Tutorial for BingClaw v5.6.1

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The original document was authored by Jihwan Kim, on February 28, 2017, for the version of BingCLAW designed for Clawpack v5.3.1. This extensive documentation covered installation of Clawpack and two codes: `voellmy_claw` and `bingclaw`. In this reduced documentation, I have removed now obsolete notes on the installation and instead ask the user to follow the instructions provided on

```
https://github.com/norwegian-geotechnical-institute/BingCLAW_5.6.1
```

I have also removed the description of the Coulomb and Voellmy friction model (`voellmy_claw`) and have replaced the Byneset example with the Storegga slide.

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Steven J. Gibbons, NGI, August 22, 2025

1 Introduction

BingClaw is developed to predict the run-out of debris flows. *BingClaw* is a quasi-3D model, or a depth-averaged model with two horizontal dimensions. Thus numerical simulatios can be performed on the general 3-D terrain. BingClaw is based on the Herschel-Bulkley rheology, and it can be applied to the quick-clay landslide and submarine landsilde.

BingClaw is developed based on the GeoClaw which is a variant of Clawpack. Details of GeoClaw and Clawpack can be found at `http://www.clawpack.org/`. Clawpack stands for Conservation LAW PACKage, and it is developed for hyperbolic conservation laws, but can be used as a general PDE solver. The version of the code here requires version 5.6.1 of clawpack:

```
https://github.com/clawpack/clawpack/files/3781620/clawpack-v5.6.1.tar.gz
```

2 BingClaw

2.1 Governing equations

For simple shear, the Herschel-Bulkley rheological model can be described as

$$\left|\frac{\dot{\gamma}}{\dot{\gamma}_r}\right|^n = \begin{cases} 0, & \text{if} \quad |\tau| \leq \tau_y, \\ \frac{\tau}{\tau_y \operatorname{sgn}(\dot{\gamma})} - 1, & \text{if} \quad |\tau| > \tau_y, \end{cases} \tag{1}$$

where $\dot{\gamma}$ is a strain rate, $\dot{\gamma}_r$ is a reference strain rate defined as $\dot{\gamma}_r = (\tau_y/\mu)^{1/n}$ with a dynamic viscosity μ and an exponent n. Moreover, τ and τ_y are the shear stress and the yield stress, respectively. The parameter n is chosen between 0 and 1, and $n = 1$ is the Bingham fluid case.

The mass balance equation integrated over the entire flow depth and two separate momentum balance equations integrated over the plug (subscript p) and shear layer (subscript s), respectively, can be formulated as follows with two horizontal dimensions:

$$\frac{\partial}{\partial t}(h_p + h_s) + \nabla \cdot (\boldsymbol{u}_p(h_p + \alpha_1 h_s)) = 0, \tag{2}$$

$$\begin{aligned} &\frac{\partial}{\partial t}(h_p \boldsymbol{u}_p) + ((h_p \boldsymbol{u}_p \cdot \nabla) \boldsymbol{u}_p + \boldsymbol{u}_p (\nabla \cdot h_p \boldsymbol{u}_p)) \\ &\quad + g' h_p \nabla (h + b) + \boldsymbol{u}_p \left(\frac{\partial}{\partial t} h_s + \nabla \cdot (\alpha_1 h_s \boldsymbol{u}_p) \right) = -\frac{\tau_y \boldsymbol{u}_p}{\rho_d U}, \end{aligned} \tag{3}$$

$$\begin{aligned} &\alpha_1 \frac{\partial}{\partial t}(h_s \boldsymbol{u}_p) + ((h_s \alpha_2 \boldsymbol{u}_p \cdot \nabla) \boldsymbol{u}_p + \alpha_2 \boldsymbol{u}_p (\nabla \cdot h_s \boldsymbol{u}_p)) \\ &\quad + g' h_s \nabla (h + b) - \boldsymbol{u}_p \left(\frac{\partial}{\partial t} h_s + \nabla \cdot (\alpha_1 h_s \boldsymbol{u}_p) \right) = -\frac{\tau_y \beta}{\rho_d} \boldsymbol{f}_s, \end{aligned} \tag{4}$$

where

$$U^2 = u_p^2 + v_p^2, \quad \text{and} \quad \boldsymbol{f}_s = \left(\frac{U}{|\dot{\gamma}_r h_s|} \right)^n \frac{\boldsymbol{u}_p}{U}.$$

In this expression, h_p and h_s are the depth of the plug and shear layer. Moreover, $\boldsymbol{u}_p = (u_p, v_p)$ is the velocity of the plug layer. The density of the ambient and debris flow are denoted as ρ_a and ρ_d, and g' is the reduced gravity $g' = \left(1 - \frac{\rho_a}{\rho_d}\right) g$, and $b(x, y)$ represents the bathymetry. The parameters α_1, α_2 and β are expressed in terms of n as

$$\alpha_1 = \frac{1/n + 1}{1/n + 2}, \tag{5}$$

$$\alpha_2 = 1 - \frac{2}{1/n + 2} + \frac{1}{2/n + 3}, \tag{6}$$

$$\beta = \left(1 + \frac{1}{n}\right)^n. \tag{7}$$

Here, we assume that shear stresses acting in planes normal the tangential plane of the bathymetry are neglected. For example, the x-momentum equations do not contain friction forces that can be contributed by the velocity difference in y-direction.

The equation (2) is the conservation of mass for the entire layer, and the equations (3) and (4) states the momentum equations for the plug and shear layer respectively. The normal stresses in the tangential plane are assumed to be hydrostatic. In particular, this does not take into account the cohesion of the material under compression or extension. Notice that the terms $\boldsymbol{u}_p\left(\frac{\partial}{\partial t}h_s + \nabla\cdot(\alpha_1 h_s \boldsymbol{u}_p)\right)$ denotes the momentum transfer between two layers ... associated with cahanges of the depth of the shear layer.

In addition, we have two algebraic equations for the depth (h) and velocity ($\boldsymbol{u}$) of the entire debris flow,

$$h = h_s + h_p, \tag{8}$$

$$\boldsymbol{u} = \frac{(h_p + \alpha_1 h_s)}{h}\boldsymbol{u}_p. \tag{9}$$

2.1.1 Hydrodrag

The hydrodynamic drag is split into the friction drag and pressure drag terms. The friction drag is approximated as,

$$\boldsymbol{f}_f = \frac{\tau_f}{\rho_d} = \frac{1}{2}\frac{\rho_a}{\rho_d}C_F\,\|\boldsymbol{u}\|\,\boldsymbol{u},$$

and the pressure drag term $\boldsymbol{f}_p$ is modeled as

$$\boldsymbol{f}_p = \frac{1}{2}\frac{\rho_a}{\rho_d}C_P\min\left[0,\nabla h\right]\|\boldsymbol{u}\|\,\boldsymbol{u},$$

where C_F and C_P are drag coefficients. In general, the coefficients are $C_F = \mathcal{O}(10^{-2})$ and $C_P = \mathcal{O}(1)$. This pressure drag term is only applied at the front face of the slide.

2.1.2 Remolding

The effect of remolding or softening due to water intake by reducing the yield strength can be approximated as a function of accumulated shear:

$$\tau_y(\gamma) = \tau_{y,\infty} + \left(\tau_{y,0} - \tau_{y,\infty}\right)e^{-\Gamma\gamma}, \tag{10}$$

where $\tau_{y,0}$ and $\tau_{y,\infty}$ are the initial and residual yield strength, γ is the total shear deformation and Γ is a dimensionless coefficient. This remolding model's numerical results are sensitive to the value of Γ.

The total shear strain at the bottom of the debris flow can be calculated as

$$\gamma = \int_0^t \left\|\frac{\partial\vec{\mathbf{u}}}{\partial z}\right\|_{z=0} dt = \frac{n+1}{n}\int\frac{\|\vec{\mathbf{u}}_p\|}{h_s}dt. \tag{11}$$

In the numerical implementation, the variable γ as the accumulated shear strain at the bed is advected with the advection speed equal to $\alpha_1 u$, and the following equation is solved for γ,

$$\gamma_t + \alpha_1 u\gamma_x = 0.$$

In the remolding model, the change in τ_y due to the remolding process is proportional to (-$e^{\Gamma\gamma}$). Therefore, small Γ implies that large accumulated shear γ is needed for remolding, and vice versa.

Figure 1 shows the yield strength $\tau(\gamma)$ with different Γ values. In this figure, $\tau_{y,0}$=20 kPa and $\tau_{y,\infty}$=0.2 kPa. Two yield strengths $\tau_{y,0}$ and $\tau_{y,\infty}$ are connected by an exponential function.

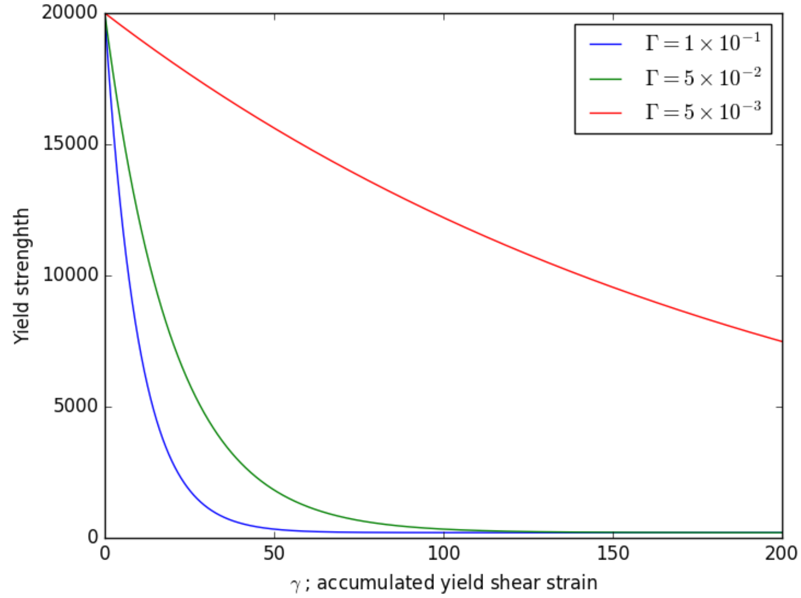

Figure 1: Dependency on Γ of the remolding model for the case $\tau_{y,0} = 20$ kPa, $\tau_{y,\infty} = 0.2$ kPa and three different values of the remolding shear strain Γ.

2.1.3 Added Mass

'When a body immersed in a fluid is accelerated, the fluid mass near the body also must be accelerated. This added-mass effect manifests itself as an extra inertial force in the equation of motion and is proportional to the acceleration of the body and the mass of the fluid disturbed by the motion of the body. It can be approximated by multiplying the acceleration terms in the equation of motion by a factor that depends on the shape of the body and the density ratio between ambient fluid and slide material:'

$$
\begin{aligned}
&\frac{\partial}{\partial t}(h_p + h_s) + \nabla \cdot (\boldsymbol{u}_p(h_p + \alpha_1 h_s)) = 0, \\
&\left(1 + C_m \frac{\rho_a}{\rho_d}\right)\left[\frac{\partial}{\partial t}(h_p \boldsymbol{u}_p) + ((h_p \boldsymbol{u}_p \cdot \nabla)\, \boldsymbol{u}_p + \boldsymbol{u}_p (\nabla \cdot h_p \boldsymbol{u}_p))\right] \\
&\quad + g' h_p \nabla (h + b) + \boldsymbol{u}_p \left(\frac{\partial}{\partial t} h_s + \nabla \cdot (\alpha_1 h_s \boldsymbol{u}_p)\right) = -\frac{\tau_y \mathrm{sgn}(\boldsymbol{u}_p)}{\rho_d}, \\
&\left(1 + C_m \frac{\rho_a}{\rho_d}\right)\left[\alpha_1 \frac{\partial}{\partial t}(h_s \boldsymbol{u}_p) + ((h_s \alpha_2 \boldsymbol{u}_p \cdot \nabla)\, \boldsymbol{u}_p + \alpha_2 \boldsymbol{u}_p (\nabla \cdot h_s \boldsymbol{u}_p))\right] \\
&\quad + g' h_s \nabla (h + b) - \boldsymbol{u}_p \left(\frac{\partial}{\partial t} h_s + \nabla \cdot (\alpha_1 h_s \boldsymbol{u}_p)\right) = -\frac{\tau_y \beta}{\rho_d} \boldsymbol{f}_s,
\end{aligned}
$$

where C_m is an added mass coefficient. Including the added mass will also be necessary for a deformable submarine landslide, but the choice of the parameter C_m will require further studies.

2.2 Set-up and parameters

An example of BingClaw is given for the Storegga slide. The model and parameters are described extensively by [Kim et al., 2019]. If you open the `setrun.py` file, parameters for the slide can be chosen.

The following is a sample choice of the parameters, guided by [Kim et al., 2019]. You may edit and try with different parameters.

```
rho_a = 1000.0       # Density of ambient fluid
rho_s = 1860.0     # Density of slide
n_param = 0.5       # Bing rheology parameter
gamma_r = 100.0     # Reference strain rate
c_mass = 0.1       # Added Mass
hydrodrag = True     # Use hydrodrag force?
cF_hyd = 0.01     # Hydro-dynamic friction coeff.
cP_hyd = 1.0     # Hydro-dynamic pressure ceff.
remolding = True   # remolding?  if not, only tauy_i is used
tauy_i = 12000.0     # initial yield strength (Pa)
tauy_r = 300.0       # residual yield strength (Pa)
remold_coeff = 5e-4     # remolding parameter
qinit_style = 3     # topotype style initial conditions
```

Ambient density `rho_a` can be set around $1\,\mathrm{kg/m^3}$ if subaerial, and around $1000\,\mathrm{kg/m^3}$ if underwater. The density `rho_s` represents the density of the debris flow. Parameters `n_param` and `gamma_r` are explained in the Section 2.1. Added mass parameter and hydro-drag parameters are explained above. If we set `remolding = False`, then the remolding model is disabled, and `tauy_i` is used as the constant yield strength, and `tauy_r` is ignored. If `remolding = True`, then the remolding model is applied and three parameters, `tauy_i`, `tauy_r` and `remolding_coeff`, need to be chosen. When we use a variable yield strength, we provide a file. This file should contain information on γ rather than τ_y.

Visco-plastic models need a threshold to define a pseudo static state. In our model, we can use a velocity threshold by choosing a value of `vel_tol`. This threshold needs to be applied after `t_vel_tol` seconds which needs to be chosen appropriately.

In the solver, 6 variables are used, and each represents the h, u_p, v_p, hu, hv, and γ. The last variable γ is the accumulated shear, which is solved with an advection equation with the advection speed $\alpha_1 u$. There are 7 auxiliary variables set as `clawdata.num_aux = 7`. The first three variables are used for topography, and next two are the local slope of the topography in x and y direction respectively. The last two variables are used as flags, which are applied to the Riemann solver.

2.3 Spatial domain

If we set:

```
geo_data.coordinate_system = 1
```

then Cartesian coordinates are used, and the unit of the distance is in m. Otherwise, if we set:

```
geo_data.coordinate_system = 2
```

then geographical coordinates (i.e. latitude and longitude) are used, and the unit of the distance is in degree(°). We can specify the range of the computational domain and grid size:

```
# Lower and upper edge of computational domain:
clawdata.lower[0] = -5.0
clawdata.upper[0] = 7.0
clawdata.lower[1] = 62.0
clawdata.upper[1] = 68.0

# Number of grid cells:
clawdata.num_cells[0] = 313
clawdata.num_cells[1] = 334
```

2.4 Topography and initial conditions

The format of the files can be found at `http://www.clawpack.org/topo.html#topo`. You can provide the topography file by editing line 420 or so of `setrun.py` file. For example, the following is the Byneset slide topography

```
# == settopo.data values ==
topofiles = rundata.topo_data.topofiles
# for topography, append lines of the form
# [topotype, minlevel, maxlevel, t1, t2, fname]
fname = 'PaleoNorthAtlantic.tt3'
topofiles.append([-3, 1, 3, 0., 1.e10, fname])
```

We can set `minlevel` and `maxlevel` as 1 because we are not using adaptive mesh refinements. We can provide multiple topography files by adding two lines;

```
fname2 = '../../topo_ics/example/another_file.tt3'
topofiles.append([3, 1, 1, 0., 1.e10, fname2])
```

For the initial conditions, we can use the same format as GeoClaw, which only supports topotype=1 which is xyz format. I have extended the model so that we can use ESRI ASCII Grid format (topotype 3). In order to use ESRI format for the initial conditions, we need to set

```
qinit_style = 3     # topotype style initial conditions
```

Then we provide the initial condition as follows,

```
# == setqinit.data values ==
rundata.qinit_data.qinit_type = 1
rundata.qinit_data.qinitfiles = []
qinitfiles = rundata.qinit_data.qinitfiles
qinit_fname = 'storegga_ini.tt3'
qinitfiles.append([0,0,qinit_fname])
```

For this example, the file `slide_dx5.tt3` provides the height of the initial release volume. This file only needs to cover the landslide release area. This provided data can be processed in two ways as shown in Figure 2. If `qinit_type`$= 3$, the topography data is not modified and the initial release volume is added on top. If `qinit_type`$= -3$, then the topography data is modified so that the initial volume is subtracted.

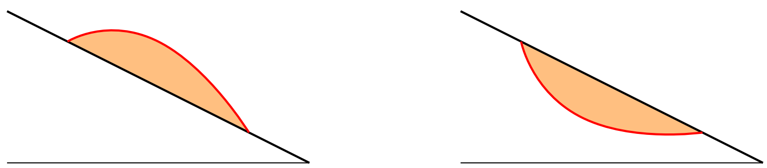

Figure 2: Initial release volume with `qinit_type`$= 3$ (left) and `qinit_type`$= -3$ (right).

2.5 Storegga slide

The topography and the initial release volume are given for this case. You may run the simulation with the following command:

```
python setrun.py
```

followed by an execution of the BingCLAW module in the directory in which the `.data` files have been generated.

A directory `BingClaw_fortfile_display_example` has been provided with a set of GMT-based tools for displaying the output.

And you may see a result similar to Figure 3, but the results may vary depending on the parameters.

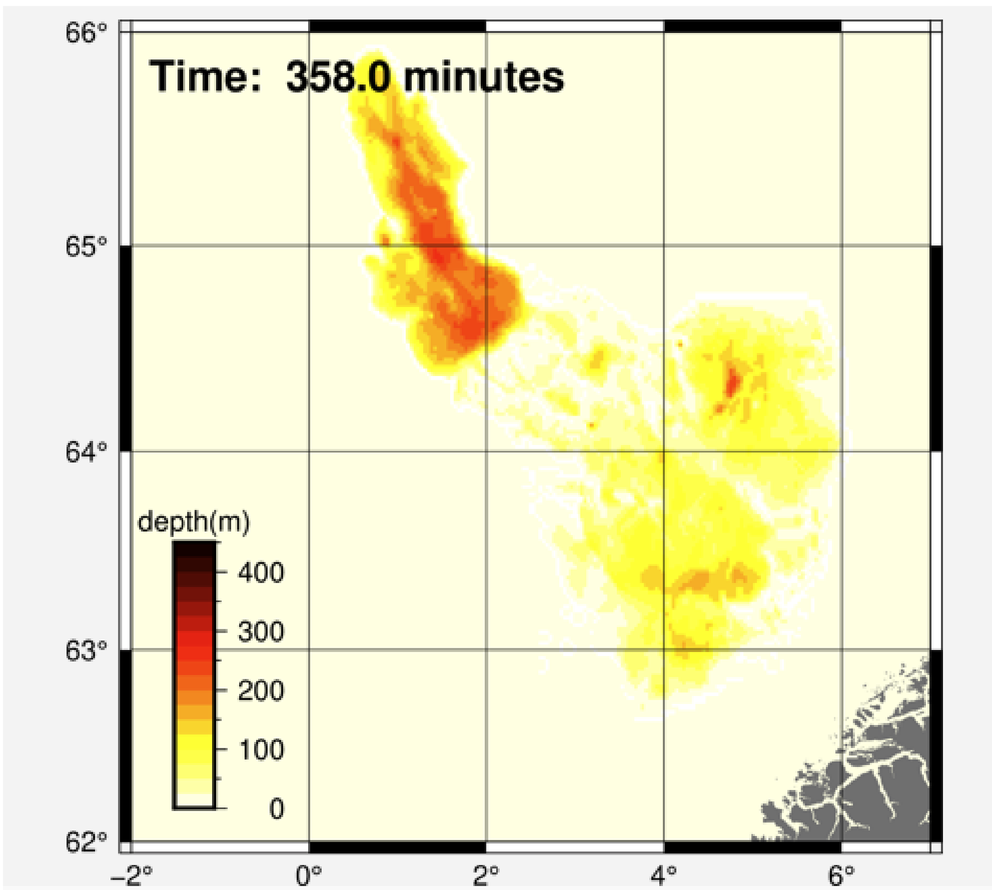

Figure 3: A snapshot at t=358 min. BingClaw result of the Storegga slide. The reddish colors indicate the flow/deposit depth (in m) at this time step.

3 Applicability and future directions

3.1 Grid dependency

Results of numerical flow simulations depend on the grid size in general. For example, the Byneset quick-clay landslide moved along narrow valleys and the outlet point was also narrow. In our current model, the Byneset slide simulation with $\tau_{y,0} = 22\,\mathrm{kPa}$ does not move and stays at the initial location when $\Delta x = \Delta y = 10\,\mathrm{m}$. If we decrease the grid size to $\Delta x = \Delta y = 5\,\mathrm{m}$, then the quick-clay moves along the valleys. Because the outlet gate of the quick-clay is narrow.

When the landslide is open-field type, the initialization of the slide movement is also affected by the grid size. In order to decide the movement of the landslide, the earth pressure gradient and the yield stress are compared, and the flow motion is initiated if the earth pressure is larger than the yield stress. The earth pressure gradient is approximated as,

$$\rho_s g h (h+b)_x \approx \rho_s g h_i \frac{h_{i+1} + b_{i+1} - h_{i-1} - b_{i-1}}{2\Delta x}.$$

The approximated earth pressure gradient may become significantly different at the boundary of the slide. For example, consider a dam-break problem with

$$h(x) = \begin{cases} 0, & \text{if } x < 0, \\ 2, & \text{otherwise,} \end{cases}$$

where $b(x) = 0$, ρ_s=2000 kg/m^3 and g=9.81 m/s. If Δx=1 and τ_y=45 kPa, then the approximated earth pressure is equal 39,240 Pa, and the movement is not initiated since the earth pressure is less than the yield strength. If the grid size is Δx=0.5 m, then the computed earth pressure gradient becomes twice as large and thus the movement is initiated.

3.2 Parameter dependency

For the Herschel-Bulkley model, we need to choose two parameters, n and $\dot{\gamma}_r$. The parameter n is a fluid index with $0 < n \leq 1$, and $\dot{\gamma}_r$ is a reference strain rate defined as $\dot{\gamma}_r = (\tau_y/\mu)^{1/n}$ with a dynamic viscosity μ (Pa·s). Two parameters τ_y and μ are inter-dependent, and one of them is determined by the choice of the other. In the current version, we choose the parameter γ_r. If $\dot{\gamma}_r$ is large, then μ is small, and the debris is easily deformable. Discussion on the choice of these parameters can be found at [Issler et al.,].

When the remolding model is invoked, four parameters ,$\tau_{y,0}$, $\tau_{y,\infty}$, and Γ, are required to be chosen carefully so that they represent the field and laboratory observations. The parameter Γ can be determined empirically. Based on preliminary studies, we suggest Γ between 1×10^{-2} and 10^{-1} for medium scale problems such as Byneset, Kattmarka and Rissa slides, and 5×10^{-4} and 5×10^{-3} for large scale events such as Storegga and Trænadjupet slides. However, the combination of the three parameters affects the remolding process. More studies are necessary to justify the parameter choice.

3.3 Initial conditions

The previous numerical simulations are calculations of the quick-clay slides that have already occurred. Since we have enough topographic information before and after the slide, we can choose the initial release volume based on these data.

There are uncertainties in the choice of the initial volume when the landslide did not occur. The prediction can be based on the analysis by the 3D models or slope stability analysis tools, and the initial slide surface can be chosen based on these results. More studies are required to connect the slope stability analysis and the initial release volume.

There is also uncertainty in choosing the rheological parameters. When we apply the results from the 3D analysis, we need to use depth-averaged values for the BingClaw parameters.

3.4 Miscellaneous

There are other factors that can affect the numerical results; depth and velocity thresholds, and CFL number.

In numerical models, a depth threshold is necessary to define wet and dry states. For example, if the flow height (h) is less than 10^{-3} m, then we assume that the state is dry and set $h = 0$. This threshold needs to be small ($< 10^{-5}$ m) when we apply the model to small scale problems.

Generally, a drawback of visco-plastic models is that a velocity threshold is required to define *static* state. When the speed of the slide is *small enough*, we assume that the landslide movement has stopped. Without a threshold, the debris model will continue to flow with very small speed. If the velocity threshold is applied from the beginning, the landslide will not move at all. Thus the velocity threshold needs to be applied at the stage where the landslide motion is expected to stop. This velocity and time thresholds need to be chosen differently depending on the scale of the problem. For the Storegga slides, one may choose the velocity and time threshold as 0.1 m/s and 1 hr respectively. For the Kattmarka case, one can choose 0.01 m/s and 1 min instead.

When the debris flow runs a long distance, the yield stress may change at the front area of the flow. For example, the picture of the Byneset slide shows that the front of the flow picks up other materials on the path, and the yield stress and friction have increased as a result. Since this property is not implemented in the current model, the run-out distance can be over-estimated.

The visco-plastic model is *friction-dominated* so that the friction terms can become large as to stop the flowing motion. In the current numerical scheme, the friction term is handled with the *fractional step method*, i.e., first we solve the conservation of mass and momentum equations without friction terms, then the friction terms are included separately. For this reason, the CFL number ($:= u\Delta t/\Delta x$) may affect the numerical results, but the difference may not be large.

A Appendix

A.1 Outputs and visualization

In default, all the output files are stored in the folder `_output`. The data files (`*.data`) are copied to this directory.

A.1.1 fort.q*

These are main output files. The header lines are:

```
1   grid_number
1   AMR_level
240   mx
300   my
0.54625000E+06   xlow
0.70470000E+07   ylow
0.10000000E+02   dx
0.10000000E+02   dy
```

We may ignore the first two lines since we do not use adaptive mesh refinement. From the next line, there are 7 columns of data, which represent $()h, u_p, v_p, hu, hv, \gamma, \eta)$. As a reminder, γ is an accumulated shear strain at the bottom, and η repersents the surface elevation, $\eta = h + b$. The output starts from xlow and ylow in x-direction.

A.1.2 fort.a*

They contain the data of the auxiliary variables. The header lines are same as `fort.q` files.

A.1.3 fort.t*

These files contain the time information of the outputs.

```
0.00000000E+00   time
7   meqn
1   ngrids
7   naux
2   ndim
2   nghost
```

These `fort.a*` files are referred when `fort.q*` files are used for plotting.

References

[Issler et al.,] Issler, D., Cepeda, J. M., Luna, B. Q., and Venditti, V. Back-analyses of run-out for norwegian quick-clay landslides. *NIFS report available at www.naturfare.no.*

[Kim et al., 2019] Kim, J., LÃ¸vholt, F., Issler, D., and Forsberg, C. F. (2019). Landslide Material Control on Tsunami Genesis: The Storegga Slide and Tsunami (8,100 Years BP). *Journal of Geophysical Research: Oceans*, 124(6):3607–3627.