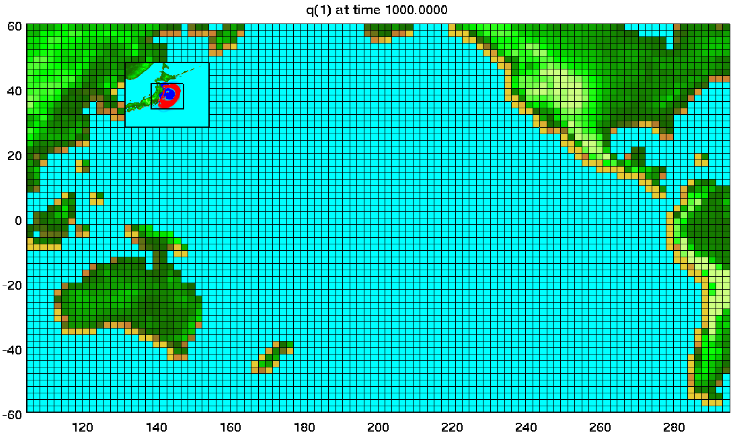
$$\int_b^\eta \left[\rho_t + \nabla \cdot \rho\vec{U}\right] \, dz = 0,$$

$$\int_b^\eta \left[\left(\rho\vec{U}\right)_t + \nabla \cdot \left[\rho\vec{U}\vec{U}^T + \sigma\right] - \rho\vec{g}\right] \, dz = 0.$$

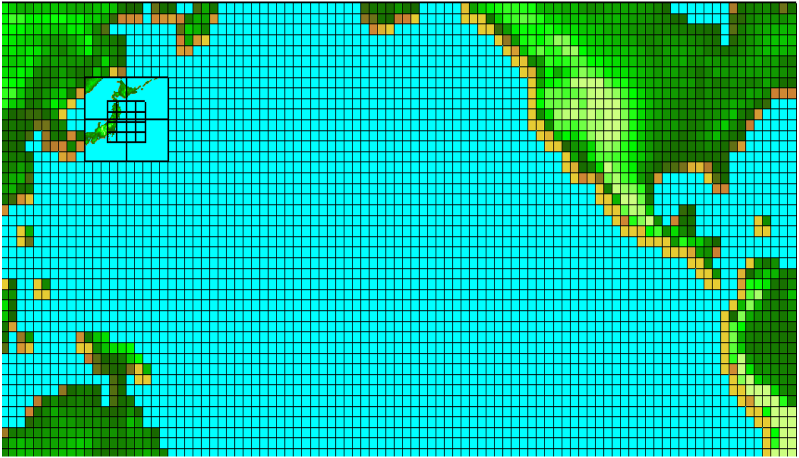
GeoClaw: software for Earth-surface flows

- Advanced algorithms designed for commonalities of free-surface flows (landslides, tsunamis, etc.);
- Adaptive mesh refinement allows efficient computation of large-scale problems;
- Robust algorithms capture moving inundation fronts over varying topography;
- Dynamic processing of topography data sets facilitates use of increasingly available high-resolution DEMs;

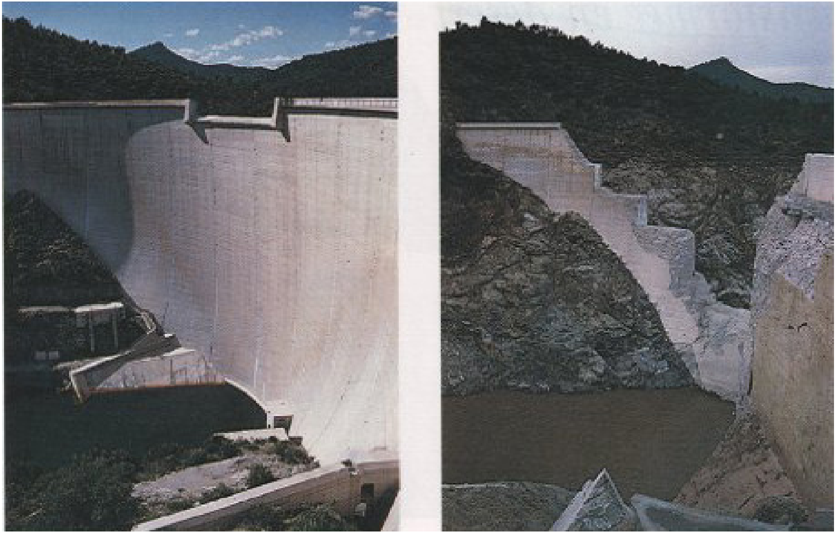
Tsunamis: Honshu-Tohoku 2011



Tsunamis: Honshu-Tohoku 2011



Flows in rugged terrain: Malpasset dam, France 1959



Overland flooding: Malpasset dam, France 1959