UNIVERSITÁ DI SALERNO (ITALY)
Department of Civil Engineering

Mechanisms and consequence of bed entrainment for landslides of the flow type (and countemeasures)

Sabatino Cuomo

scuomo@unisa.it

ACKNOWLEDGMENTS

Prof. Leonardo Cascini (Univ. of Salerno, Director of LARAM School, www.laram.unisa.it)

LARAM SCHOOL

LANDSLIDE RISK ASSESSMENT AND MITIGATION - UNIVERSITY OF SALERNO

www.laram.unisa.it

(hosting in September 2016 the 8th Olek Zienkiewicz Course "Geomechanics of landslides")

Prof. Manuel Pastor (UPM)

Prof. Giuseppe Sorbino,

Dr. Bouchra Haddad,

Dr. Luca Piciullo,

Ilaria Rendina,

Vittoria Capobianco,

Pooyan Ghasemi,

Stefano Petrosino,

Stefania Vitale,

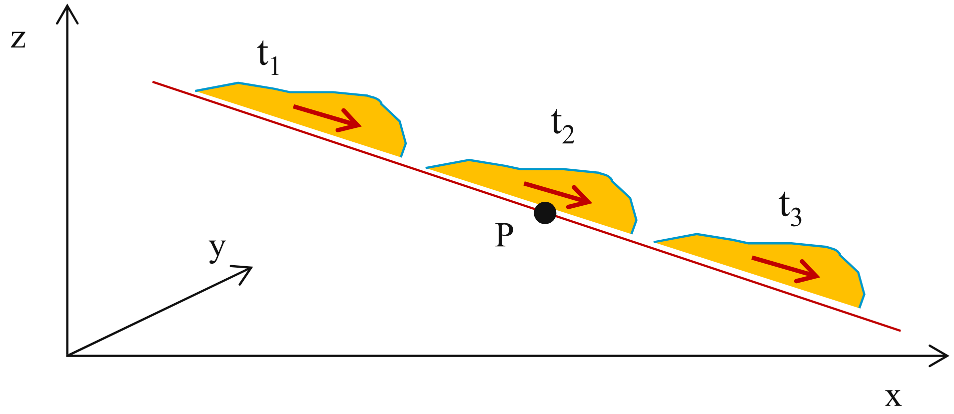
Giuseppe Castorino,

Mario Coppola

MECHANISMS

BED ENTRAINMENT

SCHEME



$e_r = -\partial z / \partial t$	e_r: entrainment (or erosion) rate @ P
$h_{er} = \int_0^{t_{er}} e_r \, dt$	h_{er}: erosion height @ P (during t_{er})
$V_{er} = \int_{A_{er}} h_{er} dxdy$	V_{er}: volume eroded (in A_{er})
$V_f = V_i + V_{er}$	V_f, V_i: final (and initial) volume
$A_f = V_f / V_i$	A_f: amplification factor

EXAMPLE

Tsing Chan event (Hong Kong, 2001)

small triggering volume ($V_i = 345$ m^3)

↓

bed entrainment

↓

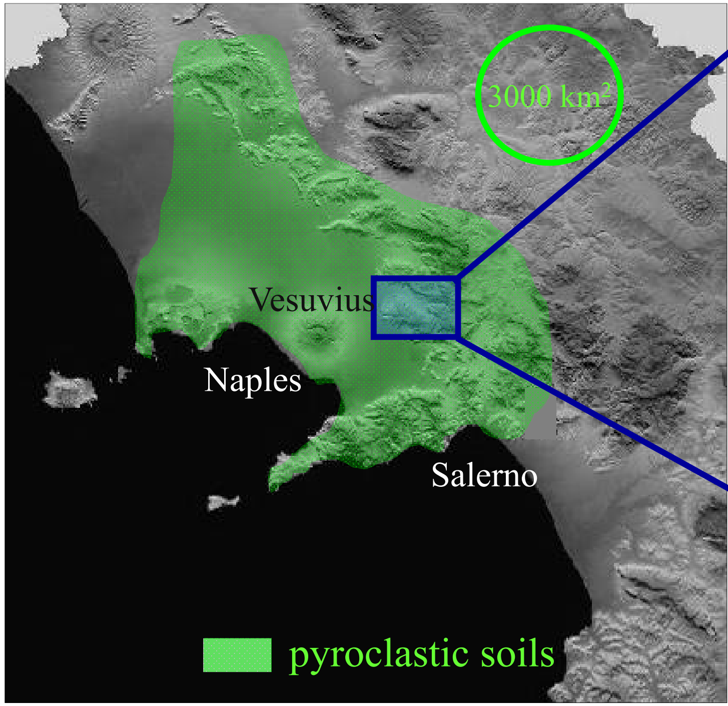
huge final volume ($V_f = 20{,}000$ m^3)

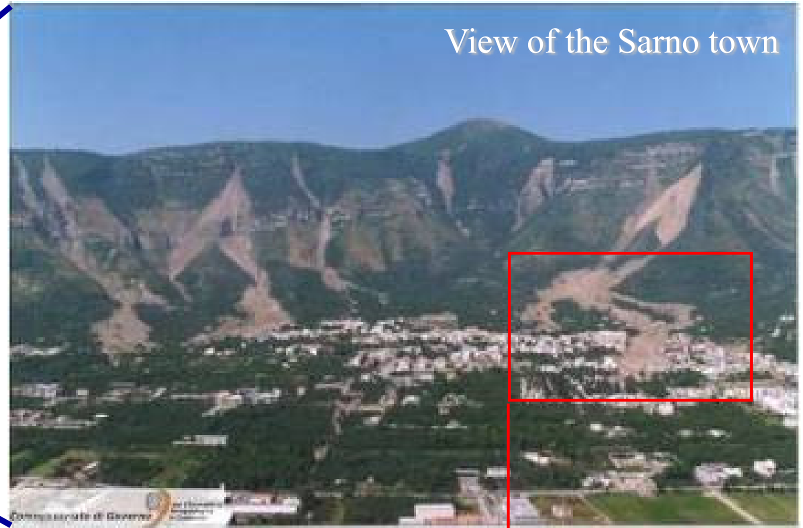
↓

$A_f = 57.9$

MORE EXAMPLES

Study area (Vesusius district)



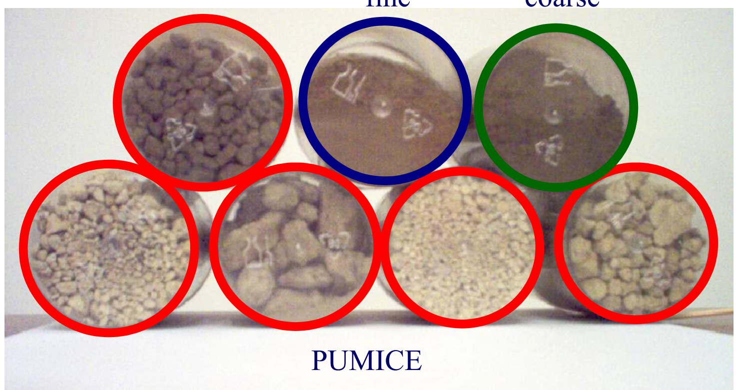


http://www.commissario2994.it

1cm

ASHES fine

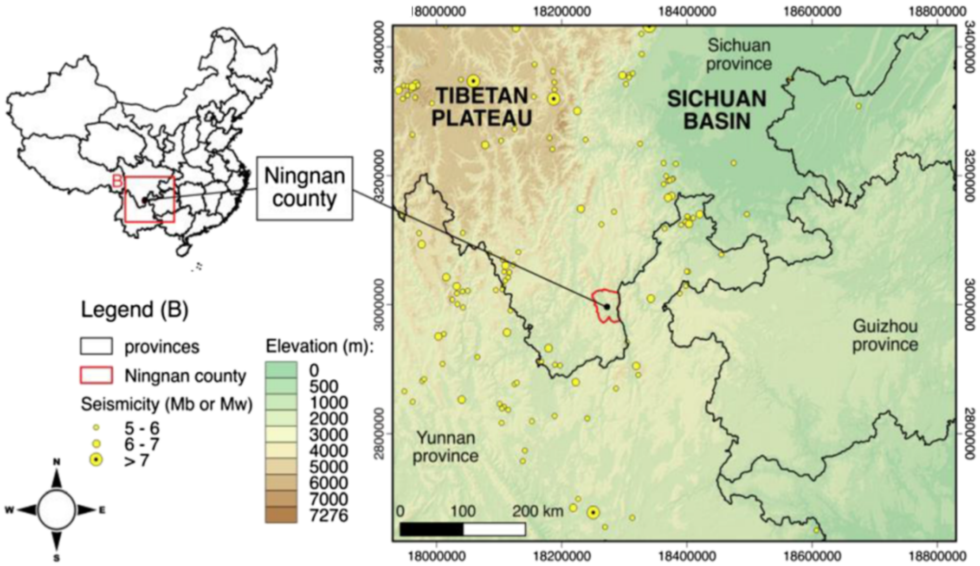
ASHES coarse

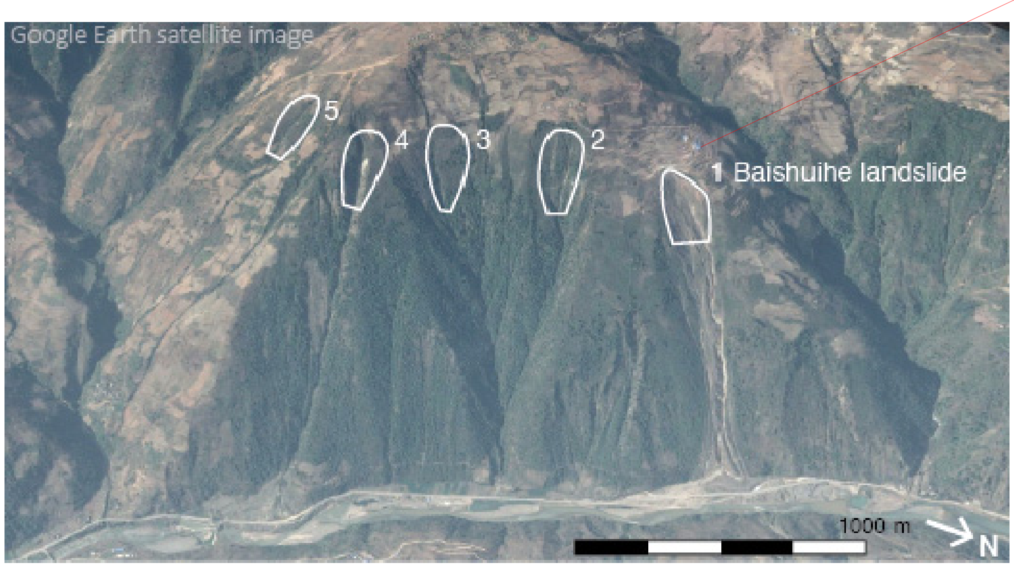


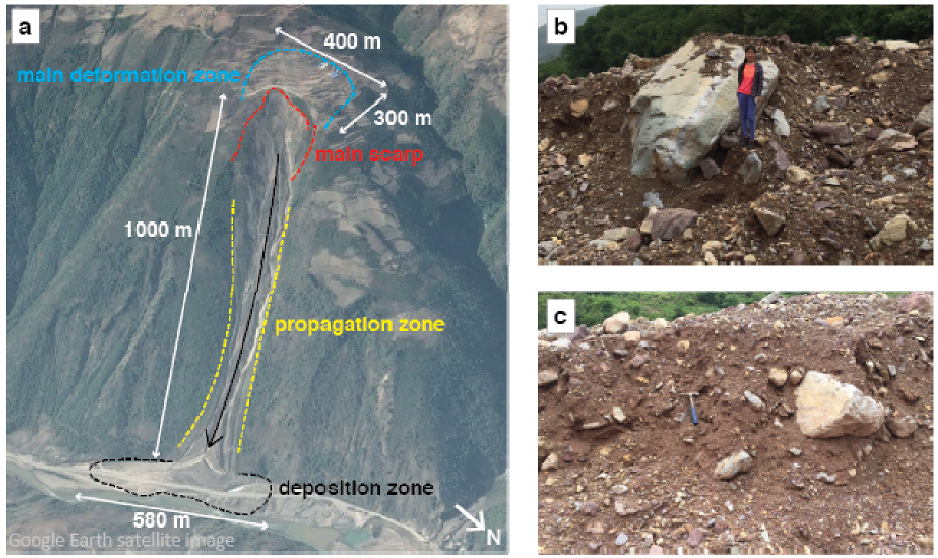
Cascini L., Cuomo S., Guida D. (2008). Typical source areas of May 1998 flow-like mass movements in the Campania region, Southern Italy. Engineering Geology, 96, pp. 107 - 125 (doi:10.1016/j.enggeo.2007.10.003)

AND MORE EXAMPLES …

Sichuan province (China)





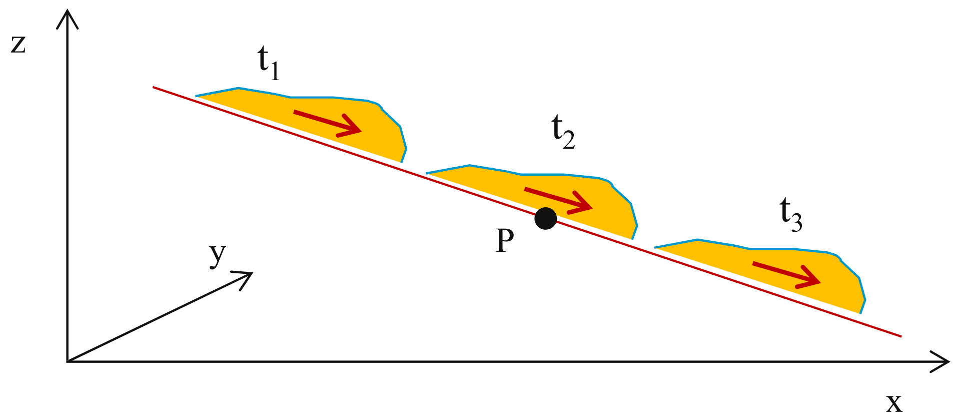


Braun, A., Wang, X., Petrosino, S., Cuomo, S. (2017). SPH propagation back-analysis of Baishuihe landslide in south-western China. Geoenvironmental Disasters, 4(1), 2.

Braun, A., Cuomo, S., Petrosino, S., Wang, X., L. Zhang (2017). Numerical SPH analysis of debris flow run-out and related river damming scenarios for a local case study in SW China. Landslides. (DOI: DOIhttps://doi.org/10.1007/s10346-017-0885-9).

MECHANISMS

SCHEME



$e_r = -\partial z / \partial t$ — e_r: entrainment (or erosion) rate

$h_{er} = \int_0^{t_{er}} e_r \, dt$ — h_{er}: erosion height @ point P (during t_{er})

$V_{er} = \int_{v,t} h_{er} \, dv dt$ — V_{er}: volume eroded (in whole landslide)

$V_f = V_i + V_{er}$ — V_f, V_i: final (and initial) volume

$A_f = V_f / V_i$ — A_f: amplification factor

FACTORS

- propagation height: *h (x, y, z, t)* ? yes
- velocity: *v (x, y ,z, t)* ? yes
- ground slope angle: θ *(x, y, z, t)* ? yes

Hungr et al. (2005)

$$e_r = h \cdot v \cdot E_S$$

$$E_s = \ln\left(\frac{V_f}{V_i}\right)\frac{1}{L}$$

E_s: from empirical observations

Blanc et al. (2011)

$$e_r = h \cdot v \cdot \tan(\vartheta)^{2.5} \cdot K$$

K: empirical factor

and many other contributions …………
(a review in Pirulli and Pastor, 2012)

Hungr, O., Corominas, J., Eberhardt, E., 2005. Estimating landslide motion mechanism, travel distance and velocity. Landslide Risk Management. 99-128.

Blanc, T., Pastor, M., Drempetic, M. S. V., Haddad, B. 2011. Depth integrated modelling of fast landslide propagation. European Journal of Environmental and Civil Engineering, 15(sup1), 51-72.

Pirulli, M., Pastor, M. (2012). Geotechnique 62, No. 11, 959–972.

WHERE? HOW?

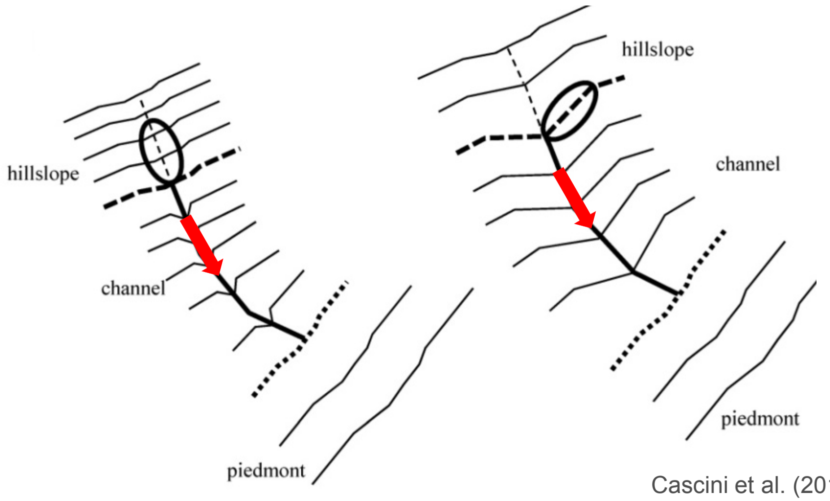
DEBRIS FLOWS

- "V" shaped channels (with steep flank)
- entry of channel, height and velocity increase
- along the channel, **bed entrainment**
- exit of channel, stopping/diversion/bifurcations

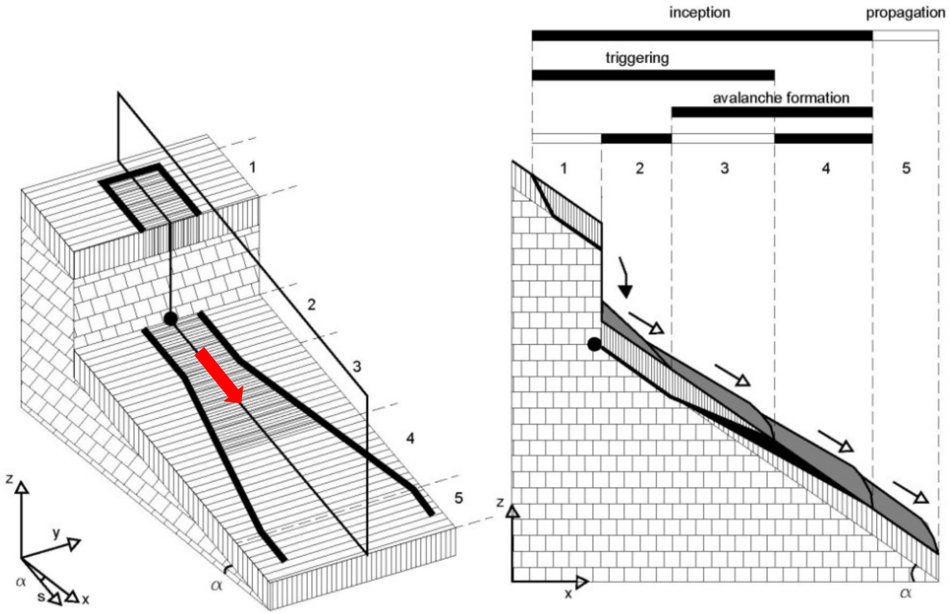
- shape/extent of propagation area unknown a priori

DEBRIS AVALANCHES

- open slopes (constant soil cover and slope angle)
- zone 1, small slides upslope bedrock outcrops
- zone 2, impact / water springs below bedrock outcrops
- zone 3, trust of failed material and/or **bed entrainment**
- zone 4, **bed entrainment**
- width of zones 3 e 4 unknown a priori



Cascini et al. (2013)



Cascini et al. (2012)

Cascini L., Cuomo S., Pastor M. (2013). Inception of debris avalanches: Remarks on geomechanical modelling. Landslides, 10(6), 701-711.

Cascini L., Cuomo S., Pastor M., Sorbino G., Piciullo L. (2014). SPH run-out modelling of channelized landslides of the flow type. Geomorphology, 214, 502-513.

AND SO?

Better, go simple (for the moment) !

Why?

- Relevant Factors are many.
- Soil is never bare (vegetation, trees, even waste material along slopes)
- And, what about real field measurement of bed entrainment?

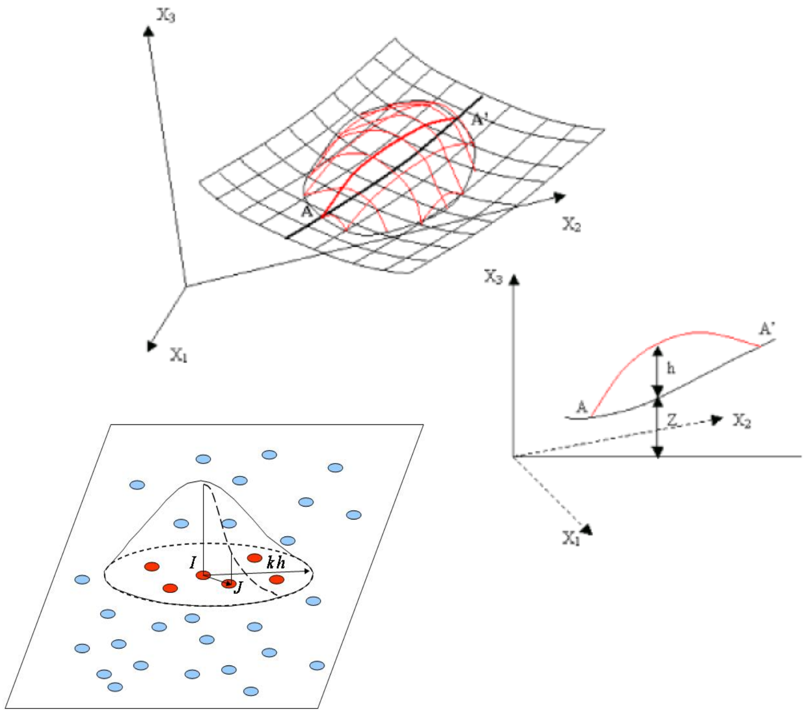
  as most, order of magnitude or eroded heights, few (or some) local measurements

But, entrainment is a $f\,(x,\ y,\ z,\ t)$

Yes, go simple with Hungr et al. (2005) and Blanc et al. (2011) EMPIRICAL models

GeoFlow-SPH depth-integrated coupled model

- Proposed by Pastor et al. (2009)
  - equations:



balance of mass, depth integrated equation:

$$\frac{Dh}{Dt} + h\,\mathrm{div}(\bar{v}) = e_r$$

balance of linear momentum, depth integrated equation :

$$\rho\frac{D(h\bar{v})}{Dt} + \mathrm{grad}\left(\frac{1}{2}\rho g h^2\right) = -\frac{1}{\rho}e_r\bar{v} + \rho b h + \mathrm{div}(h\bar{s}) - \rho g h \,\mathrm{grad}\,Z - \tau_b - \rho\, h\,\bar{v}\,\mathrm{div}(\bar{v})$$

defined by frictional rheological model:

$$\tau_b = -\left((1-n)(\rho_s - \rho_w)g\cdot h - p_w^b\right)\tan\phi_b \cdot \mathrm{sgn}(\bar{v})$$

τ_b = shear stress at the basal surface

p_w = pore pressure at the basal surface

1D vertical consolidation depth integrated equation:

$$\frac{\partial}{\partial t}\left(P_{w_1} h\right) + \frac{\partial}{\partial x_k}\left(\bar{v}_k P_{w_1} h\right) = -\frac{\pi^2}{4h^2} c_v P_{w_1}$$

entrainment law (Hungr et al., 2005):

$$e_r = E_s \times h \times v$$

$$E_s = \ln\left(\frac{V_f}{V_i}\right)\frac{1}{l}$$

h = flow depth
v = depth-averaged velocity
E_s (amplification rate) is independent on flow depth and velocity
V_i = volume entering the erosion zone
V_f = total volume exiting the erosion zone,
l = average path length of the erosion zone

entrainment law (Blanc et al., 2011):

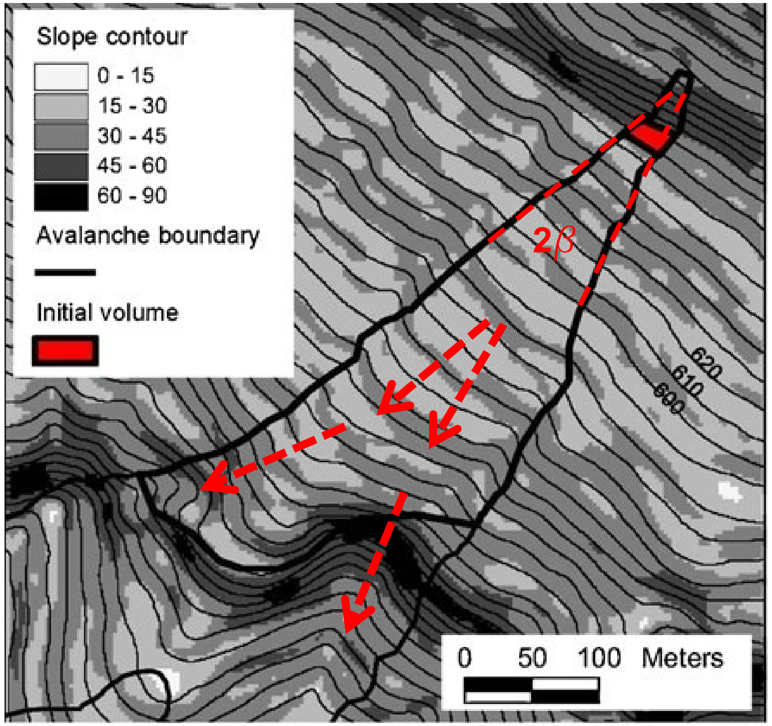
$$e_r = K\cdot v\cdot h\cdot(\tan\vartheta)^{2.5}$$

K = empirical factor
θ = slope angle of ground surface

Pastor, M., Haddad, B., Sorbino, G., Cuomo, S. & Drempetic, V. 2009. A depth-integrated, coupled SPH model for flow-like landslides and related phenomena. Int. J. Numer. Anal. Meth. Geomech 33: 143-172.

CONSEQUENCES

Case #1 – SPREAD & SPLIT



- hillslope 35° steep
- B_{trig}=30m, L_{trig}=25m, initial mass **1’400 m³**
- mobilized volume **30’000 m³ (A_f = 75)**
- 510 m propagation along an open slope
- lateral spreading (2β=20°)
- bifurcation of the mass into two debris flows

Cortadonica Debris Avalanche (Italy), 1998

NUMERICAL MODEL

- Digital Elevation Model (DTM) 3m x 3m
- 639 points (intially 1 m spaced)
- Runge-Kutta numerical algorithm(dt ≤ 0.1 s)

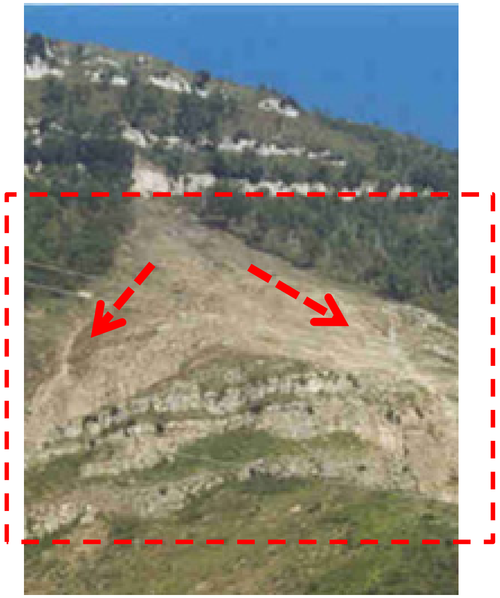
ANALYZED CASES

- friction angle (φ’): 22.5°,
- water table height ≈1/4 propagation height (h_w^{rel}=0.25÷0.4)
- pore water pressures from literature (p_w^{rel}=1)
- entrainment : $E_s = 4.0\times10^{-3}$ m^{-1}

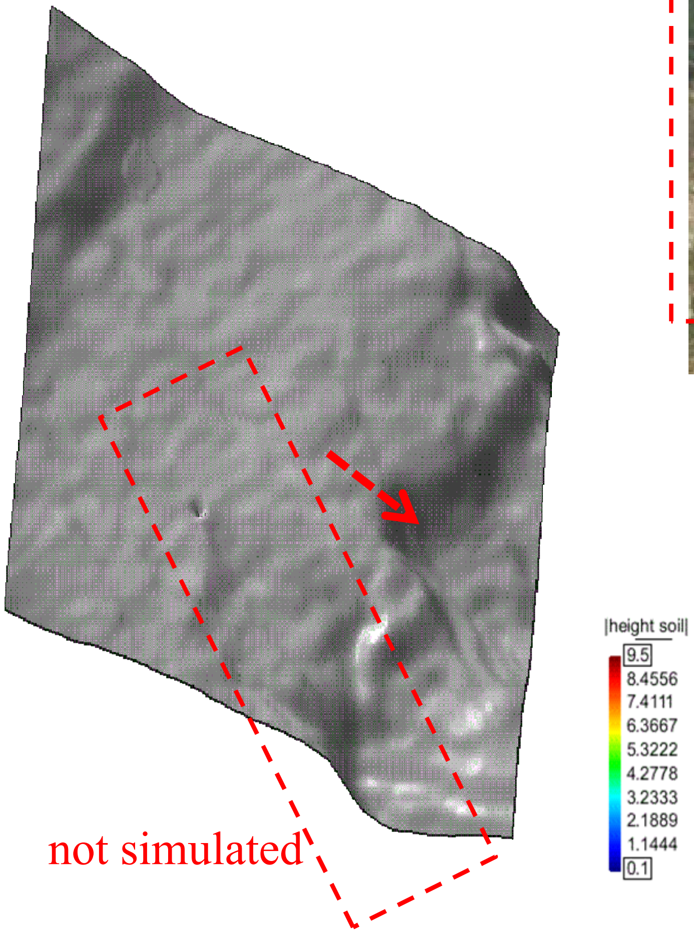
Cuomo S., Pastor M., Cascini L., Castorino G.C. (2014). Interplay of rheology and entrainment in debris avalanches: a numerical study. Canadian Geotechnical Journal, 1-15, DOI: 10.1139/cgj-2013-0387.

Case #1 – SPREAD & SPLIT

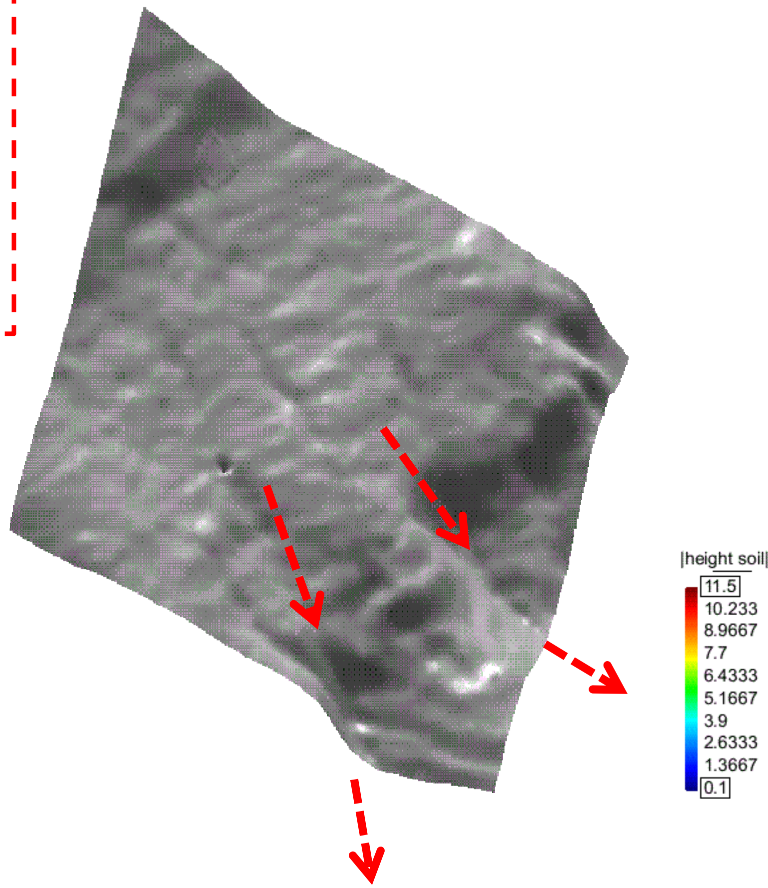
Field evidence



$E_s = 0$

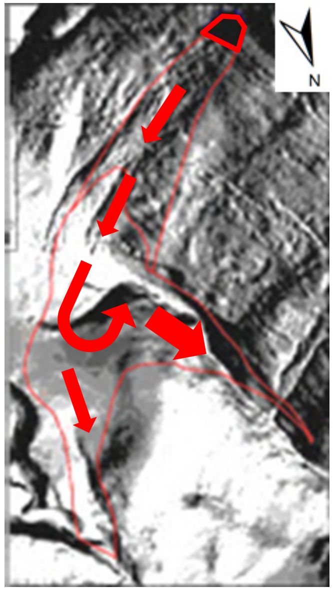


Landslide amplification rate: $E_s = 4.0\times10^{-3}$



Cuomo S., Pastor M., Cascini L., Castorino G.C. (2014). Interplay of rheology and entrainment in debris avalanches: a numerical study. Canadian Geotechnical Journal, 1-15, DOI: 10.1139/cgj-2013-0387.

Case #2 – SPREAD, PROPAGATION, DEPOSITION AND SPLIT



Cuomo et al. (2014)

- mobilized volume 30’000 m^3
- 360 m propagation along an open slope (2β=14°)
- run-up on the opposite slope ≈ 10 m
- (partial) deposition at the base of the slope
- biforcation of the mass into two debris flows
- main debris flow propagated 1’400 m

Cervinara Debris Avalanche (Italy), 1999

NUMERICAL MODEL

- Digital Elevation Model (DTM) 2m x 2m
- 1’600 points (intially 1 m spaced)
- Runge-Kutta numerical algorithm($dt \leq 0.8s$)

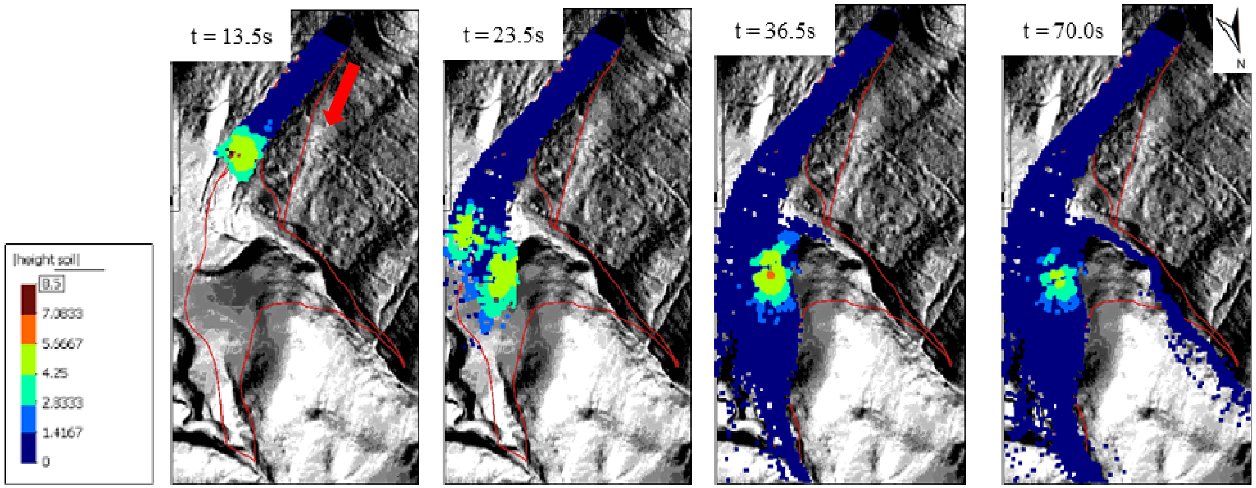
ANALYZED CASES

- friction angle (φ’): 9° ÷ 24°,
- water table height ≈1/2 propagation height (h_w^{rel}=0.5÷1)
- pore water pressures from literature (p_w^{rel}=1)
- distinct hyphoteses for entrainment: $E_s = 2\times10^{-3} \div 10^{-2}\ m^{-1}$

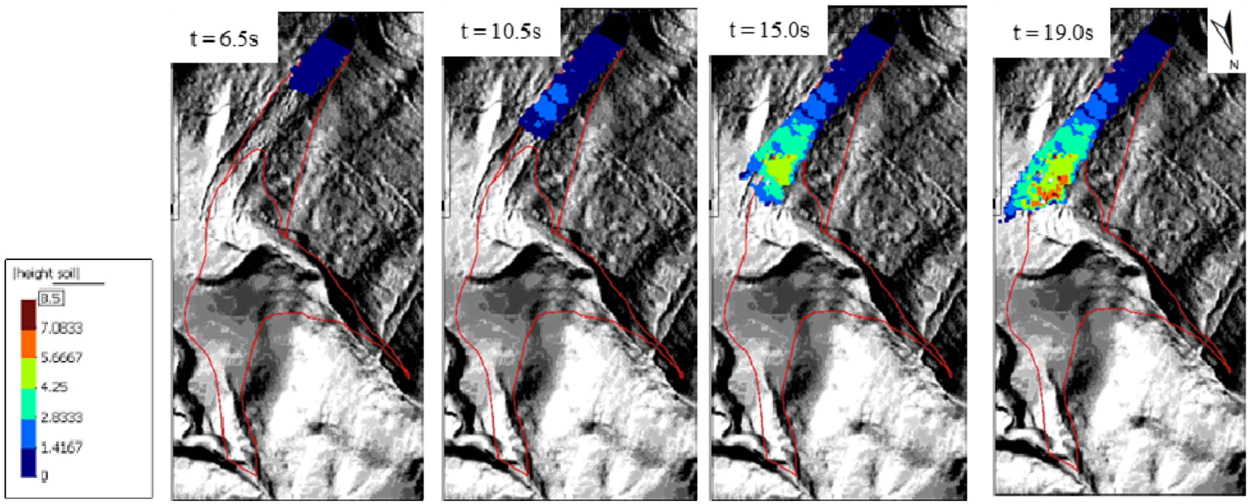
Cuomo S., Pastor M., Cascini L., Castorino G.C. (2014). Interplay of rheology and entrainment in debris avalanches: a numerical study. Canadian Geotechnical Journal, 51(11), 1318-1330

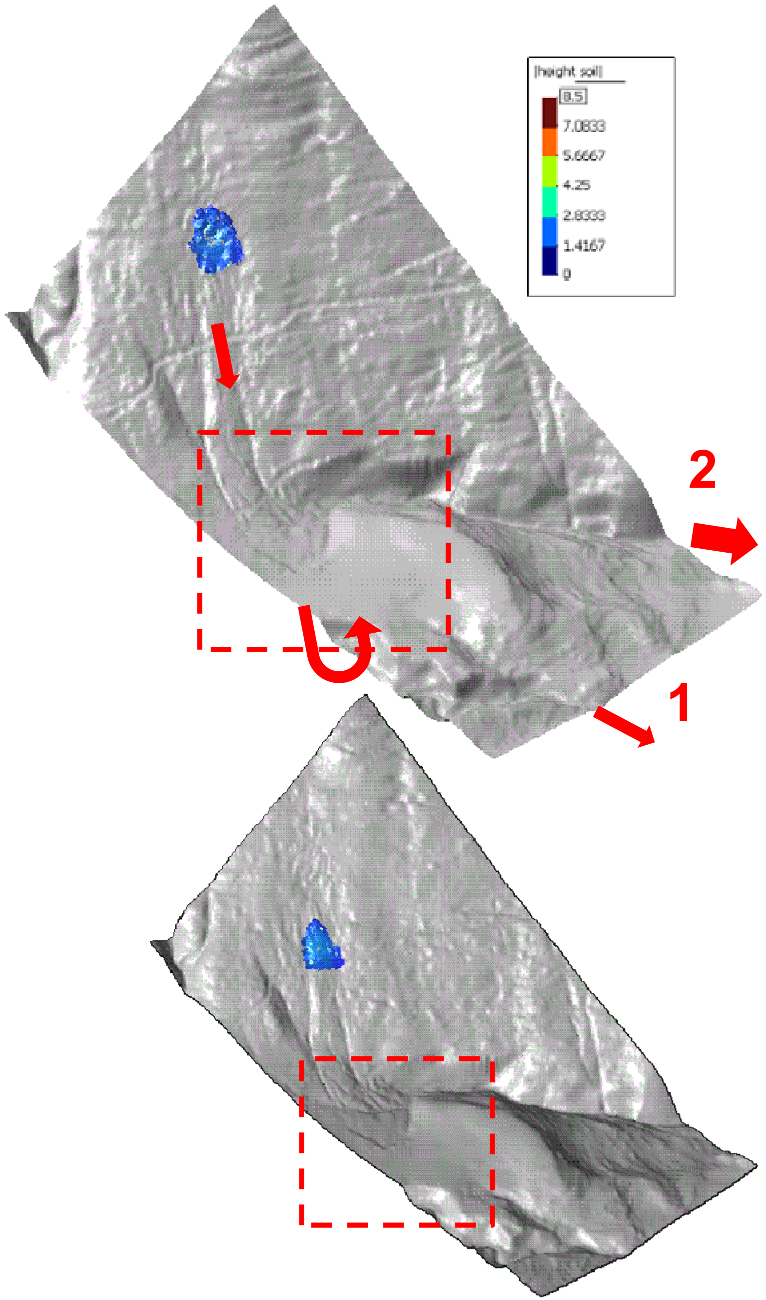
Case #2 – SPREAD, PROPAGATION, DEPOSITION AND SPLIT

Landslide amplification rate (E_S): $1.0\times10^{-2}\ m^{-1}$



$E_S = 0$

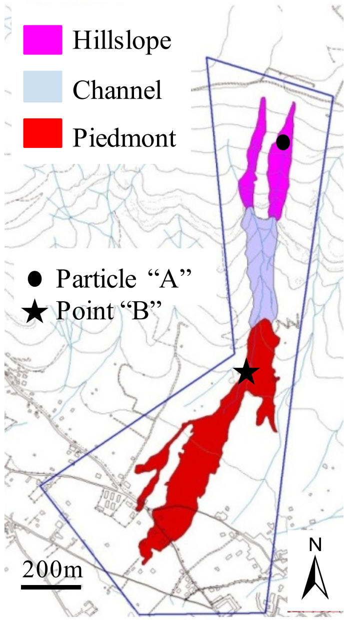


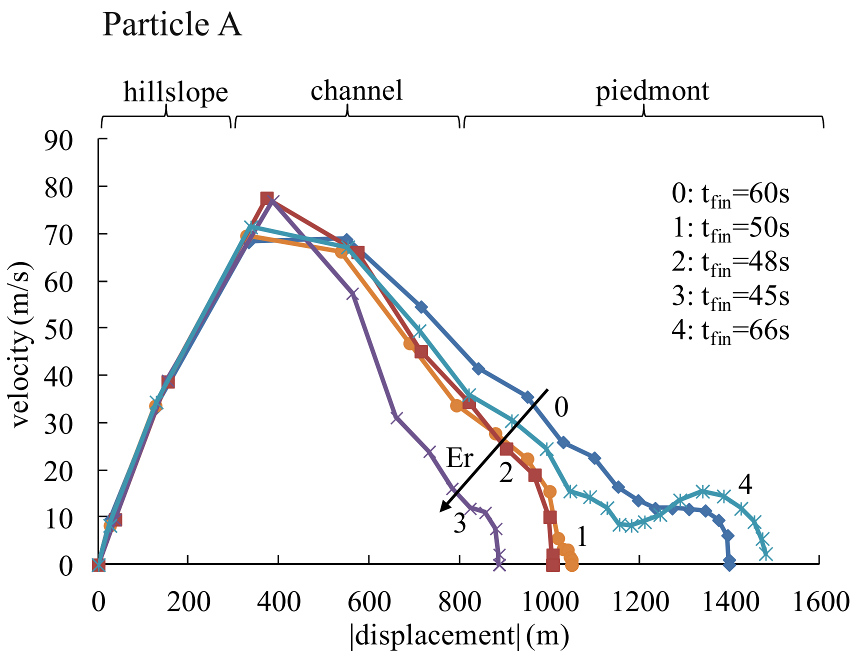


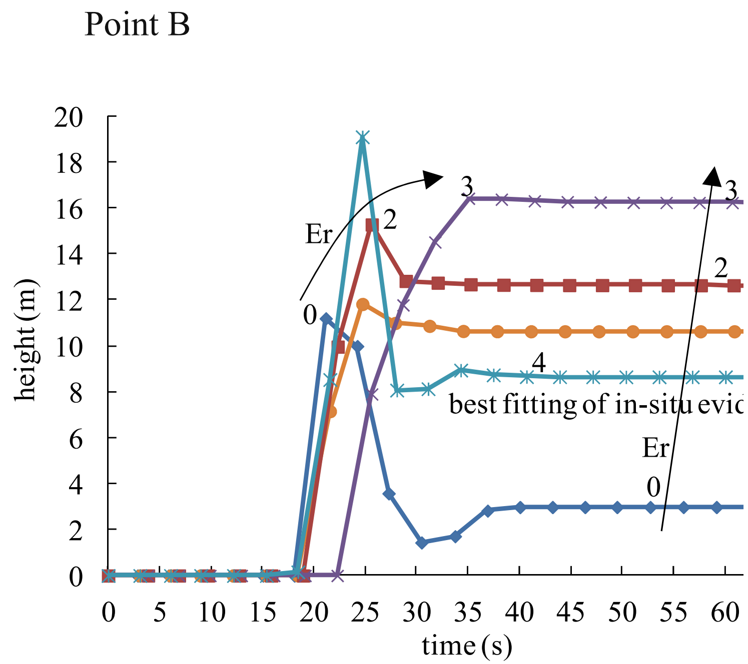
Cuomo S., Pastor M., Cascini L., Castorino G.C. (2014). Interplay of rheology and entrainment in debris avalanches: a numerical study. Canadian Geotechnical Journal, 51(11), 1318-1330

Case #3 – DEPOSITION

Tuostolo Debris Flow (Italy), 1998





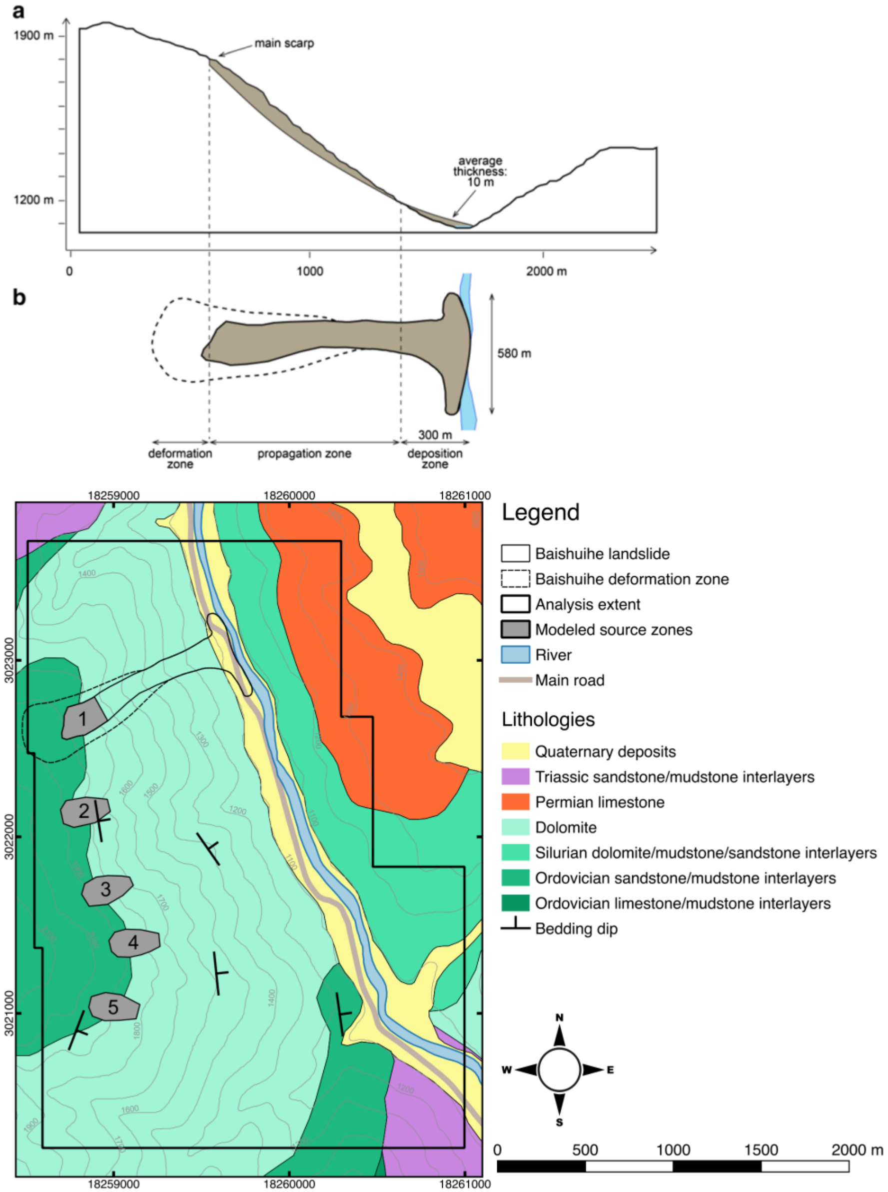


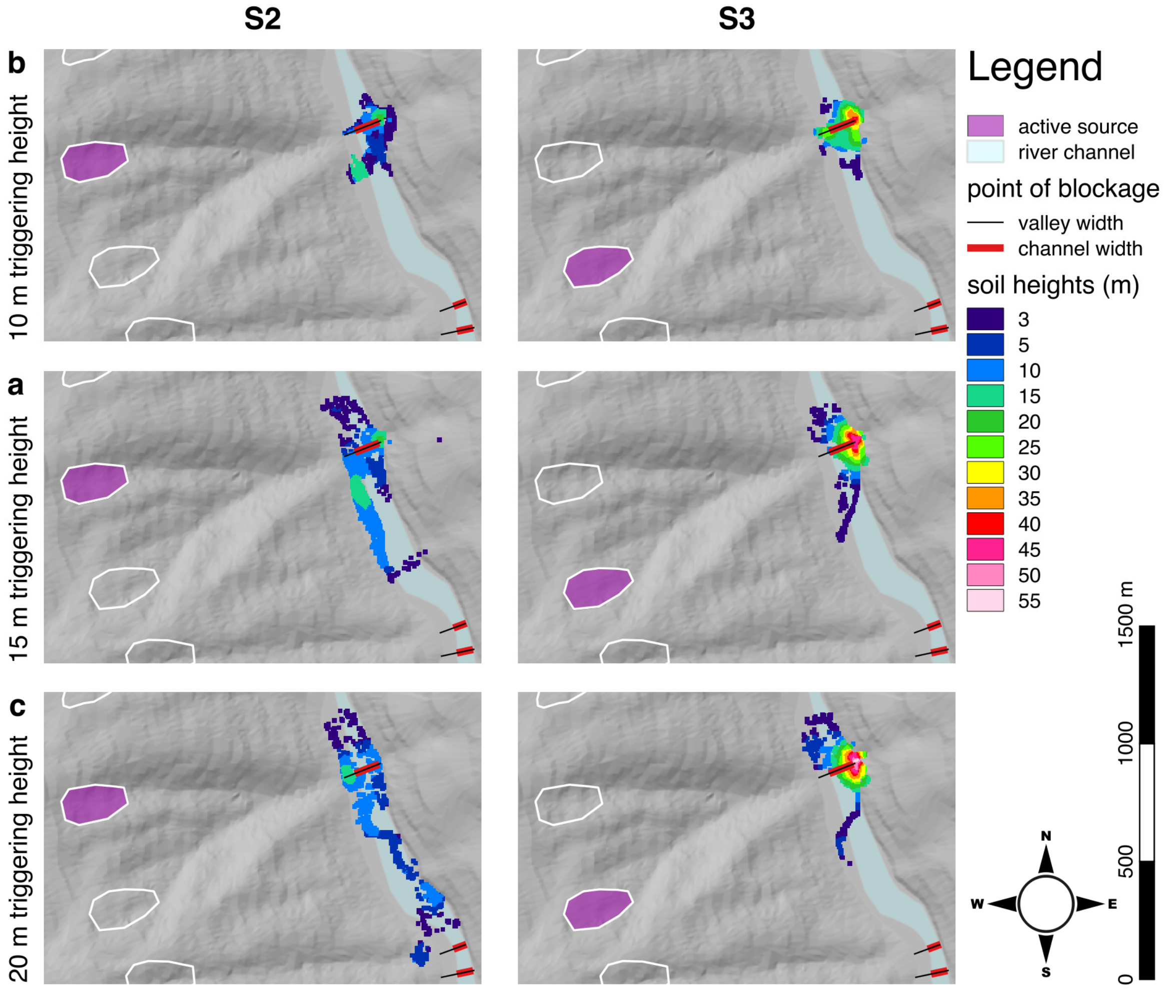
- erosion reduces landslide velocity at the front (so, in the channel and piedmont area)

Cascini L., Cuomo S., Pastor M., Sorbino G., Piciullo L. (2014). SPH run-out modelling of channelized landslides of the flow type. Geomorphology, 214, 502-513.

Case #4 – LANDSLIDE DAM

Baishuihe Debris Flow (Sichuan, China), 2012

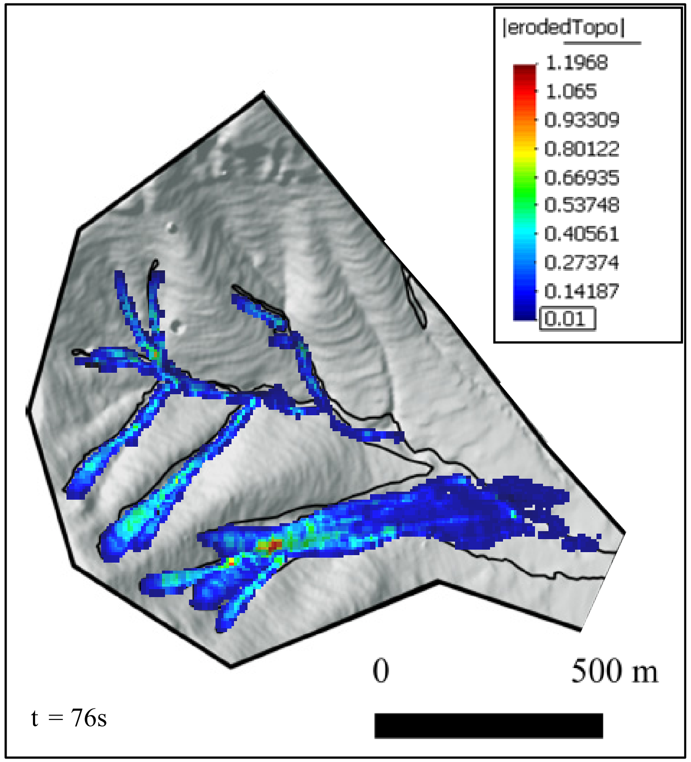


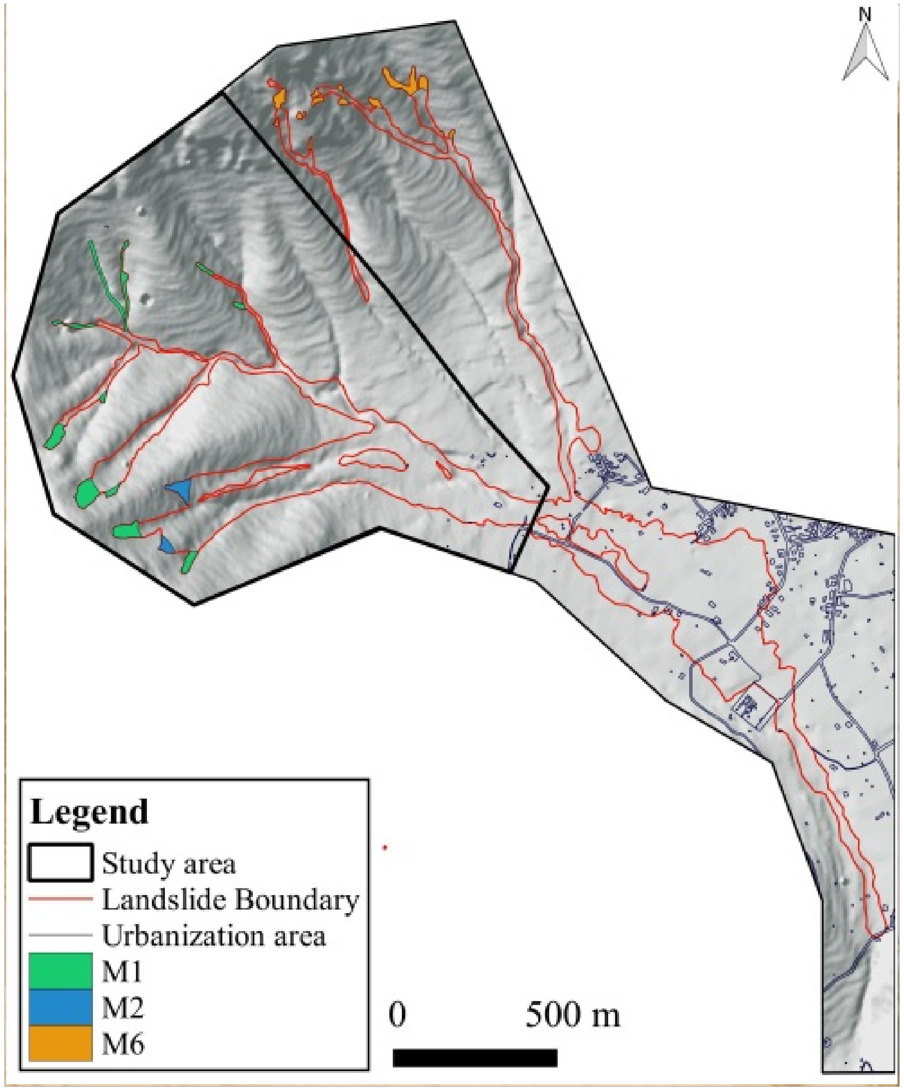


Braun, A., Cuomo, S., Petrosino, S., Wang, X., L. Zhang (2017). Numerical SPH analysis of debris flow run-out and related river damming scenarios for a local case study in SW China. Landslides. (DOI: DOIhttps://doi.org/10.1007/s10346-017-0885-9).

Case #5 – MULTIPLE MIXED FLOWS

Combination of Debris Flow and Debris Avalanche (Italy), 1998





Cuomo, S., Pastor, M., Capobianco, V., Cascini, L. (2016). Modelling the space–time evolution of bed entrainment for flow-like landslides. Engineering Geology, 212, 10-20.

COUNTEMEASURES

Examples of control works

Control of surface erosion

Installation of biomats

Installation of geotexiles

Reinforced terrains

Soil nailing

Reinforced soils

Obstacles to the flow

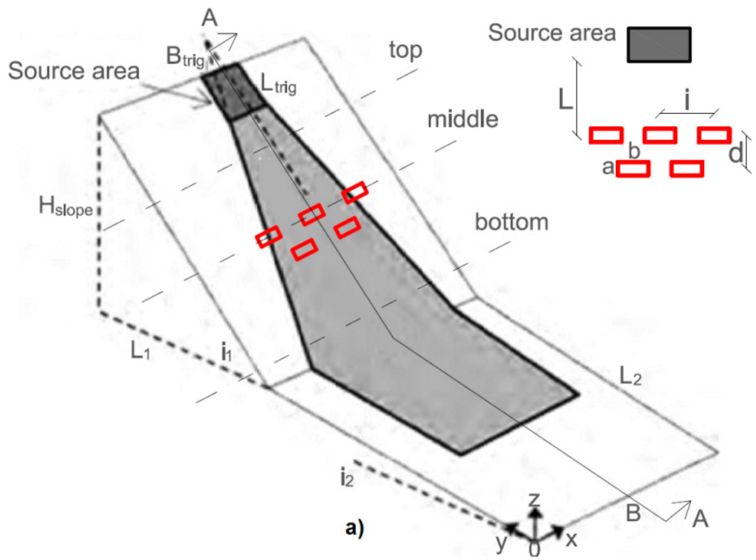
Disposition of baffles

Disposition of barriers

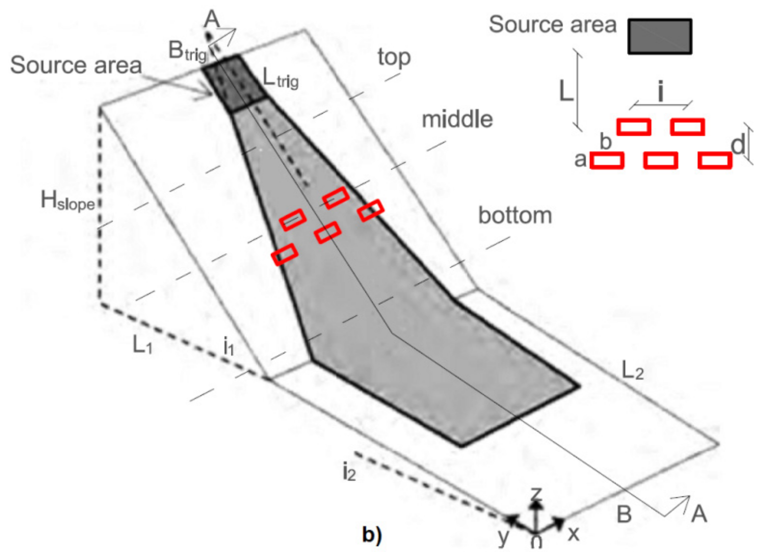
Petrosino S. (2016). Entrainment profiles for debris avalnches in engineered steep shallow covers. Master thesis, University of Salerno (in cooperation with UPM).

SLOPE ENGINEERED

just 3 × 2 combinations of 5 baffles



a)



b)

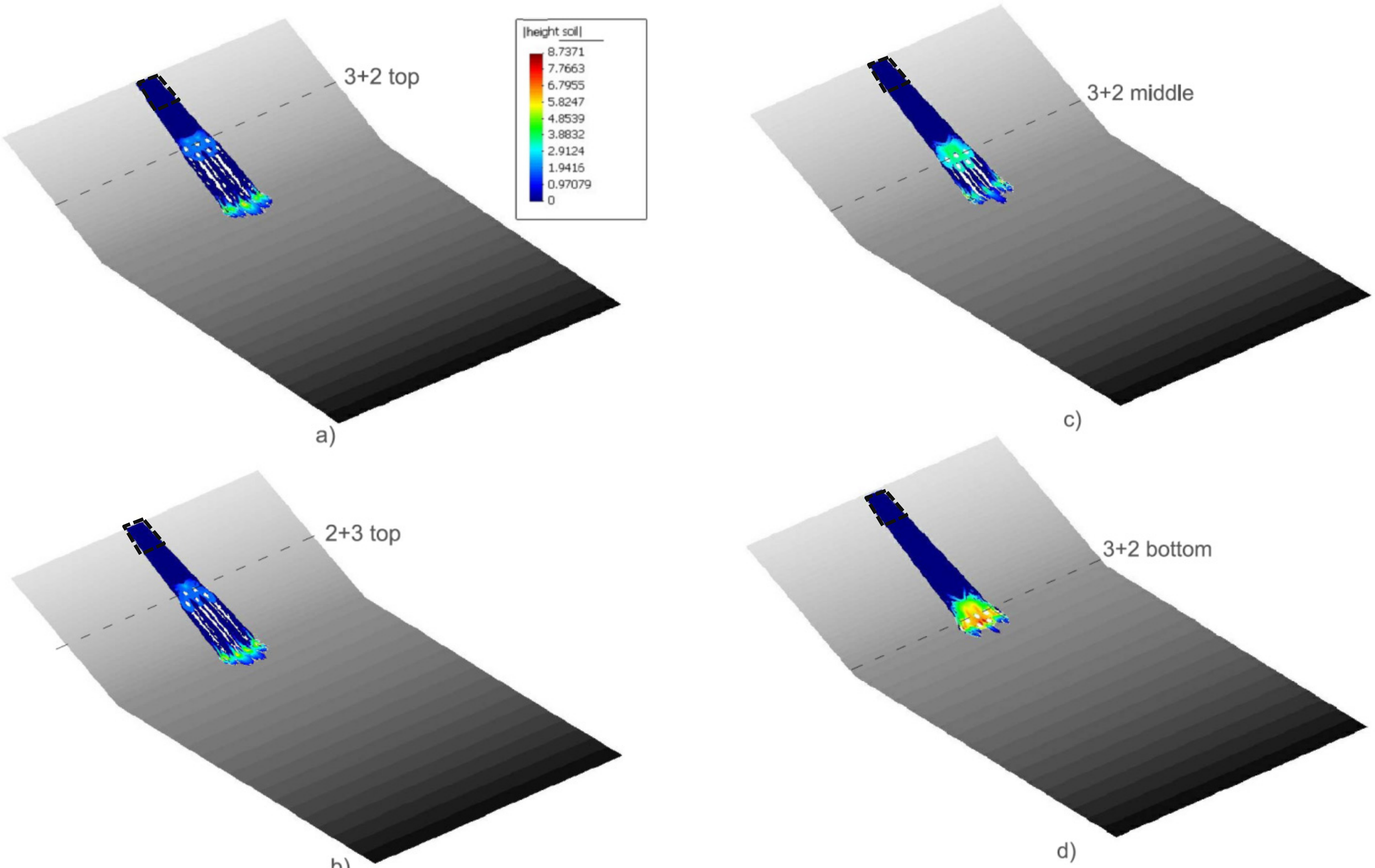
Case (-)	a (m)	b (m)	i (m)	d (m)	L (m)
3+2 top	10	5	30	15	30
3+2 middle	10	5	30	15	80
3+2 bottom	10	5	30	15	130
2+3 top	10	5	30	15	30

$\tan\phi_b$ (-)	h^{rel}_w (-)	p^{rel}_w (-)	B_{fact} (m^2s^{-1})	K_r (-)
0.50	0.4	0.5	$1.0x10^{-2}$	$3.0x10^{-2}$

Cuomo S., Cascini L. Pastor M., Petrosino S. (2017). Modelling the propagation of debris avalanches in presence of obstacles. In: 4th World Landslide Forum 2017. Springer International Publishing AG 2017, M. Mikos et al. (eds.), Advancing Culture of Living with Landslides, DOI 10.1007/978-3-319-53487-9_55

SLOPE ENGINEERED with BAFFLES

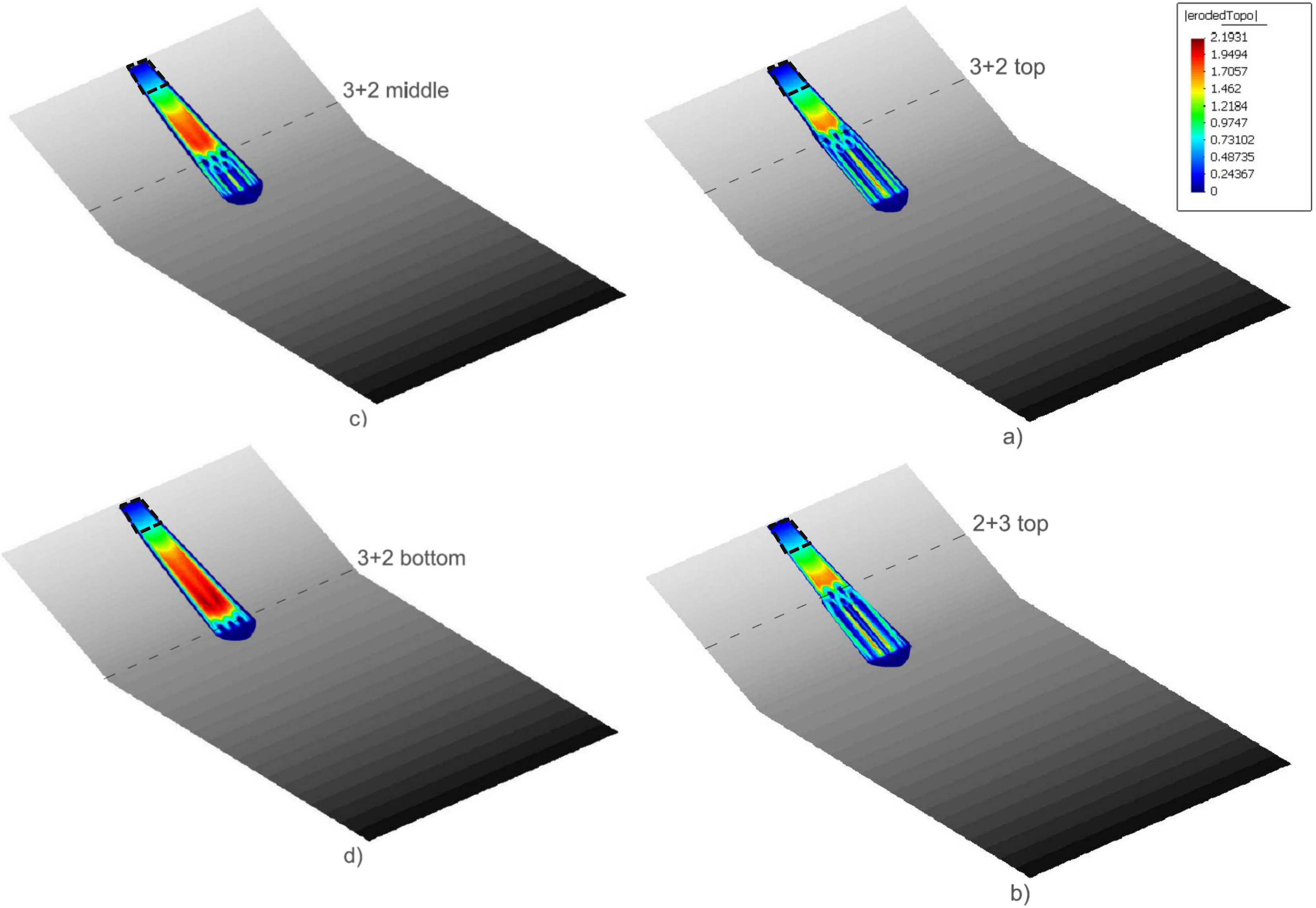
Thickness of Landslide Deposit



Cuomo S., Cascini L. Pastor M., Petrosino S. (2017). Modelling the propagation of debris avalanches in presence of obstacles. In: 4th World Landslide Forum 2017. Springer International Publishing AG 2017, M. Mikos et al. (eds.), Advancing Culture of Living with Landslides, DOI 10.1007/978-3-319-53487-9_55

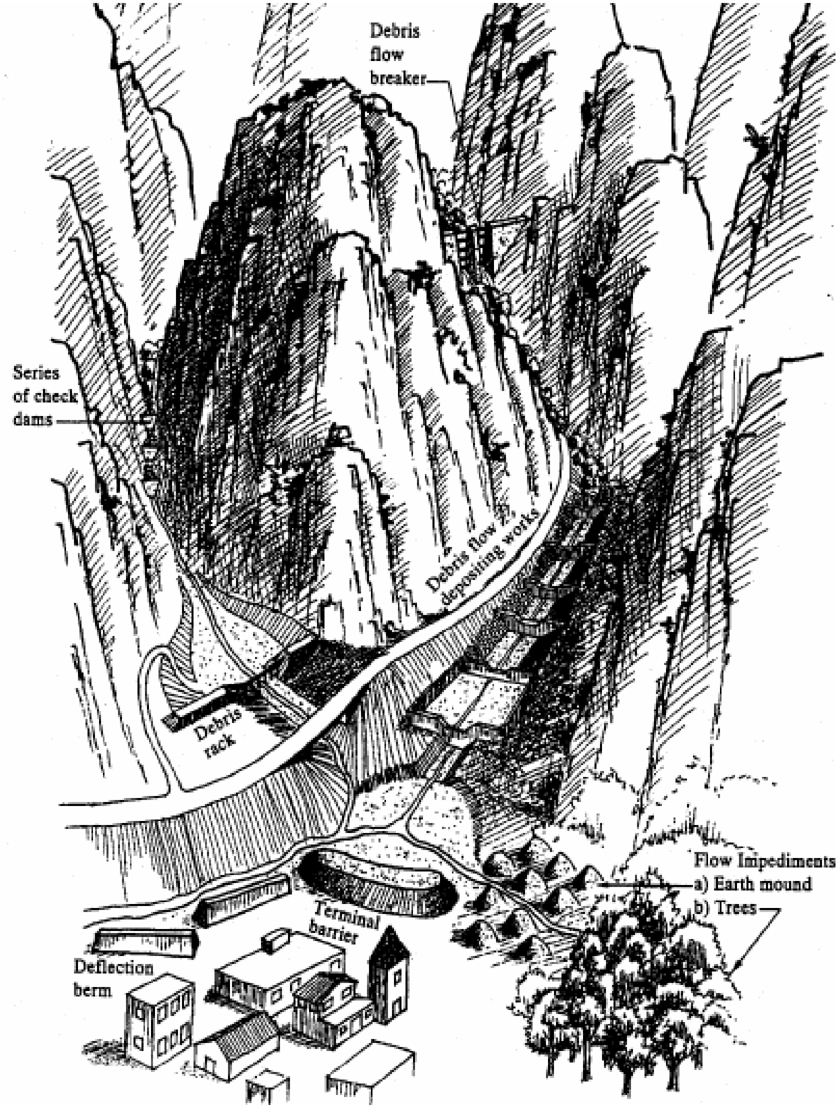
SLOPE ENGINEERED with BAFFLES

Soil eroded along the slope



Cuomo S., Cascini L. Pastor M., Petrosino S. (2017). Modelling the propagation of debris avalanches in presence of obstacles. In: 4th World Landslide Forum 2017. Springer International Publishing AG 2017, M. Mikos et al. (eds.), Advancing Culture of Living with Landslides, DOI 10.1007/978-3-319-53487-9_55

Remarks and Conclusions



Lo (2000)

- ✓ Mechanisms: relatively clear
- ✓ Modelling of entrainment: empirical
- ✓ Data from the field: problematic!!
- ✓ Existing analytical models cannot be used in real cases

So, under simple hypotheses,

- ✓ modelling of the consequences: yes

Contributions of geomechanics:

- ✓ understand where and which field measurements could be useful,
- ✓ develop analytical models (effectively usable with the data available)
- ✓ implementation of such new analytical models in the already existing powerful computation tools

Lo D.O.K. (2000). Review of natural terrain landslide debris resisting barrier design. Special Project Report:SPR1/2000, Geotechnical Engineering Office, Hong Kong.

Thank you for your attention

Sabatino CUOMO
Email: scuomo@unisa.it

UNIVERSITÁ DI SALERNO