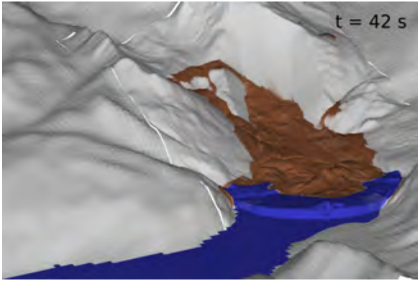
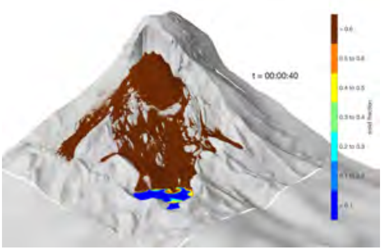
Modeling Earth-Surface Flow Hazards with D-Claw

David George[1]

[1]Cascades Volcano Observatory, U.S. Geological Survey

CSDMS 2018: Geoprocesses and Geohazards, Boulder, CO





Background and Acknowledgements

- Computational Mathematics and software developement
  - Randall LeVeque, UW
  - Marsha Berger, NYU
  - Donna Calhoun, Boise State
  - Kyle Mandli, Columbia
- Physical models for landlsides and debris flows
  - Richard Iverson, USGS
  - Debris-flow flume crews

Software

- Clawpack: (`www.clawpack.org`)
  - open-source package for general hyperbolic systems
  - shock-capturing wave-propagation algorithms
  - block-structured AMR
- GeoClaw: subset/extension of Clawpack
  - tsunamis, storm surges, overland flooding etc.
  - AMR schemes tailored to free-surface flows
  - specialized Riemann solvers
  - dynamic conservative integration of multiple arbitrary DEMs
- D-Claw: extension/generalization of GeoClaw
  - two-phase modeling for landslides and debris flows
  - reduces to geoclaw as solids volume $\to 0$
  - hybrid problems with interacting granular material and water

Modeling landslides and debris flows

In the 1980's growing interest in debris flows was spurred by

- Mount St. Helens lahars of May 18, 1980
- San Francisco Bay Area storm debris flows of January 5, 1982
- Armero, Colombia lahar of November 13, 1985

R.J. Janda photo

Landslides and debris flows

Debris flows, landslides etc.: granular-fluid mixtures.

Indonesian Lahar Movie   Ritigraben Switzerland Debris Flow Movie

Modeling landslides and debris flows

- Debris flows: variably mobile flows of saturated granular-fluid mixtures
- Landslide-generated debris flows begin when an unstable force balance is perturbed in a single source area
- Can then behave like a deforming solid, a rapidly accelerating fluid, creeping or slumping behavior, decceleration/deposition
- Predicting transitions between these regimes is difficult (sensititve to initial and material conditions)
- This range of behaviors cannot generally be reproduced with single rheological rules (eg. visco-plastic fluid)
- The apparent rheology evolves

Debris flow model summary

Model incorporates principles from fluid dynamics, granular-fluid mixture theory and quasi-static soil mechanics.

Iverson & George and George & Iverson. A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I & II. *Proc R Soc A* 2014 (470)

Properties:

- Depth-averaged shallow-flow model
- Two-phase model with pore-pressure evolution
- Strictly hyperbolic system of five PDEs
  - h: depth
  - u, v: depth-averaged mixture velocities
  - m: solid-volume fraction
  - p_b: basal pore-fluid pressure

Debris flow model summary

Motivation:

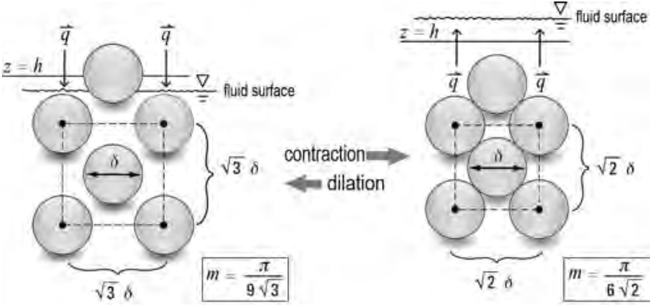
- simulation from initiation to deposition
- initialization from realistic force balances (not a “hot-start”)
- capture the transition from stability to mobility
- model the evolving apparent rheology
- slope stability $\leftrightarrow$ flow fate

Basis:

- coevolution of pore-fluid pressure and solid-volume fraction
- pore-fluid pressure/effective stress $\rightarrow$ mobility/shear resistance

Mobility and dilatancy

Coupling m and p_b



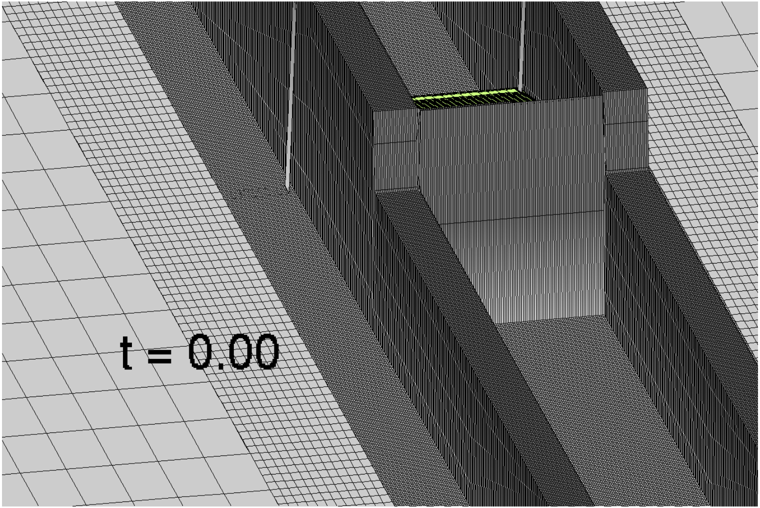
- dilation/contraction of solid phase affects pore-pressure
- pore-pressure mediates Coulomb stress

USGS experimental debris-flow flume

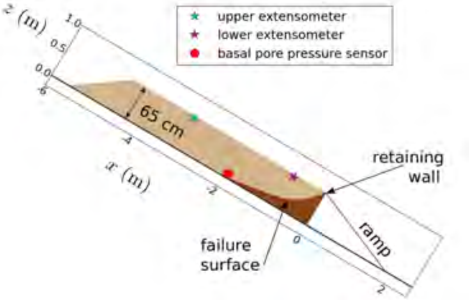
Play Movie

USGS experimental debris-flow flume

Simulating gate release dynamics



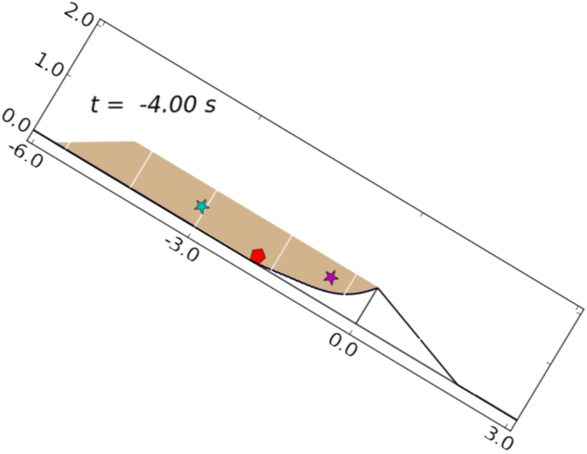
Investigating mobility and porosity

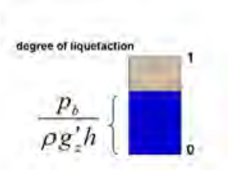


Play Movie

Model validation: investigating mobility and porosity

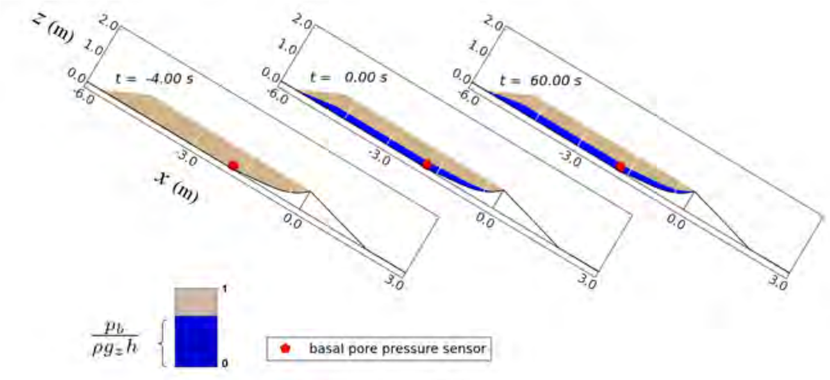
"loose soil:" $m_0 - m_{crit} = -0.08$





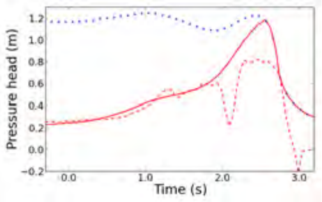
Model validation: investigating mobility and porosity

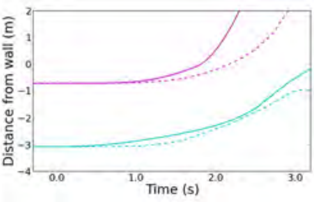
"dense soil:" $m_0 - m_{crit} = +0.03$



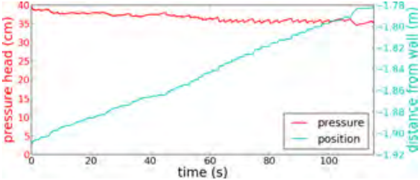
Model validation: investigating mobility and porosity

"loose soil:" $m_0 - m_{crit} = -0.08$





"dense soil:" $m_0 - m_{crit} = +0.03$



Modeling debris flows and water bodies

- D-Claw: two-phase model with evolving volume fractions
- Equations reduce to shallow water equations as solids vanish.
- We have extended the model to problems that involve interations of landslides and bodies of water
- This allows seamless computation of hybrid events without complicated model coupling

Cascading flow hazards (interacting flow bodies)

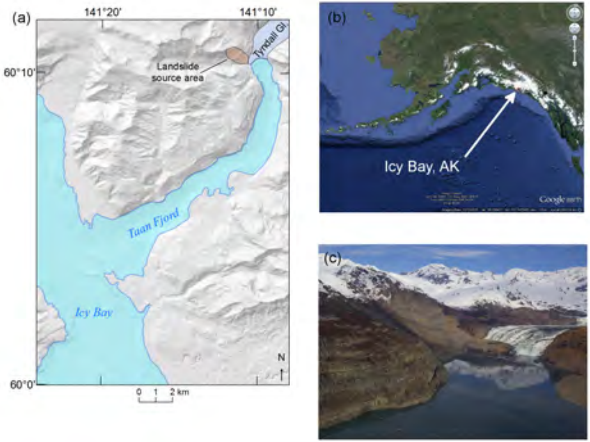
Earth-surface flow hazards often involve dynamically coupled chains of events. (Granular materials interacting with water).

- Tsunami inundation entraining debris
- Landslide-generated tsunamis
- Formation and failure of natural dams from landslides
- Flash-floods that entrain debris
- Glacial-lake outburst floods

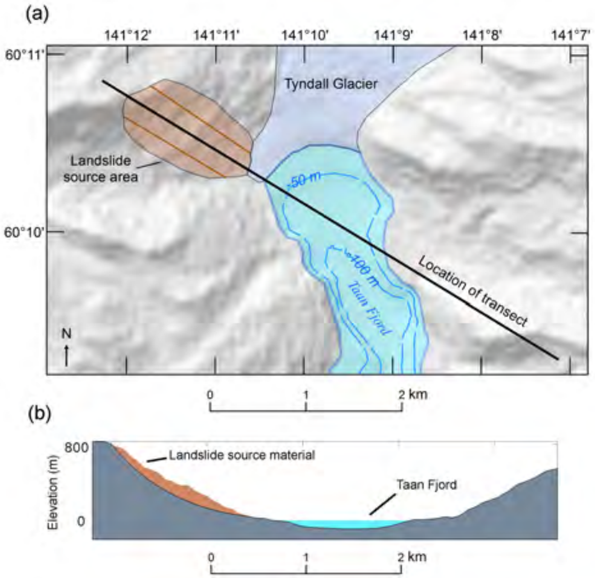
Landslide-Generated Tsunamis

- Landslide-generated tsunamis are a well-recognized hazard.
- Waves and inundation can be larger than coseismic tsunamis.
  - eg., 1958 Lituya Bay, AK, megatsunami – ≈ 500 m runup!
  - eg., 2015 Tyndall Glacier, AK (large non-volcanic landslide).
- Can be generated by submarine and subaerial landslides.
- Generation mechanisms differ (uplift vs. impulse waves).
- We use a seamless D-Claw simulation for all phases.

2015 Tyndall Glacier Landslide and Taan Fjord Tsunami



2015 Tyndall Glacier Landslide and Taan Fjord Tsunami

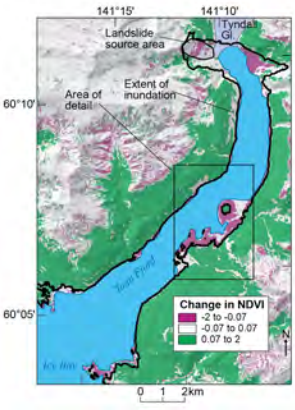


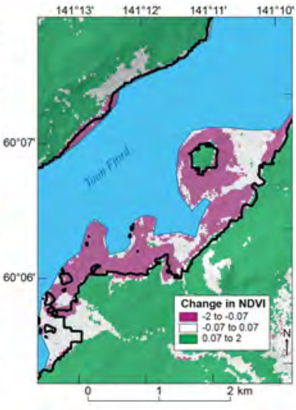
Taan Fjord Landslide

2015 Tyndall Glacier Landslide and Taan Fjord Tsunami

Taan Fjord Tsunami

2015 Tyndall Glacier Landslide and Taan Fjord Tsunami



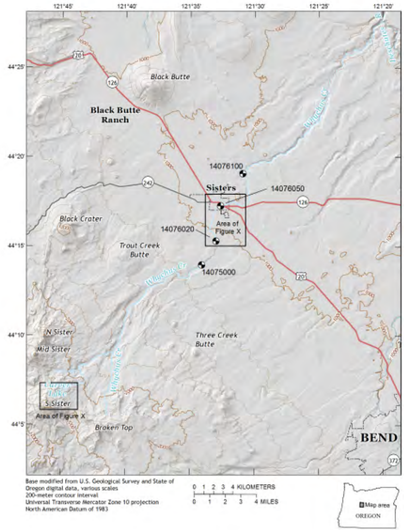


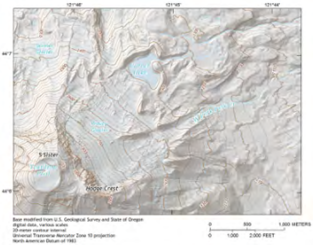
Sisters, OR, Carver Lake outburst flood

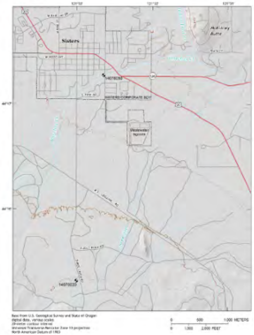
Sisters, OR, Carver Lake outburst flood

Base modified from U.S. Geological Survey and State of Oregon digital data, various scales
20-meter contour interval
Universal Transverse Mercator Zone 10 projection
North American Datum of 1983

Sisters, OR, Carver Lake outburst flood

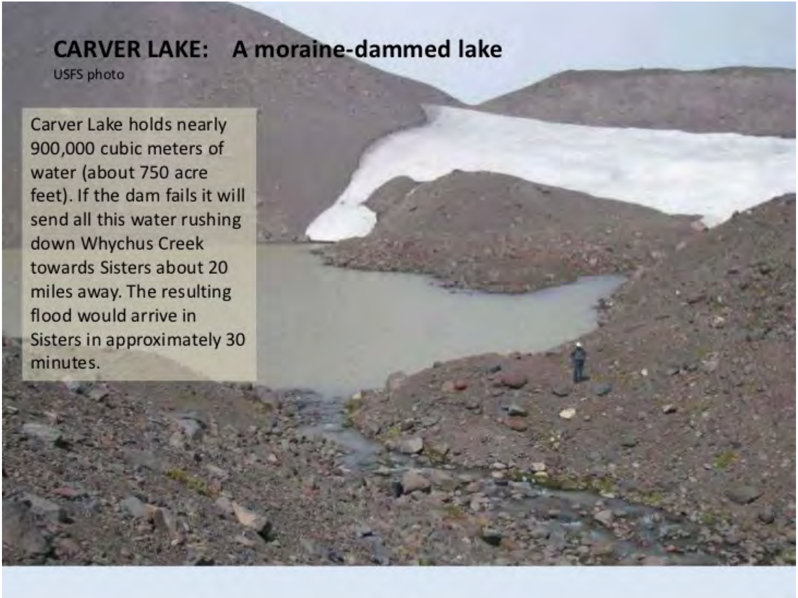






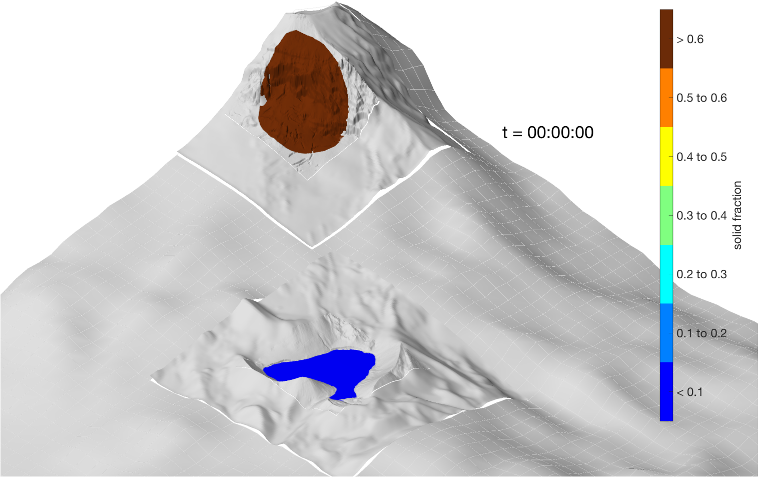
Sisters, OR, Carver Lake outburst flood

Sisters, OR, Carver Lake outburst flood

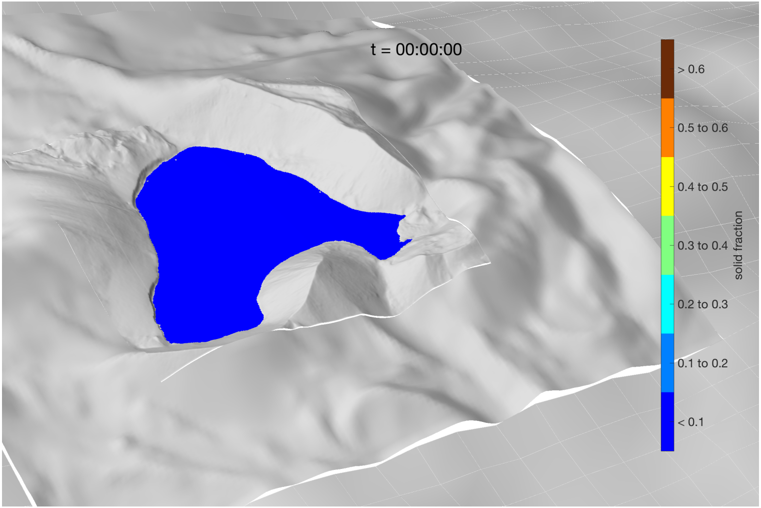


Sisters, OR, Carver Lake outburst flood

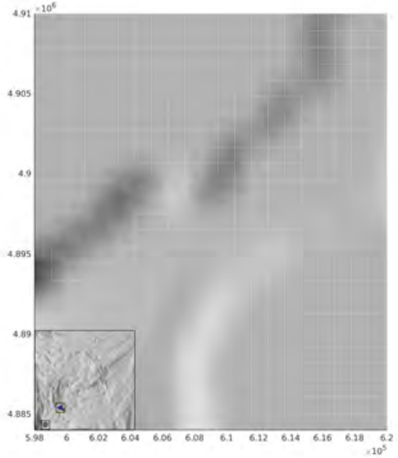
Sisters, OR, hypothetical landslide and dam failure

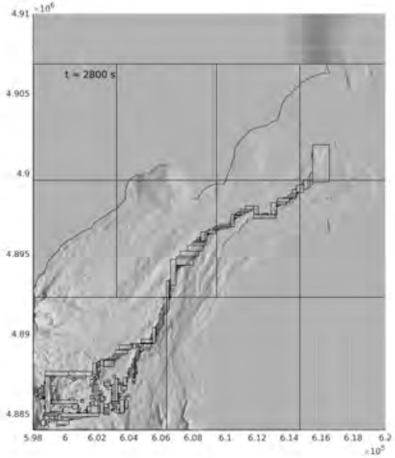


Sisters, OR, hypothetical landslide and dam failure

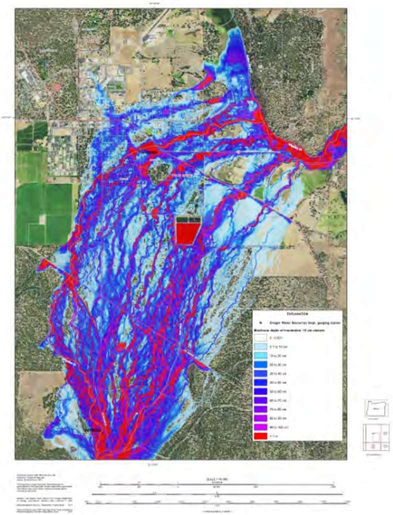


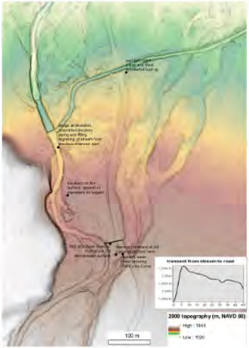
Sisters, OR, hypothetical landslide and dam failure





Sisters, OR, hypothetical landslide and dam failure

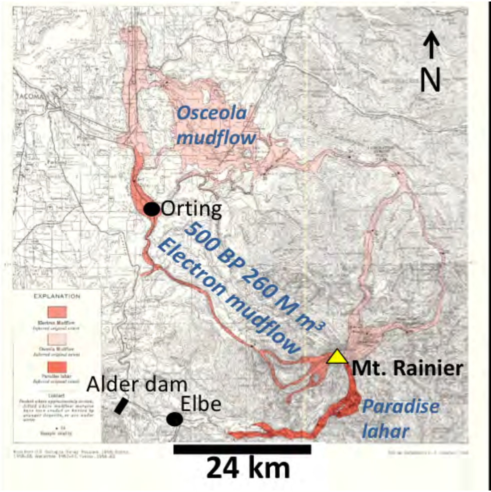




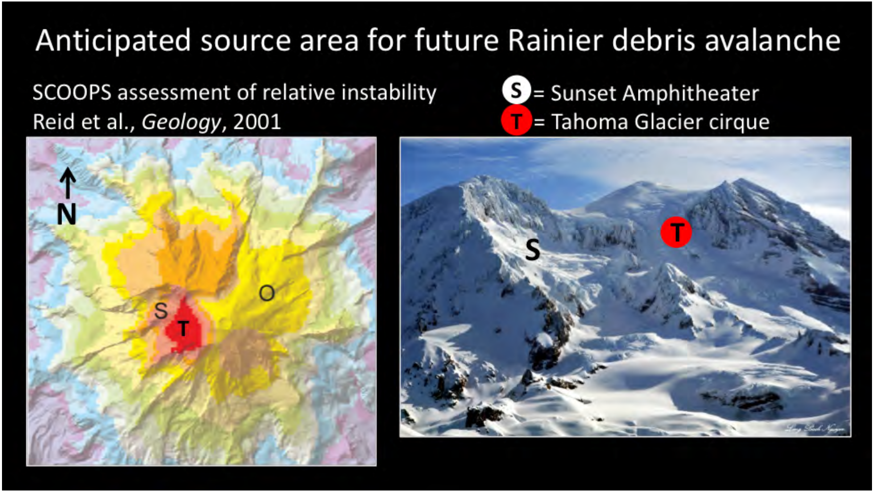
Modeling Potential Mt. Rainier Lahars

Modeling Potential Mt. Rainier Lahars

Mount Rainier
Holocene lahar paths
delineated by
D.R. Crandell, 1971
(*USGS Prof. Pap. 677*)

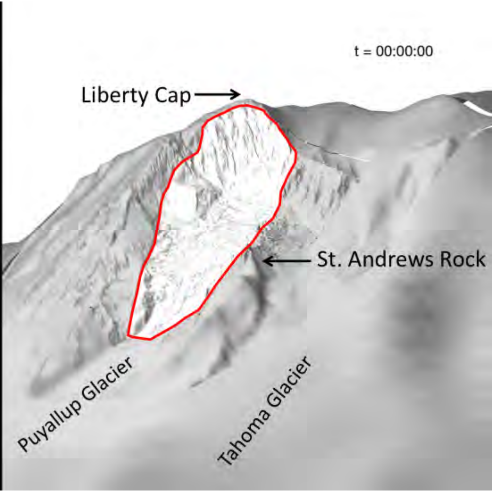


Modeling Potential Mt. Rainier Lahars

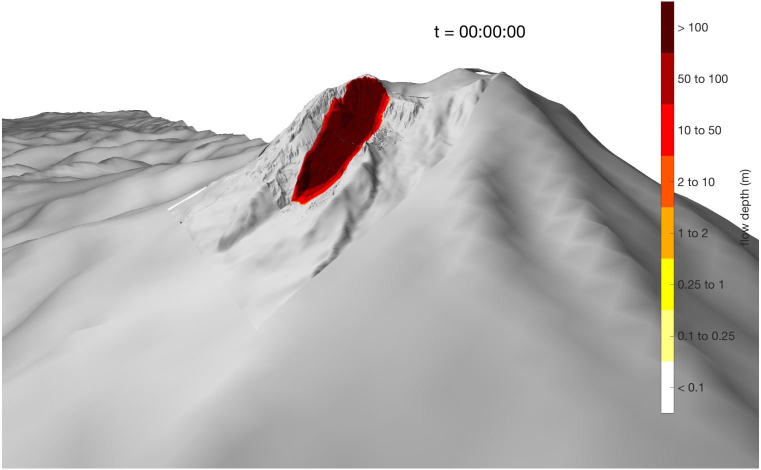


Hypothetical Mt. Rainier Lahar (Sunset Amphitheater)

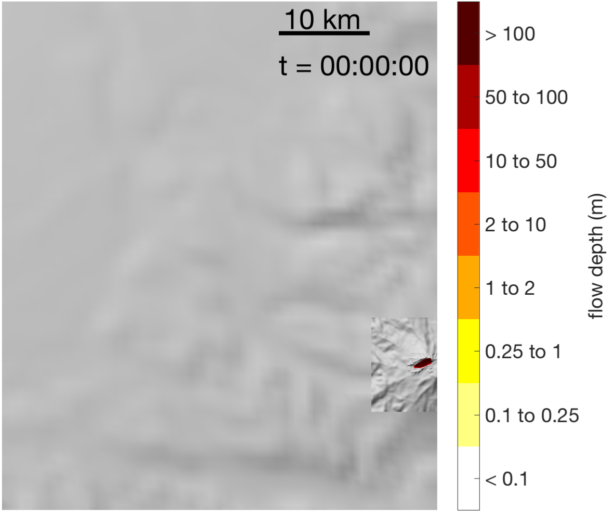
D-Claw simulation of 260 million m^3 debris avalanche in Sunset Amphitheater, Mount Rainier



Hypothetical Mt. Rainier Lahar (Sunset Amphitheater)



Hypothetical Mt. Rainier Lahar (Sunset Amphitheater)

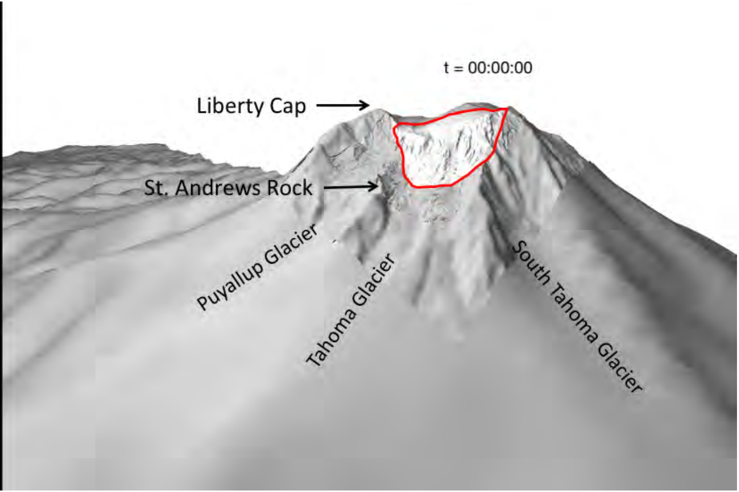


Hypothetical Mt. Rainier Lahar (Sunset Amphitheater)

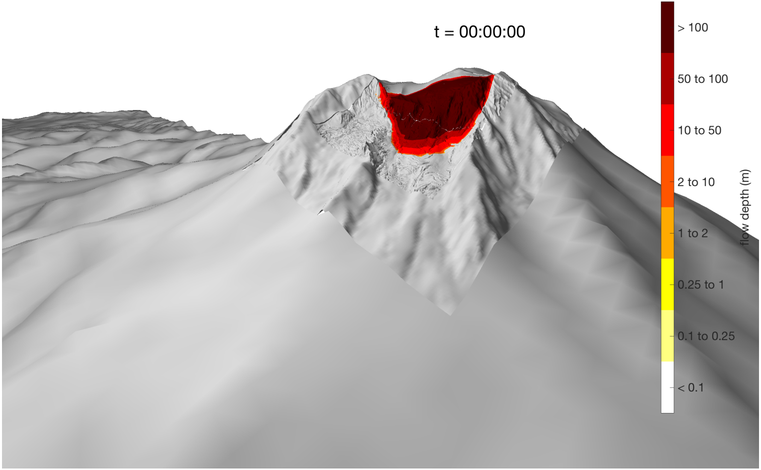
Puyallup valley movie

Potential Mt. Rainier Lahar (least stable source region)

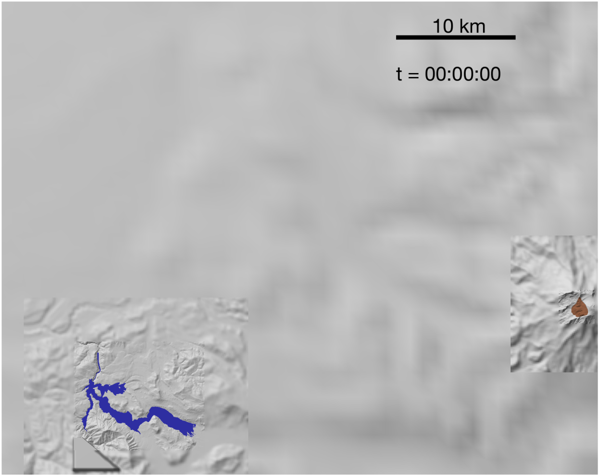
260 M m^3 debris avalanche in least-stable source region



Potential Mt. Rainier Lahar (least stable source region)

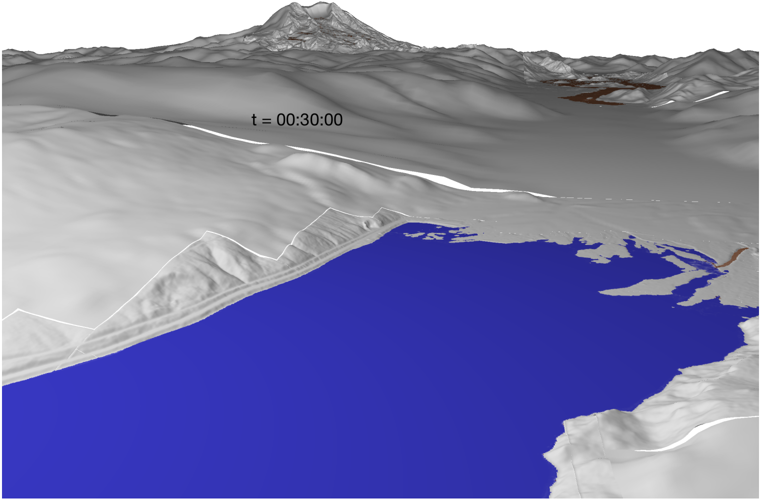


Potential Mt. Rainier Lahar (least stable source region)

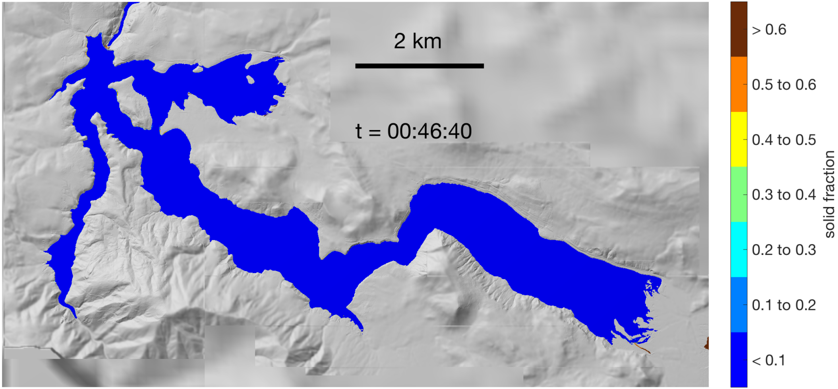


Potential Mt. Rainier Lahar (inundation of Alder Lake)

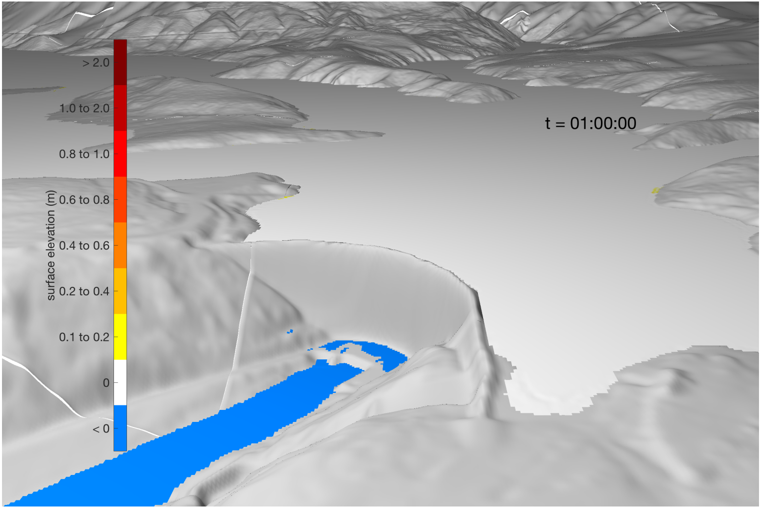
Potential Mt. Rainier Lahar (inundation of Alder Lake)



Potential Mt. Rainier Lahar (inundation of Alder Lake)



Potential Mt. Rainier Lahar (inundation of Alder Lake)



Conclusions and Future Directions

Future directions:

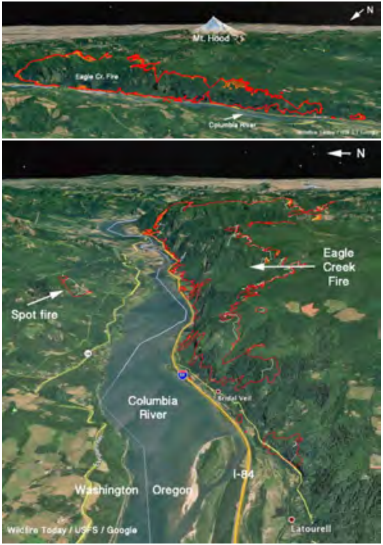
- Improved physical models for entrainment.
- Inclusion of sediment transport/deposition models.
- Rainfall infiltration models/other models for distributed-source post-wildfire debris flows.
- Multi-layered, multi-phase models with mass exchange and realistic momentum exchange

Thank you!

Post-wildfire debris flows

- Debris flows can result from overland flow (rainfall) that entrains debris
- This initialization process is very different from an isolated landslide-generated debris flow
- Can D-Claw be applied to these?

Modeling hypothetical Eagle Creek debris flows



Modeling hypothetical Eagle Creek debris flows