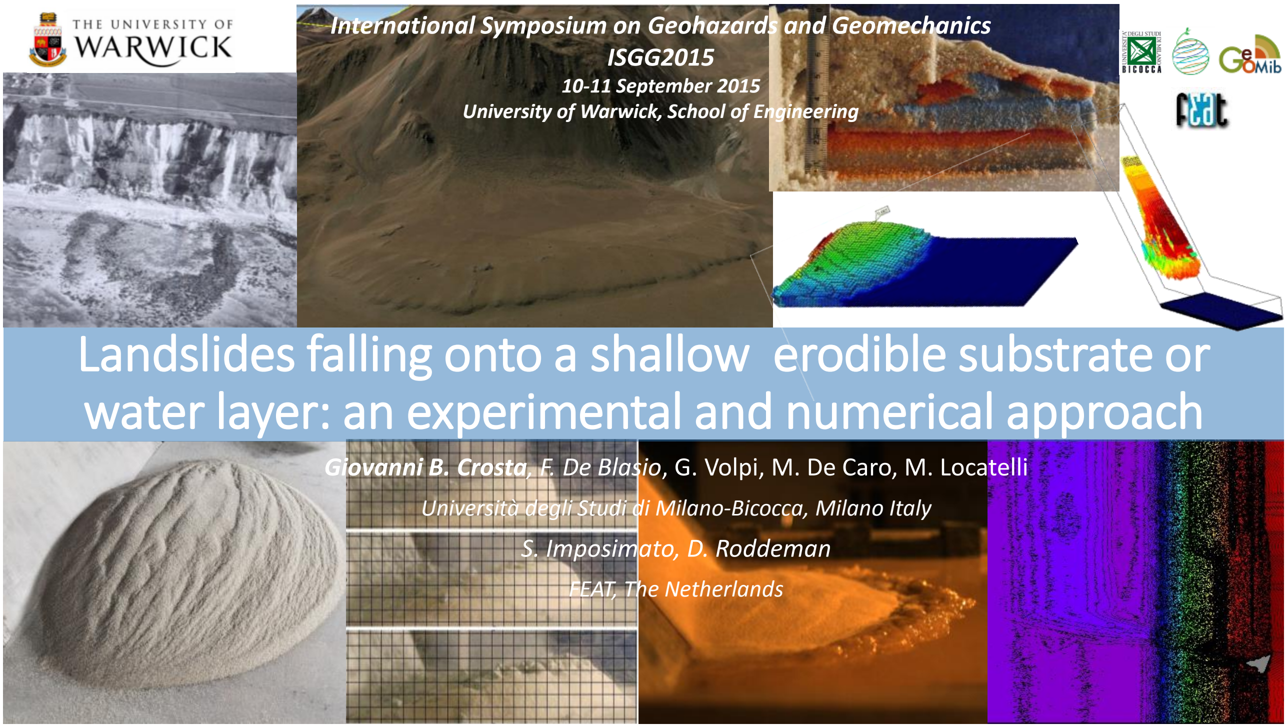


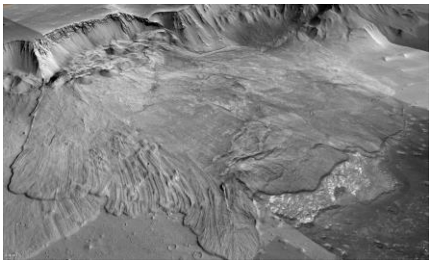
International Symposium on Geohazards and Geomechanics
ISGG2015
10-11 September 2015
University of Warwick, School of Engineering

Landslides falling onto a shallow erodible substrate or water layer: an experimental and numerical approach

***Giovanni B. Crosta**, F. De Blasio*, G. Volpi, M. De Caro, M. Locatelli
Università degli Studi di Milano-Bicocca, Milano Italy
S. Imposimato, D. Roddeman
FEAT, The Netherlands

Contents

Les Petits-Dalles, near Dieppe, 2013



Capris-Ganges Chasma, Mars

Role of **conditions along the spreading path** of a ‘flow-like’ landslide:

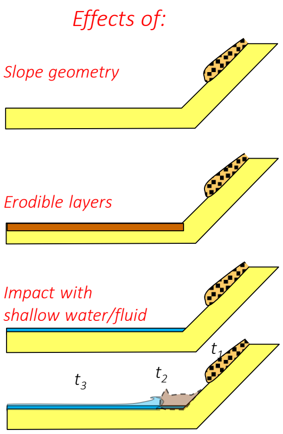
- *Slope geometry*: abrupt slope change
- *Materials:*
  - **Distribution** & **Thickness**
  - **Properties**

1 - Initial experiments & modelling

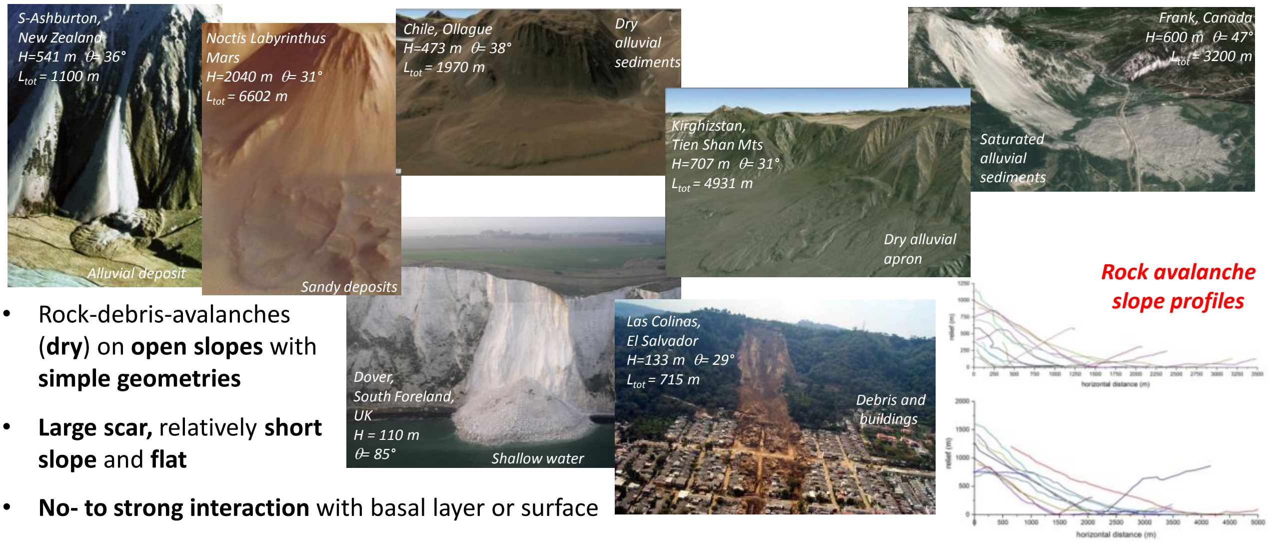
2 - Small scale experiments: deposition, erosion, time evolution

3 - FEM ALE model: M-C elasto-plastic material for flow and deposition

4 – Recents efforts: testing and modelling under different conditions



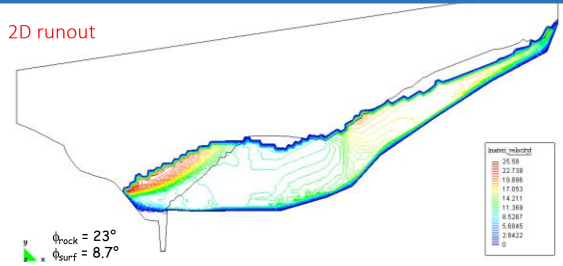
Real rock avalanches: *chosen settings*



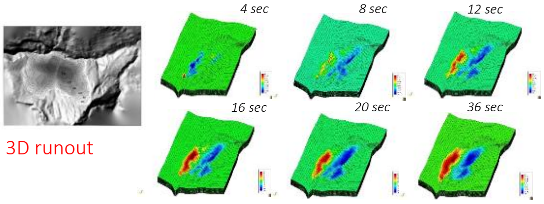
- Rock-debris-avalanches (**dry**) on **open slopes** with **simple geometries**
- **Large scar,** relatively **short slope** and **flat**
- **No- to strong interaction** with basal layer or surface

Previous Experiences
2D and 3D Runout

2D runout



ϕ_{rock} = 23°
ϕ_{surf} = 8.7°

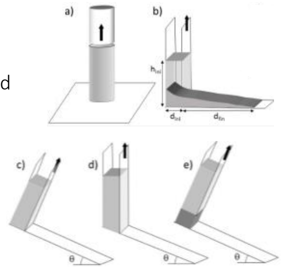


3D runout

105.000 hexahedral, 8 node elements
ϕ = 12°- 5.7°

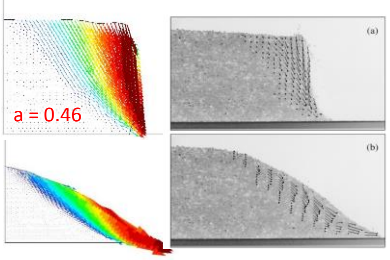
Crosta et al., 2002 NATO ARW, 2005 EGU
Crosta et al., 2007; EC LessLoss Project

Tochnog FEM code *(Roddeman, 2001, 2014)*
ALE Arbitrary Eulerian-Lagrangian calculation, Isoparametric FE, Euler backward timestepping → stability in time
Transport of state variables in space stabilised by Streamline Upwind Petrov Galerkin



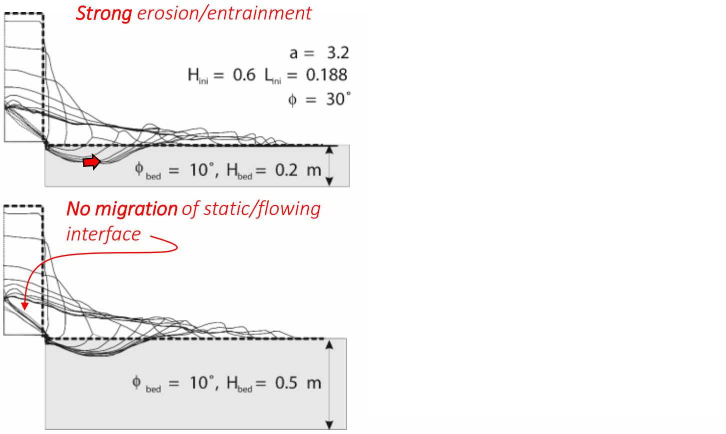
INITIAL STEPS:

- 2D slope stability and runout simulations
- 3D runout simulations in dry conditions
- 2D **granular column collapse** with different aspect ratios→**well constrained** tests



Previous Experiences

Granular column collapse on erodible layer: effect of layer properties

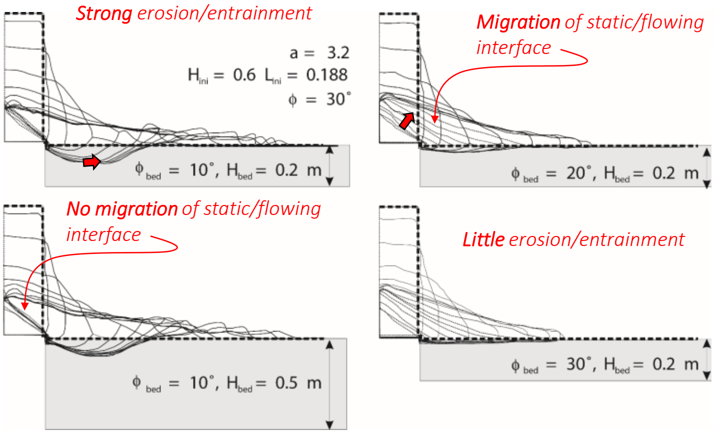

Strong erosion/entrainment

No migration of static/flowing interface

(Crosta et al., 2009)

Previous Experiences

Granular column collapse on erodible layer: effect of layer properties


Strong erosion/entrainment

Migration of static/flowing interface

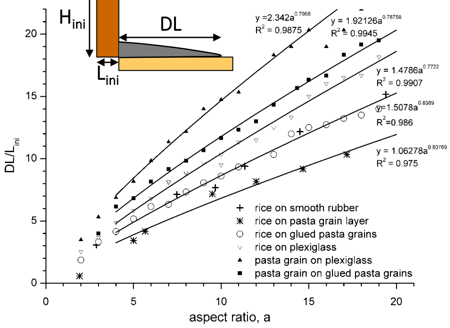
No migration of static/flowing interface

Little erosion/entrainment

(Crosta et al., 2009)

Decrease in interaction at increasing strength of the erodible layer
Erosional to depositional trend → interface migration

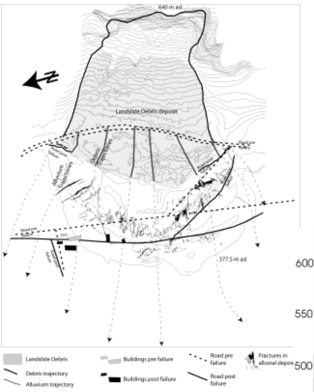
Runout/initial length versus aspect ratio on different materials



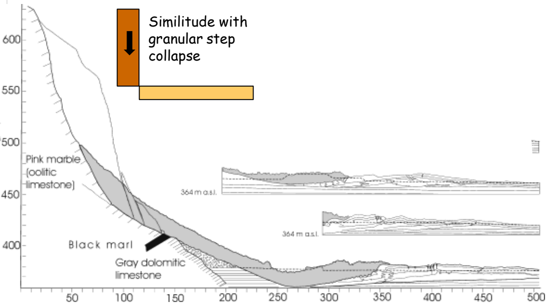
Effect of the strength and stiffness of a basal rigid surface/material

Previous Experiences

a granular step-like rock slope failure: Arvel, 1922



(Choffat, 1929)

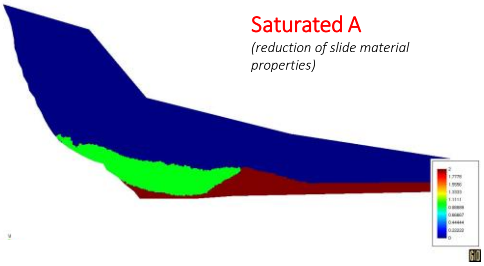

Similitude with granular step collapse

Previous Experiences

Deposit geometry (material properties, saturation)

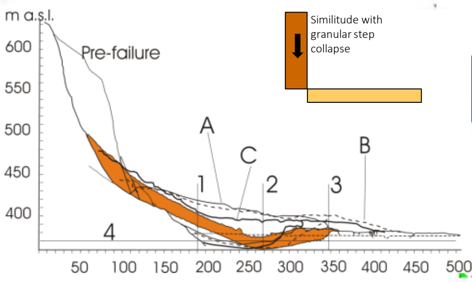
38.000 triangular three-node elements mean size = 2 m

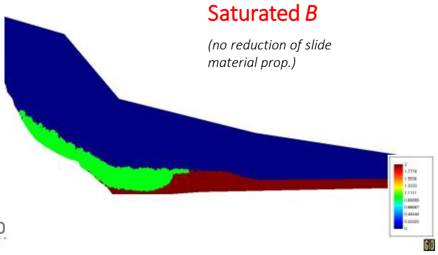
Crosta et al., 2008



(reduction of slide material properties)

both velocity and thickness of the entrained/pushed materials increase with saturation


Similitude with granular step collapse



(no reduction of slide material prop.)

Problems:

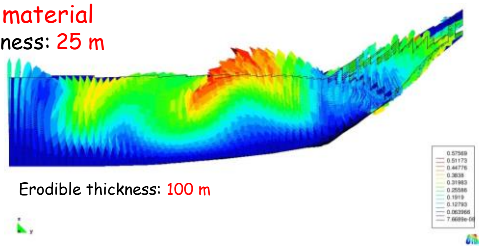
Thickness
→ bed deformation

3D effects
→ generation of an **apron shaped deposit**

Previous Experiences

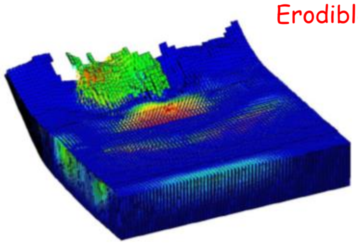
Deposit geometry (material properties, thickness)

Incoherent material
Erodible thickness: 25 m



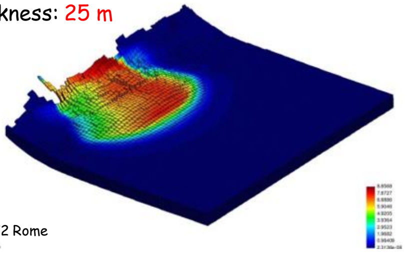
Erodible thickness: 100 m

Erodible thickness: 100 m

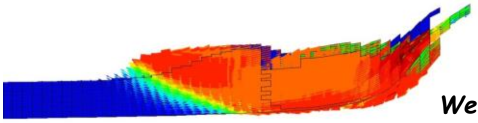


Fold-like

Cohesive material
Erodible thickness: 25 m



Crosta et al., 2011; WLF2 Rome



Wedge Thrust-like

- radial pattern of deformation
- thickness of layer inversely related to runout
- deposit area inversely related to thickness of erodible layer
- deformation larger in thicker and frictional materials

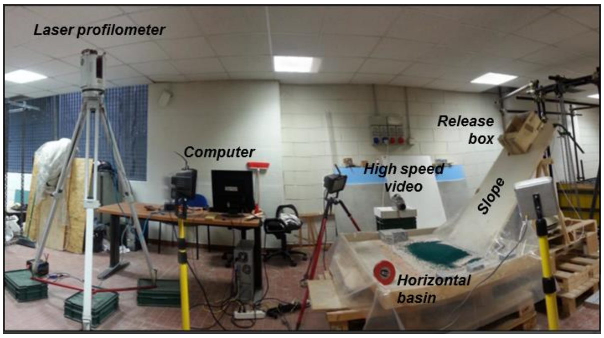
Crosta et al., 2011, 2013
Landslide Science and Practice, WLF Rome

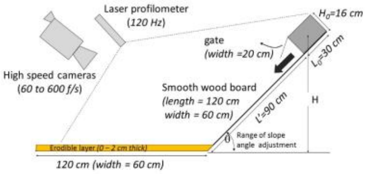
Experiments: *apparatus, materials, methods*

- Simple apparatus
- Release mechanism
- Different materials

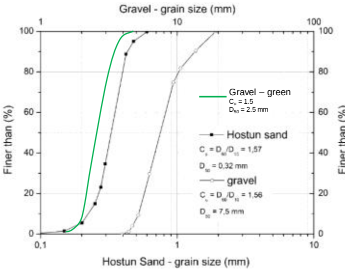
- Variable:
  - Volume of material *(1.5-5.1 L; H_o = 5-8.5 cm)*
  - Slope angle *(θ=35-66°)*
  - Erodible layer *(0-2 cm)*

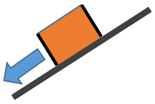
- Data acquisition:
  - High speed cameras: 60-600 fps
  - Laser beam: 120 Hz
    (beam spot: 5 mm, accuracy: 5 mm)





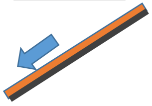
Test conditions: *materials, geometry*



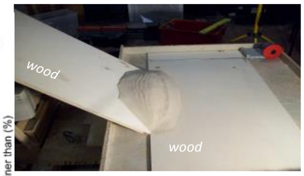


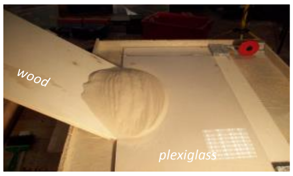
Sliding cylinder angle

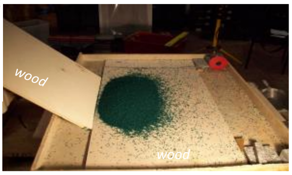
Repose angle



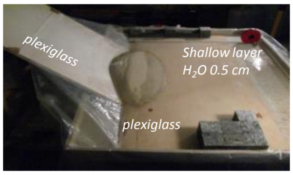
Avalanching angle

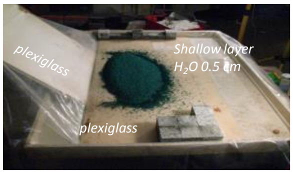


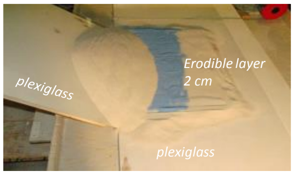




- *Different basal materials in difeerent combinations (slope, flat, → plexiglas, wood)*
- *Slope angle (35° - 60°)*
- *Granular flow materials (sand, gravels)*
- *Shallow layer in flat portion (sand, water)*

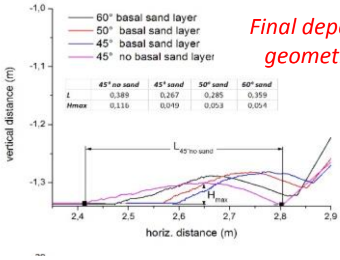






Deposit characteristics: *sand/smooth, sand/sand*

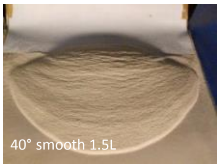
- **Smooth surface**: long **open apron**
- Slope **< 45°**: **stepped surface** laying on the inclined slope
- Slope **> 45°** : **lobate/lunate** deposit with wavy surface detached from sloping chute

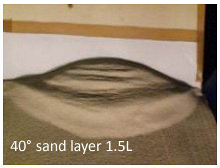


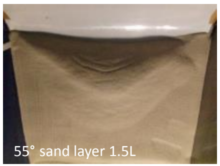
	45° no sand	45° sand	50° sand	60° sand
L	0,389	0,267	0,285	0,359
Hmax	0,116	0,049	0,053	0,054

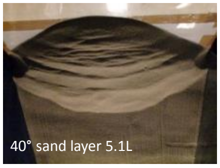
Final deposit geometry

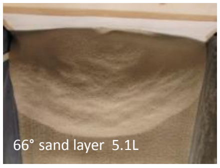
Slope angle







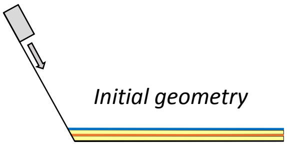


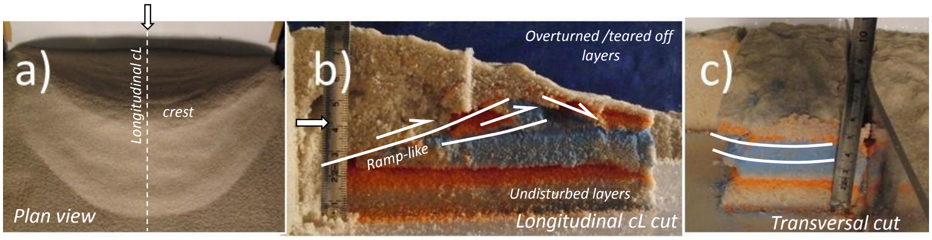


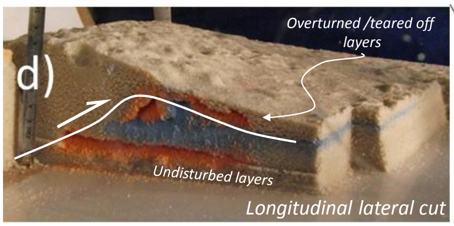
Deposit: *internal structure*

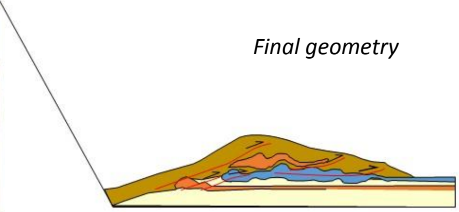
- Colored sand layers
- Internal deformation
- Erosion
- Thrusting & folding
- Double-layering

Similar to ***Rowley et al, 2011***



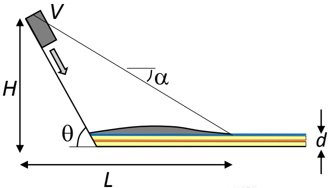


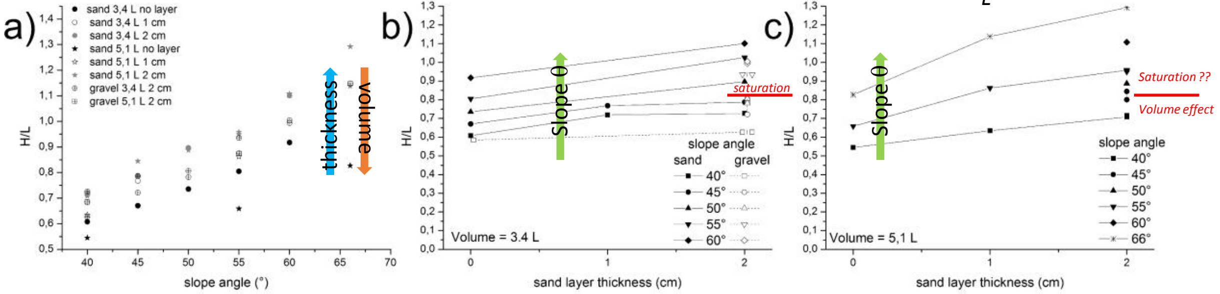




H/L ratio: *mobility vs slope angle, layer thickness*

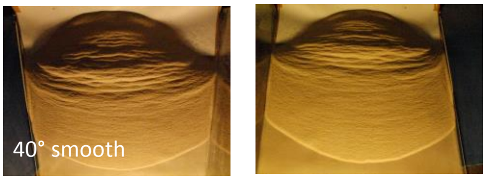
- H/L = Heim's ratio: apparent dynamic friction angle
- Effects of slope angle and erodible layer thickness on mobility
- Gravel slightly more mobile

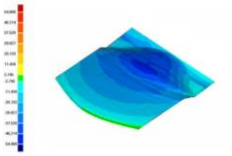




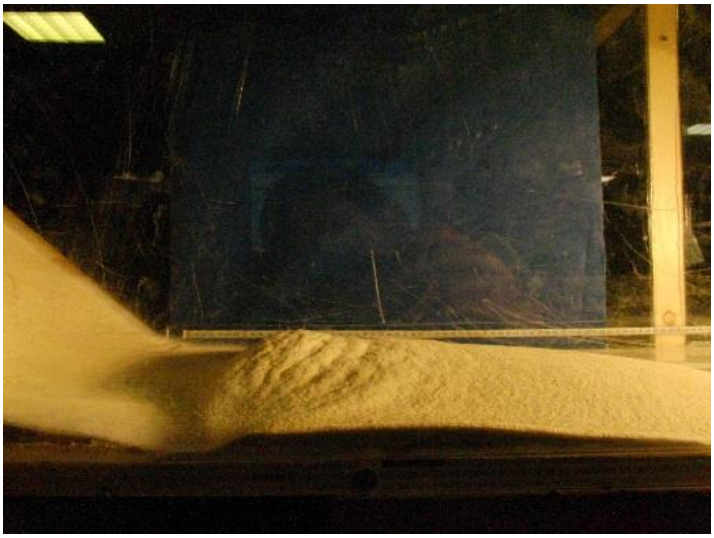
Flow and Deposit evolution: *sand/smooth*

- Smooth surface:
- 40° slope



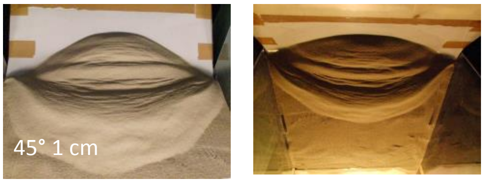


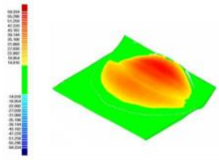
- Strong elongation
- Thin tapered deposit
- Backward propagation
- Ramp-like features



Flow and Deposit evolution: *sand/sand*

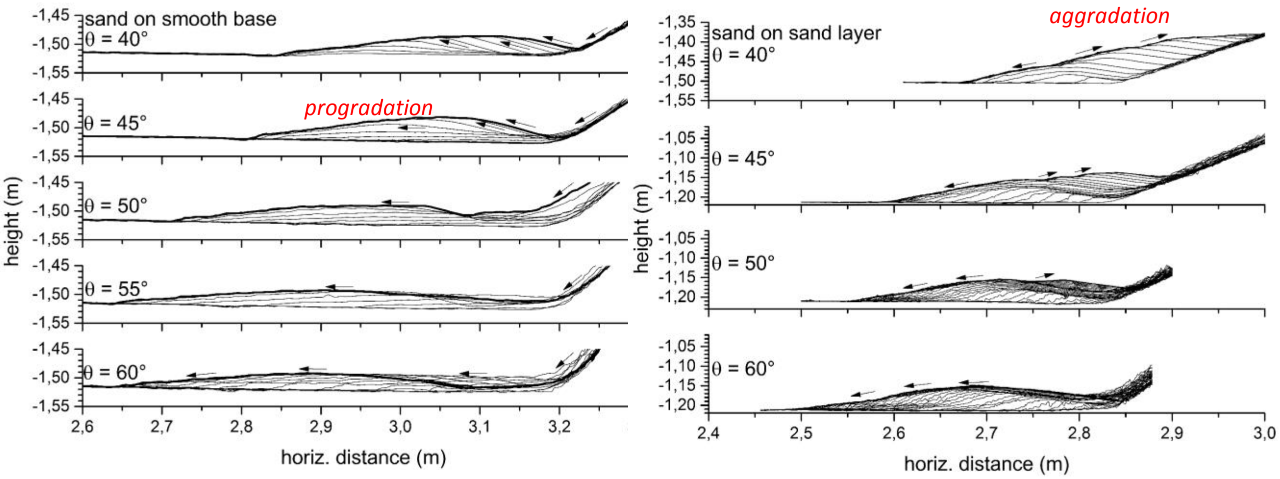
- Sand on sand
- Erodible sand layer
- 45° slope angle





- Thick deposit
- Dilation at impact
- Breaking wave
- Shallow frontal wave
- Backward propagation

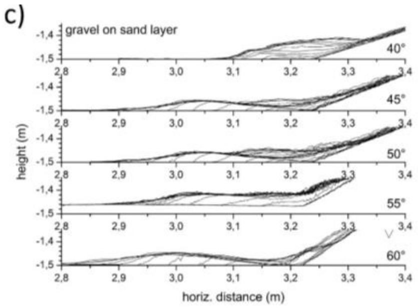
Flow and Deposit evolution: *centerline profiles → time*

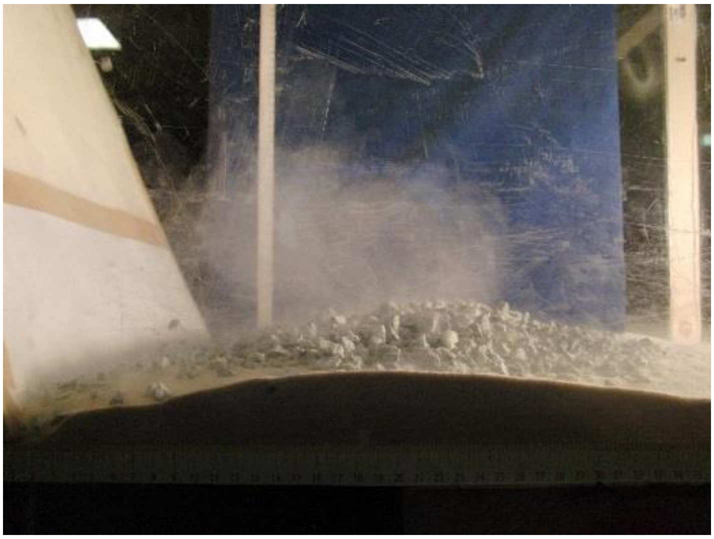


120 Hz - aggradation by backward shockwave propagation, progradation

Flow and Deposit evolution: *gravel/sand*

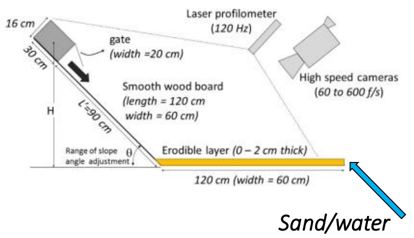
- Gravel on sand
- Erodible sand layer
- 66° slope angle
- Gravel piggy back transported by the pushed sand wave



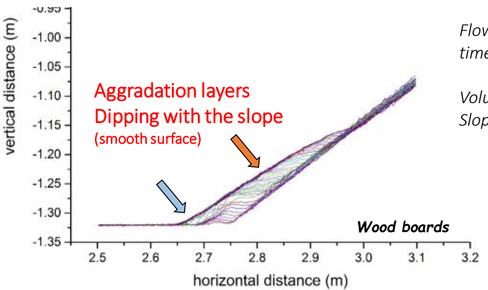


Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Flow and Deposit evolution: *effect of base material*



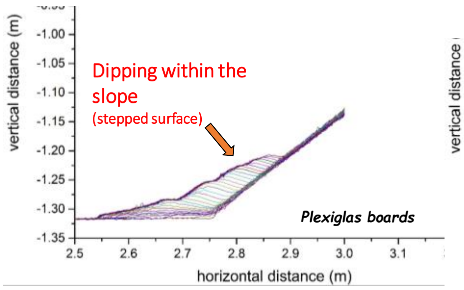
Sand/water



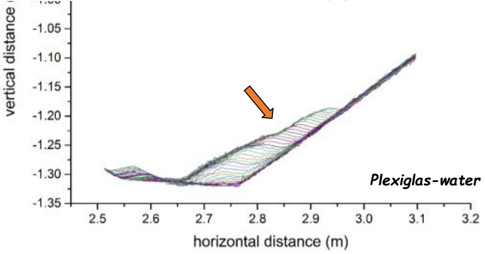
Aggradation layers
Dipping with the slope
(smooth surface)

Flow evolution through time - Hostun sand

Volume = 5.1 L
Slope = 35°

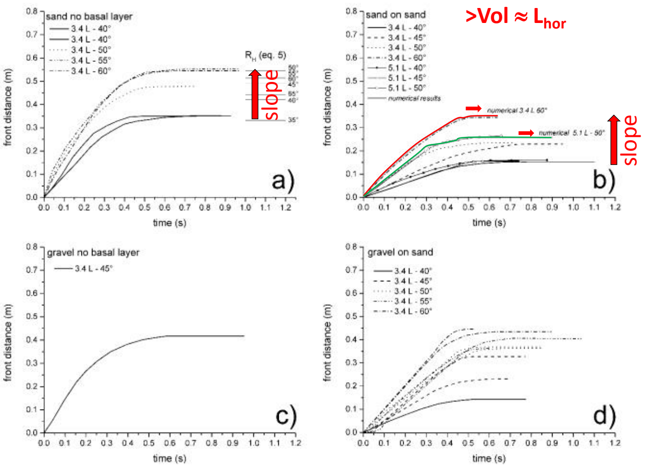


Dipping within the slope
(stepped surface)



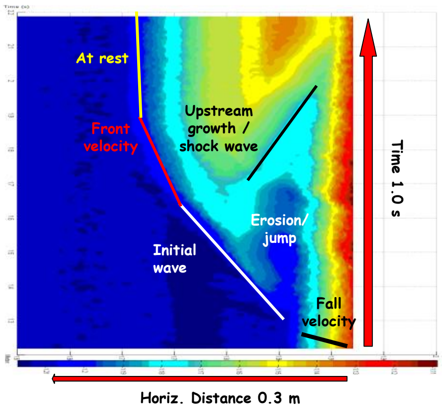
Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Flow and Deposit evolution: *front position, velocity*



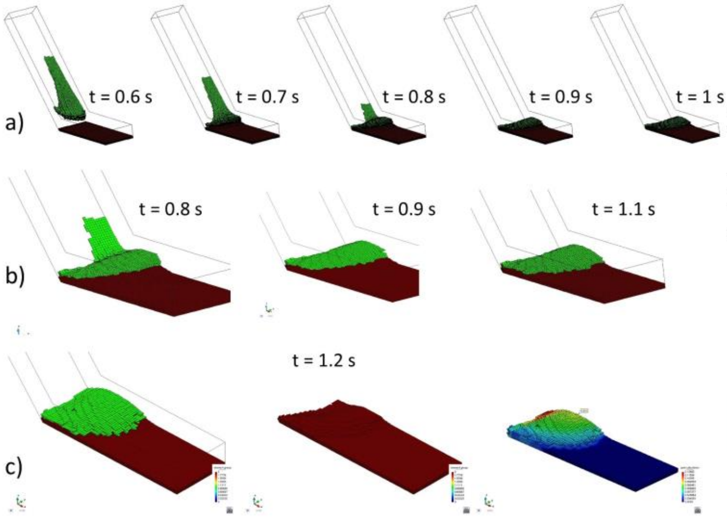
$>Vol \approx L_{hor}$

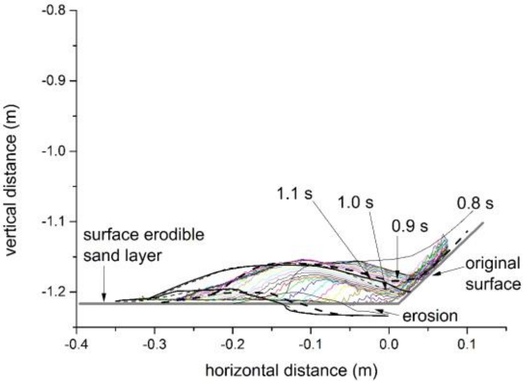
- Spatio-temporal plots
- Fall velocity
- Front propagation velocity



Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

3D Numerical Modeling: *FEM-ALE results*





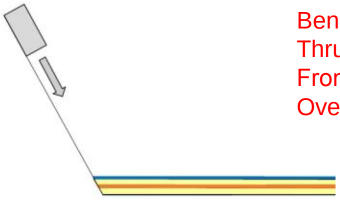
	Max deposit thickness (cm)	*Max runout distance (cm)*
Laboratory test	*7.5*	*105*
Numerical sim.	*8.3*	*110*

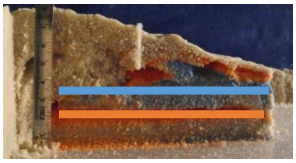
Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

2D Numerical Modeling: *internal deformation*

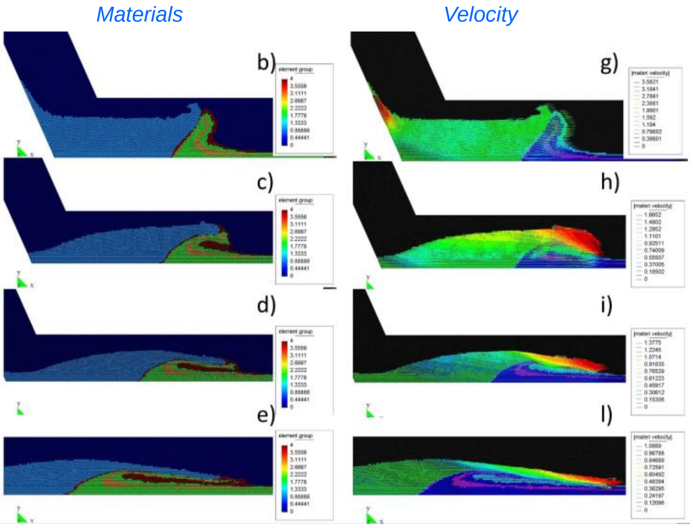
2D Plane Strain conditions
60° slope
Volume = 5.1 L
60,814 triangular elements

Internal friction = 28.5°
No cohesion - No dilatancy
Basal friction angle = 22°
Basal Layer = 2 cm
Max element size = 3 mm



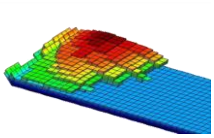


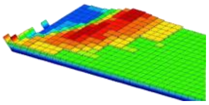
Observations:
weathering limited condition
Steep erosion front
Bending interface
Thrusting
Front “wave” instability
Overturned sequence

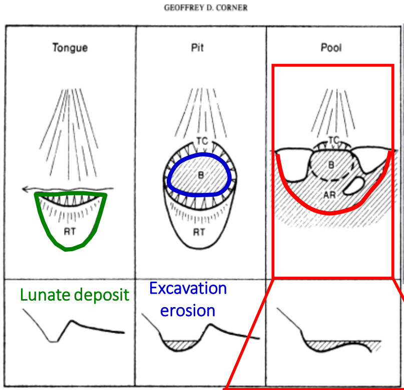


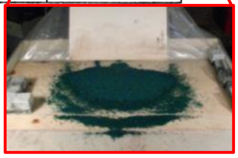
Real world analogues: *deposit geometry*

Impact structures:
snow avalanches at
toe of steep slopes





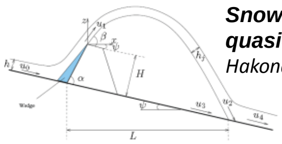




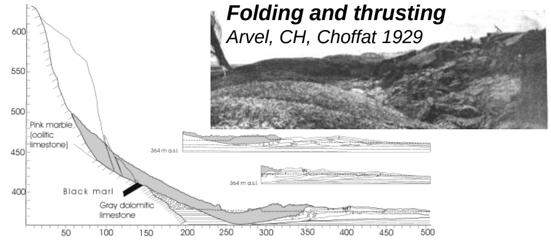
Ring deposits:
snow avalanches and
Chalk flow deposits in
shallow water

Real world analogues: *evolution*

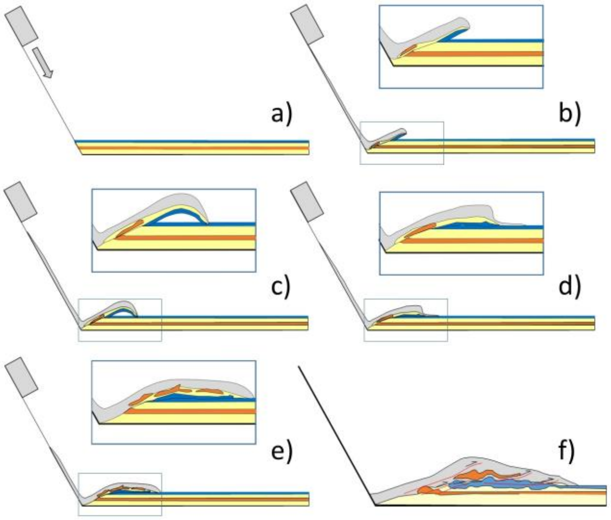
Impact and rebound
Elm rock-avalanche, CH,
Heim 1882



Snow avalanche jet in a quasi-steady state
Hakonardottir et al., 2003

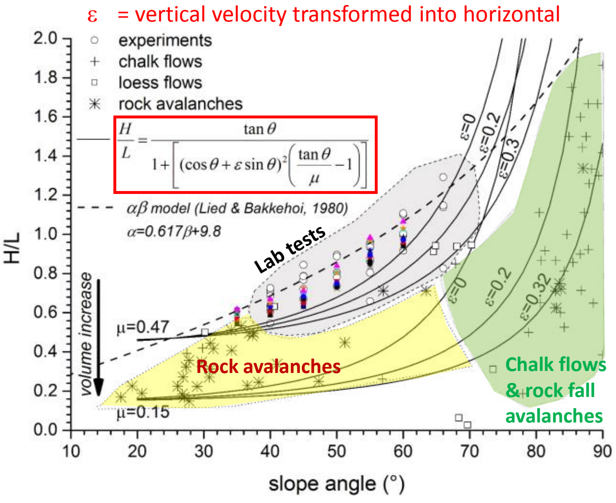


Folding and thrusting
Arvel, CH, Choffat 1929



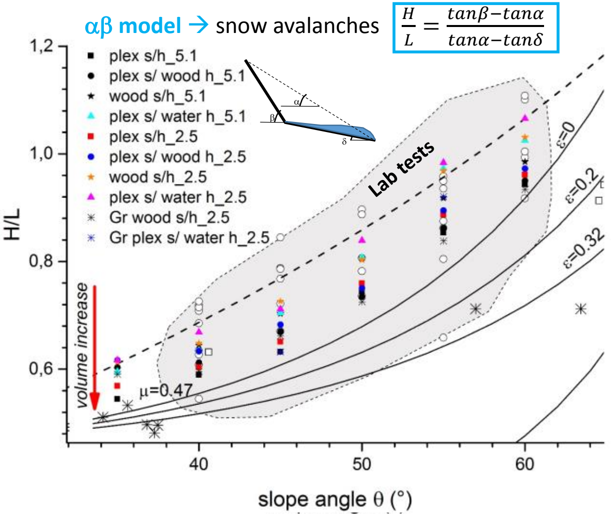
Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Simple analytical models



ε = vertical velocity transformed into horizontal

$$\frac{H}{L}=\frac{\tan\theta}{1+\left[(\cos\theta+\varepsilon\sin\theta)^2\left(\frac{\tan\theta}{\mu}-1\right)\right]}$$

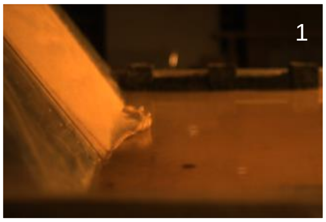


αβ model → snow avalanches

$$\frac{H}{L}=\frac{tan\beta-tan\alpha}{tan\alpha-tan\delta}$$

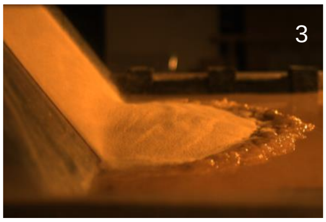
Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Flow and Deposit evolution: *shallow water/front velocity*



1

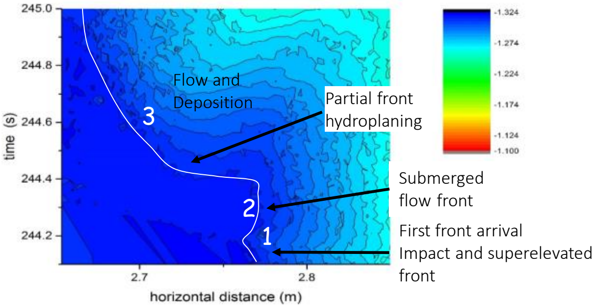
2



3

Sand less mobile than gravel in presence of water

→ True for any water depth?

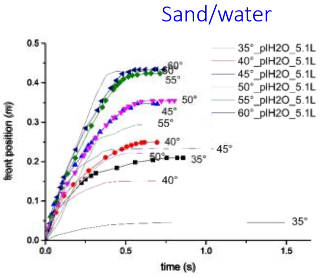


Flow and Deposition

Partial front hydroplaning

Submerged flow front

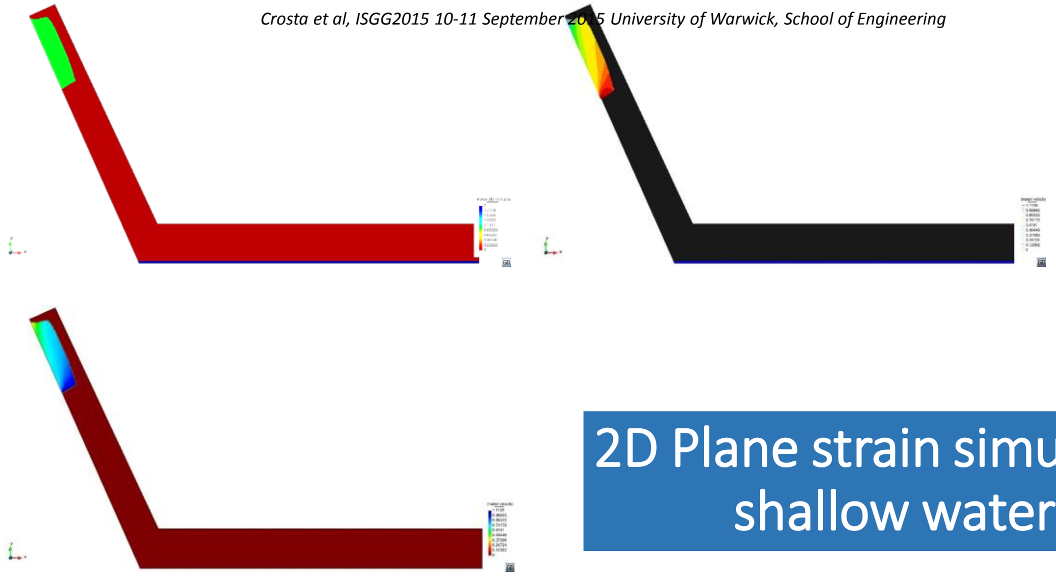
First front arrival Impact and superelevated front



Sand/water

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

2D Plane strain simulation shallow water

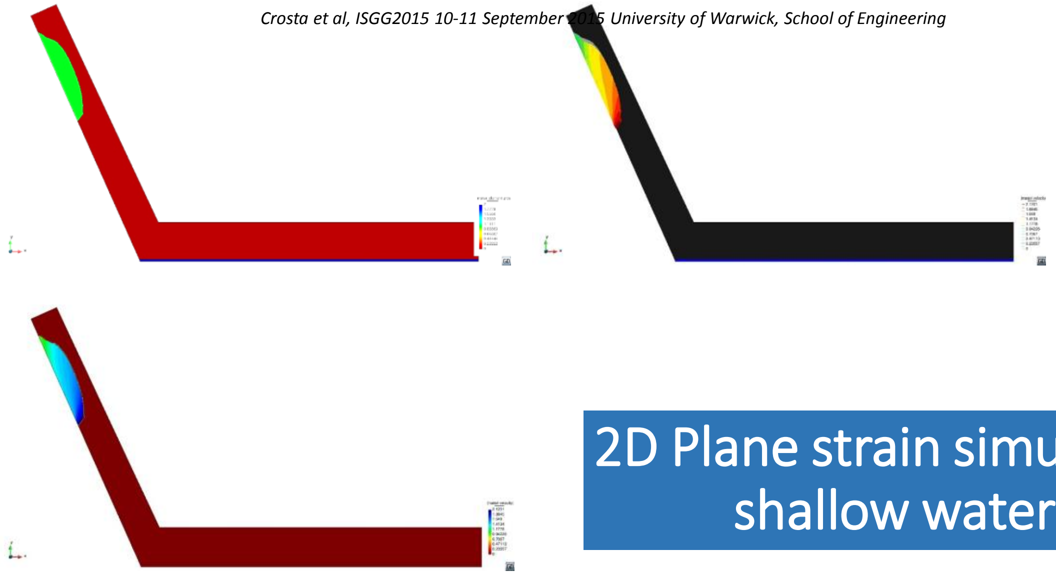


Slope angle: 65°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

2D Plane strain simulation shallow water

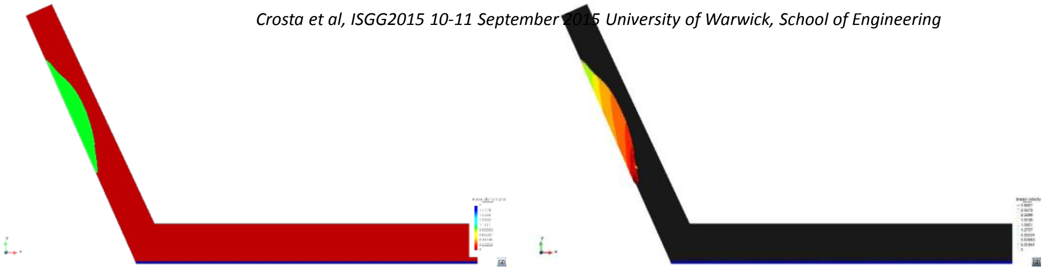


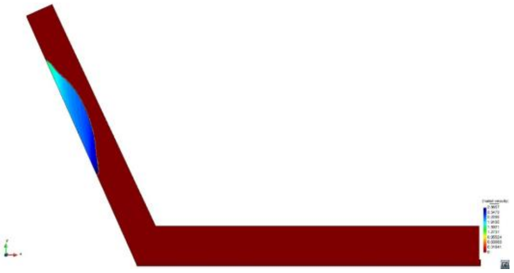
Slope angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

2D Plane strain simulation shallow water

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering



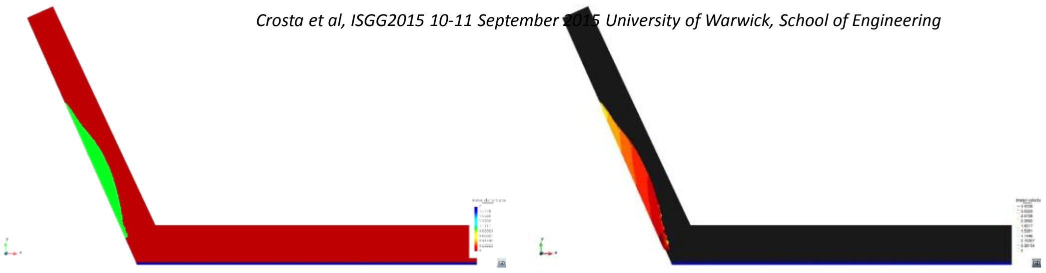


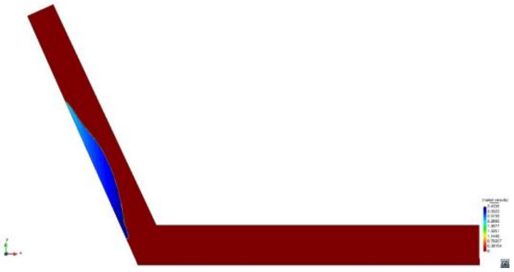
Slide angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf} = 0$ $\phi_{basal} = 21°$ $\phi_{sand/water} = 11°$

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

2D Plane strain simulation shallow water

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

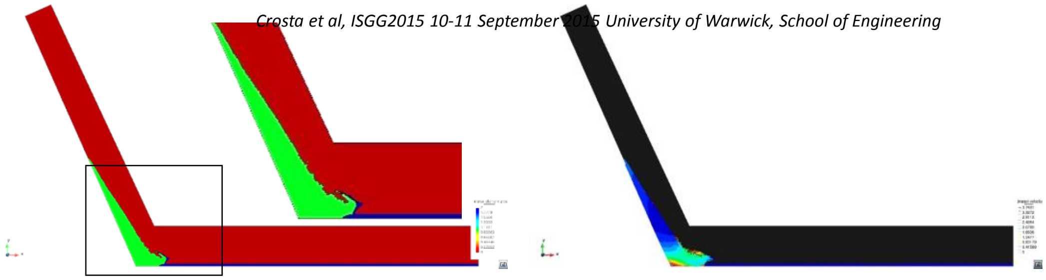


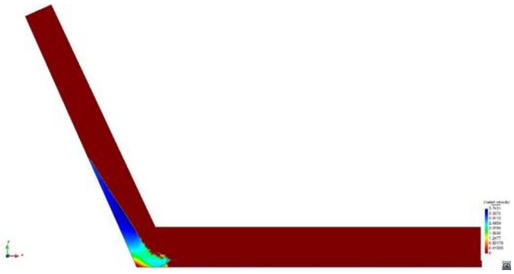


Slide angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf} = 0$ $\phi_{basal} = 21°$ $\phi_{sand/water} = 11°$

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering



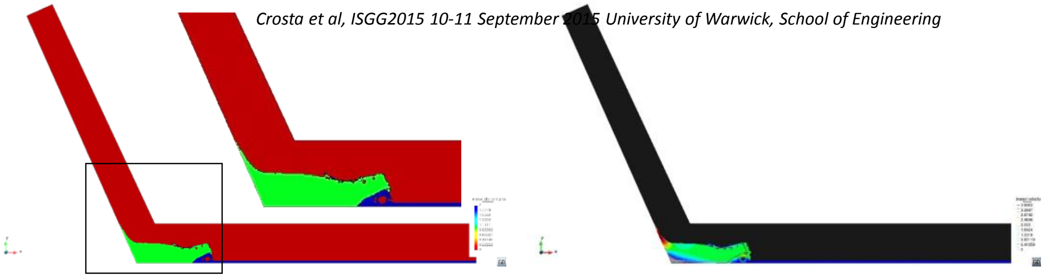


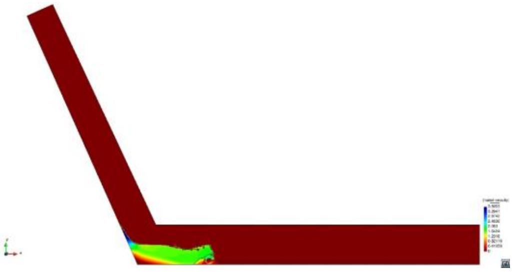
2D Plane strain simulation shallow water

Slope angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering



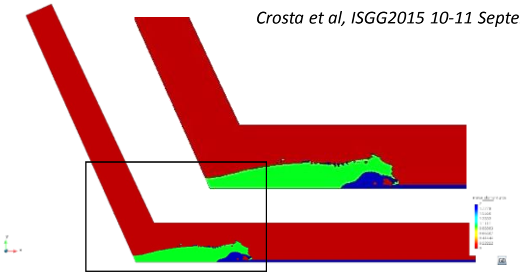


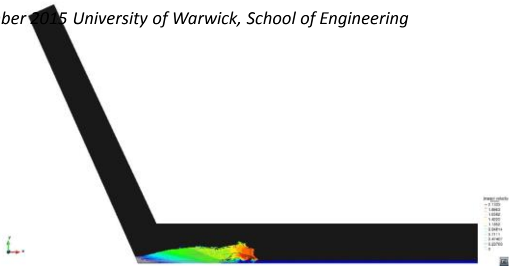
2D Plane strain simulation shallow water

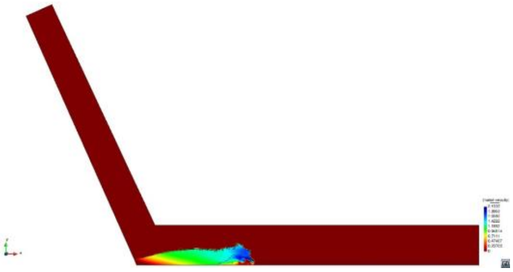
Slope angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering





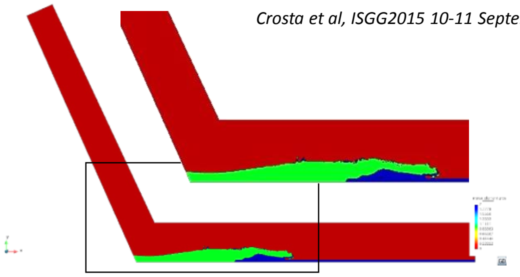


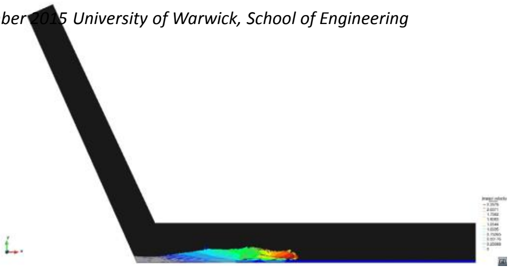
2D Plane strain simulation shallow water

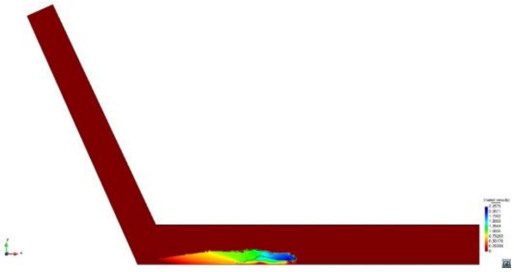
Slope angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering





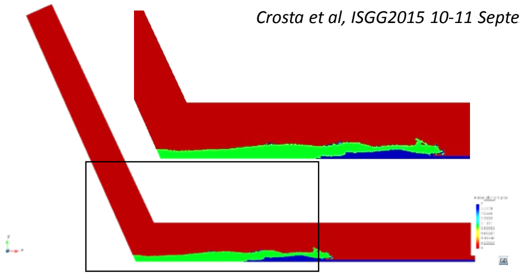


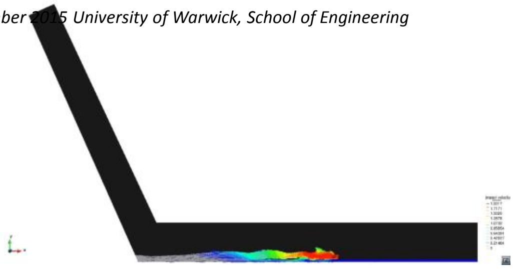
2D Plane strain simulation shallow water

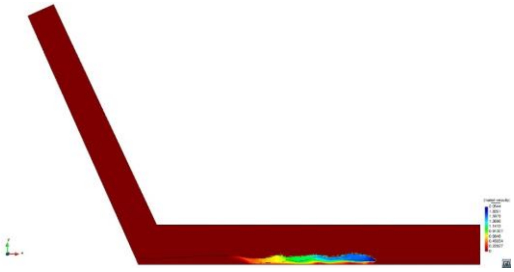
Slope angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering



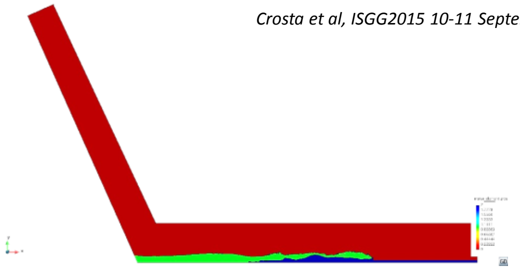


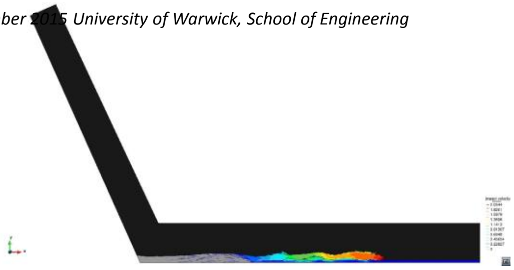


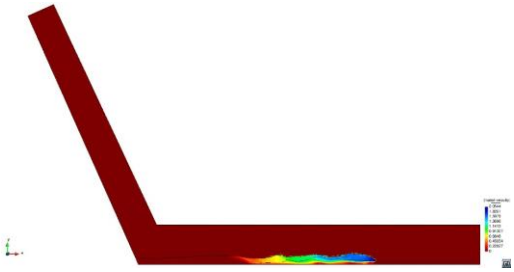
2D Plane strain simulation shallow water

Slope angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0







Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

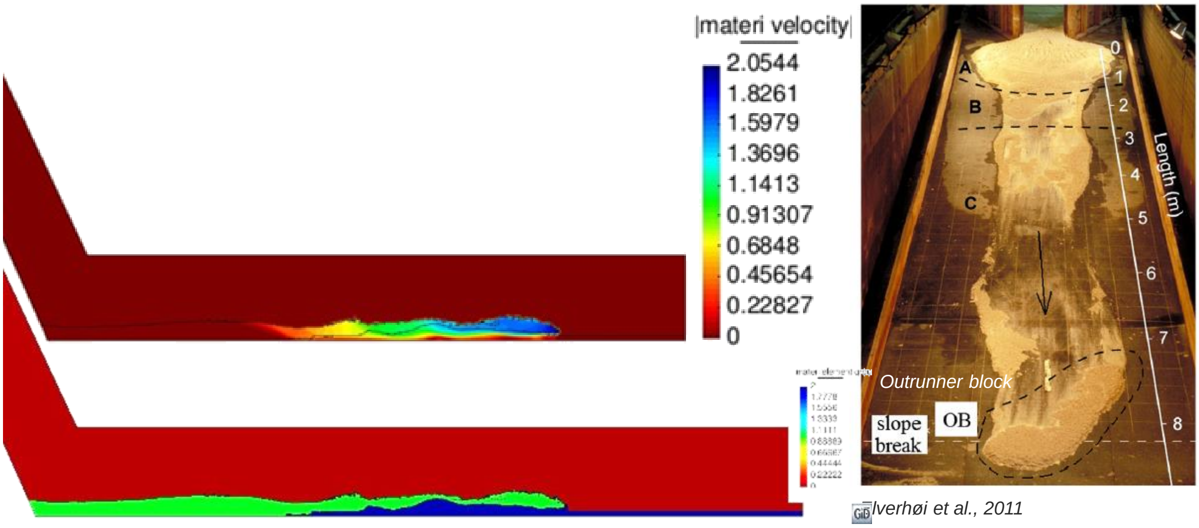
2D Plane strain simulation shallow water

Slope angle: 66°
Water depth: 1 cm
Bulk density 1450 kg/m^3
ν = 0.23
$c_{sliding\ surf}$ = 0 ϕ_{basal} = 21° $\phi_{sand/water}$ = 11°

Sand volume: 5.1 L
Ave FE element size: 2.5 mm
E = 1.e5 Pa
ϕ = 27° c = 0 psi = 0

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Interaction with shallow water: *hydroplaning*



lverhøi et al., 2011

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

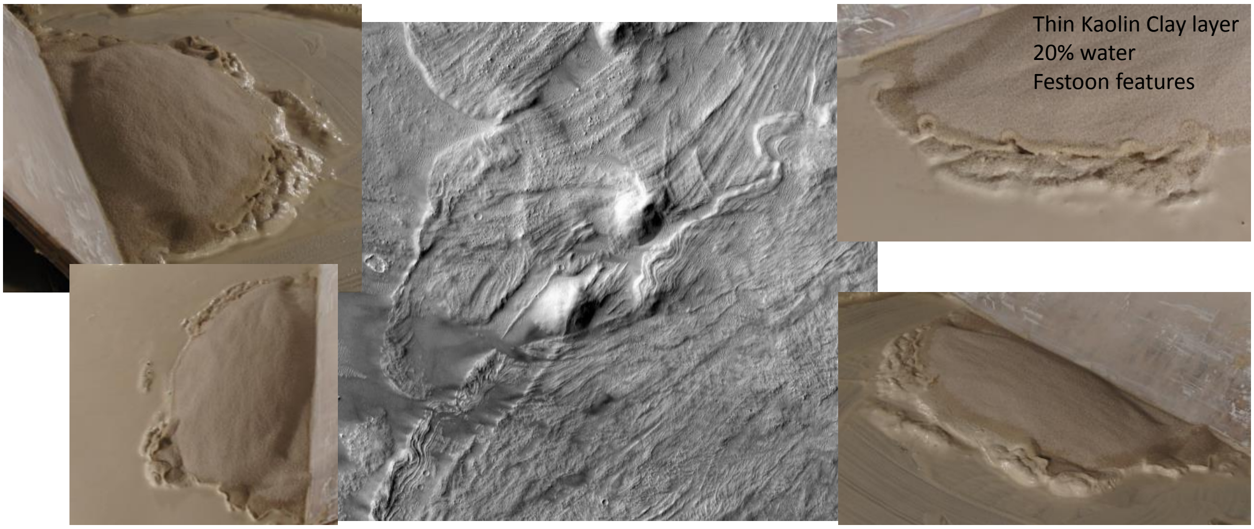
Recent efforts: *Flow and Deposit evolution interaction with dry shallow cohesive layers*

Interaction with thin layer of dry kaolin with overthrusted and suspended ring and thrust features

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Recent efforts: *Flow and Deposit evolution*

Interference features → wet layer conditions?

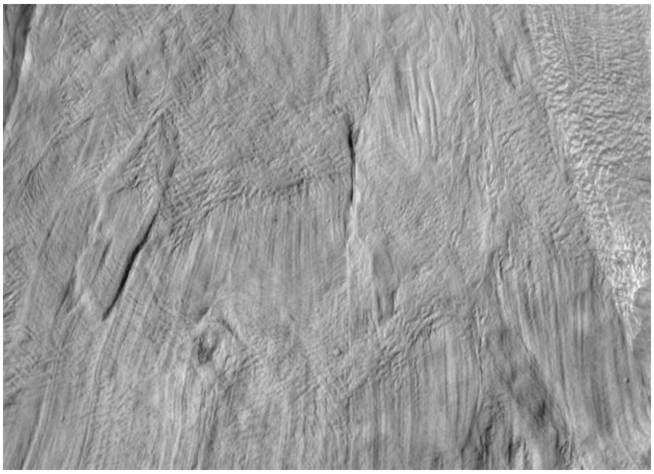


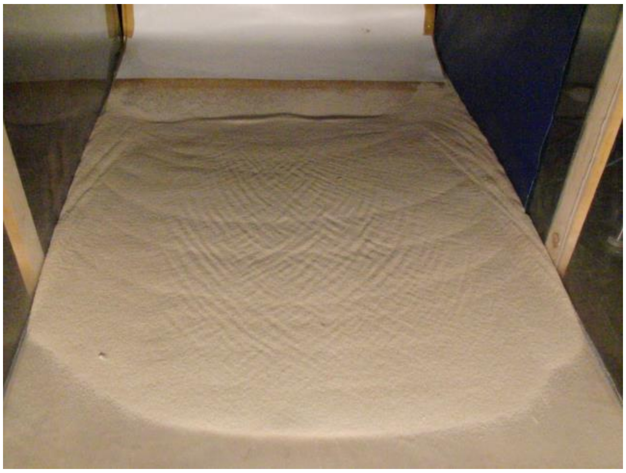
Thin Kaolin Clay layer
20% water
Festoon features

Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Recent efforts: *Flow and Deposit evolution*

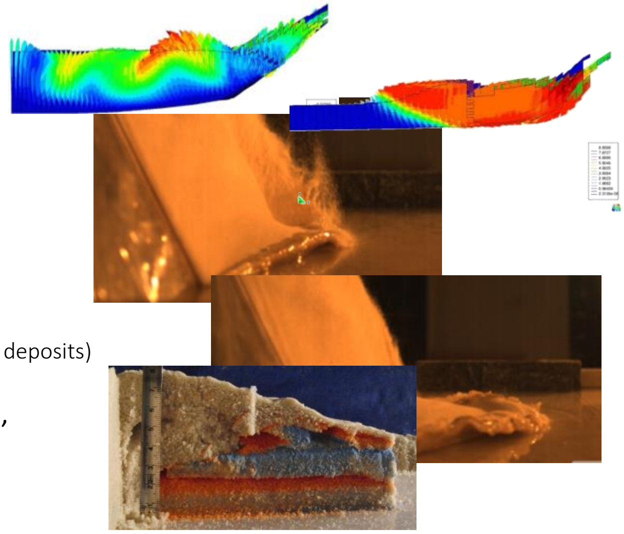
Lateral confinement and interference features





Conclusions 1/2

Sliding and **elongation/compression** as frequently **assumed** in **thin layer basal shearing approximation do not fit** the real behaviour → relevant **internal shear at slope break**
→ where **thickness is relevant**
→ **erosion is important**
→ behaviour **strongly sensitive to slope changes**



Main Features:

1) «**reflection**» and **dilation** of the flow at slope breaks
2) **complex flow motion** (e.g. steep front, multiple fronts)
3) **composite deposition** mode (frontal deposition, ramp-like deposits) controlled by the different boundary conditions
4) complex interaction with basal layer combining **erosion, expulsion, intense shearing**
5) **extreme effects of water** function of water depth

Conclusions 2/2

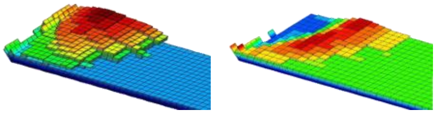
Tentative **Numerical Analysis** considering

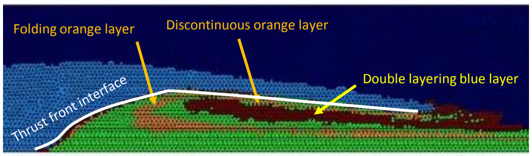
1) **different failure and entrainment** modes are replicated

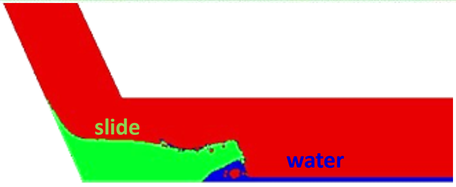
2) **basal dragging and wave-like features**

3) **different Constitutive laws** → **"standard"** material properties

- **Support interpretation** of dense shear flow and deposit
- **'Fully' integrated/interacting** slide – water systems
- **Limited in simulating extreme elongation**
- **Changing properties** (eg. Final profile of the landslide mass)
- **Computational demanding** for extremely long wave modelling
- Extreme variability of **natural conditions**







Crosta et al, ISGG2015 10-11 September 2015 University of Warwick, School of Engineering

Thank you for your attention