GDC Annual Seminar

Bright Spark Lecture Award

“Adapt to challenges, create to thrive”

Insights on Debris Flow Hazard Mitigation and Growth

THE UNIVERSITY OF HONG KONG
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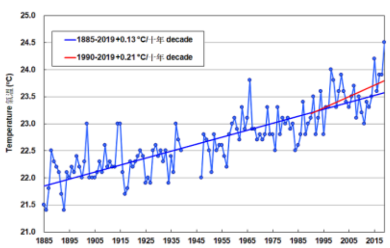
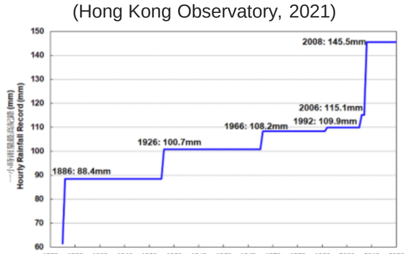
Debris flow threat due to climate change



Temperature change in Hong Kong
(Hong Kong Observatory, 2021)



Hourly rainfall records in Hong Kong
(Hong Kong Observatory, 2021)

Landslide in Hong Kong following a black rainstorm warning on 28 June 2021
(Low, 2021)

Outline

1. Debris flow hazard mitigation
2. Debris flow growth

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

土木工程拓展署 土力工程處
Geotechnical Engineering Office
Civil Engineering and Development Department

香 港 大 學
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Debris Flow Hazard Mitigation

"Understanding debris flow mechanisms and mitigating risks for a sustainable Hong Kong"

Project Coordinator: Prof. Charles W. W. Ng (HKUST)
Start date: 1 Jan. 2016
End date: 31 Dec. 2020
Project No.: T22-603/15N

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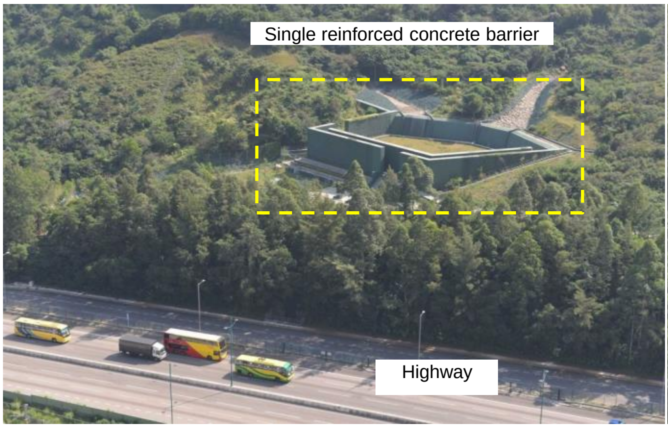
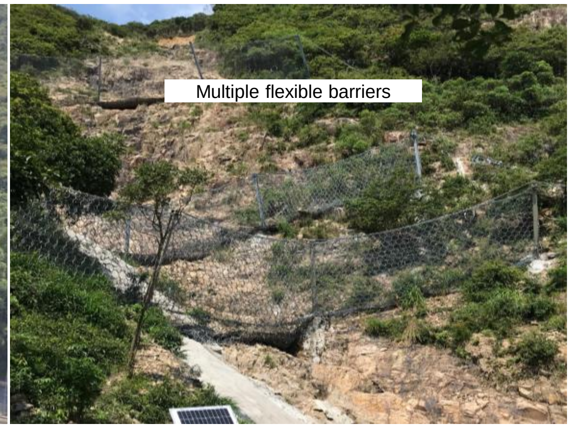
Enhancing urban resilience against debris flow hazards





How to design the impact force for barriers?

$$F = \alpha\rho v^2 h_0 w + 0.5kgh_0^2 w$$

Dynamic force (VanDine 1996; NILIM 2007; ASI 2008; Proske *et al.* 2011)

Static force $k = 1$ (NILIM 2007; Kwan and Cheung 2012)

α = dynamic impact coefficient
k = static impact coefficient
ρ = density of debris flow (kg/m^3)
v = debris velocity at impact (m/s)
h_0 = debris thickness (m)
w = debris width (m)

Region	**Pressure coefficient, α**	**Reference**
Canada	~ 1.5 times the flow thickness	Hungr *et al.* (1984)
Mainland, China	3 to 5 (field measurements from over 70 debris flows with entrained boulders)	Zhang (1993)
	1 (circular structure) 1.3 (rectangular structure) 1.5 (square structure)	MLR (2006) (Ministry of Land and Resources of the Chinese Geological Survey)
HKSAR	2 (flexible barrier) 2.5 recently changed to 1.5 (rigid barrier)	GEO (Kwan, 2012)
Italy	3.5 (more viscous flow) 1.0 to 5.3 (less viscous flow)	Scotton and Deganutti (1997)
Japan	2 (laminar and fine-grained flow)	Wantanabe and Ike (1981)
Switzerland	2 (granular flow, 1900-2300 kg/m^3) 0.7 (viscous flow or fluid-like flow, 1600-2000 kg/m^3)	Volkwein (2014)

Scale-dependent nature of debris flows

Debris flows are a scale-dependent phenomenon (Iverson 2015)

Timescale for pore pressure dissipation: $N_{\mathrm{Pore}} = \frac{(L/g)^{1/2}}{\mu \boldsymbol{h_0^2}/kE}$

Flow depth ($\boldsymbol{h_0}$)

Effect of cohesion: $N_{\mathrm{Rey}} = \frac{c_f}{\rho g \boldsymbol{h_0}}$

Effect of viscous shearing: $N_{\mathrm{Rey}} = \frac{\rho v \boldsymbol{h_0}}{\mu}$

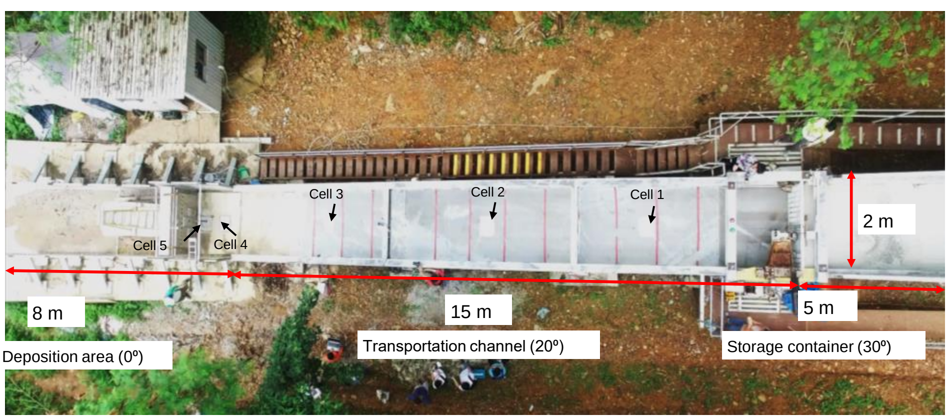
$\boldsymbol{h_0}$ is the flow depth
L is the length of flow path
σ is the internal stress
ρ is bulk density
g is gravitational acceleration
ρ is the solid density
E is bulk mixture stiffness
μ viscosity of the fluid phase
k hydraulic permeability
v flow velocity
e void ratio
c_f cohesion

Time

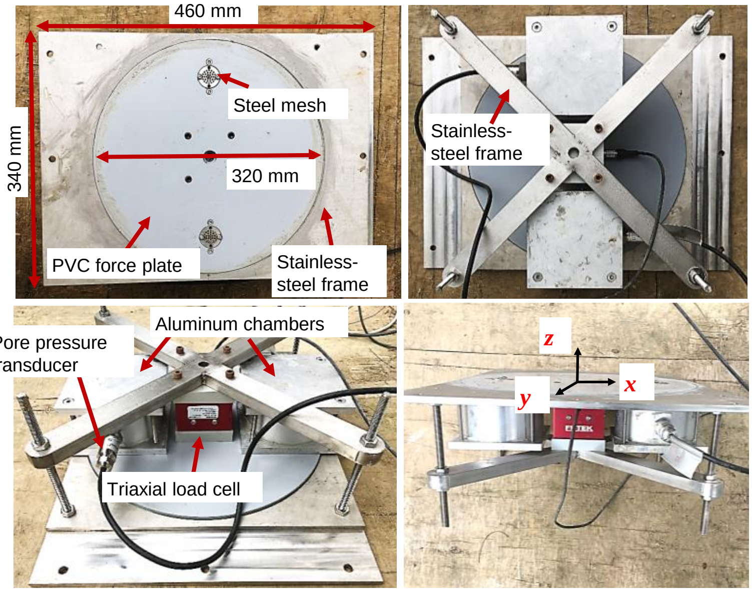
Cost

Repeatability

28-m long flume model (10 m^3)



Basal debris flow measurements



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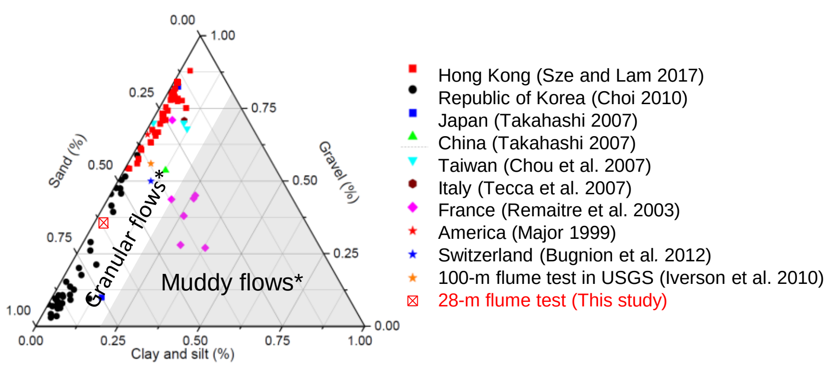
Debris flow composition



*Classification based on Baunnet-Staub (1999)

Volumetric solid fraction: 0.6

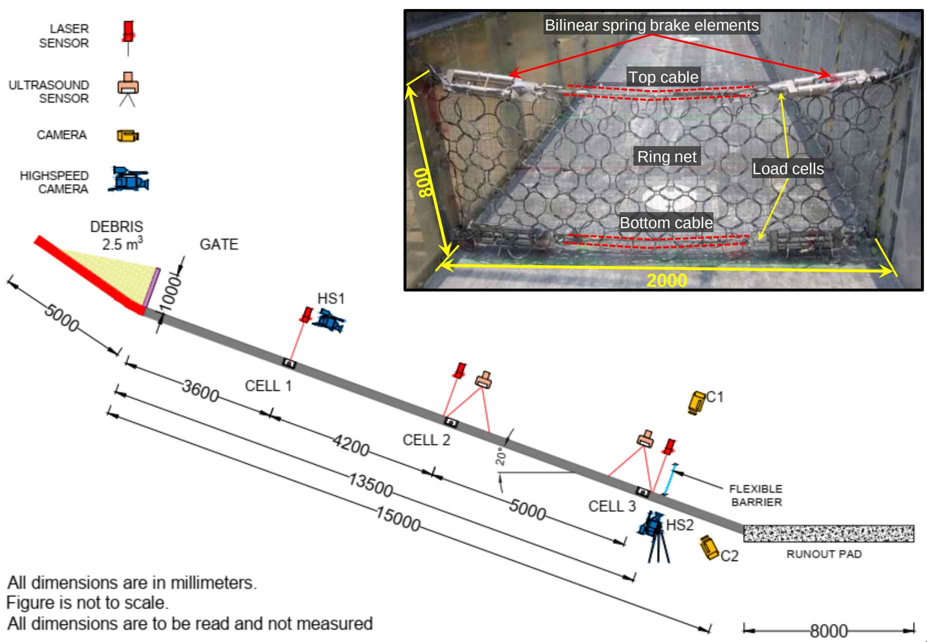
Material	Gravel	Sand	Clay
Size	20 mm	0.06-2 mm	<0.06 mm
Percentage	0.36	0.61	0.03

Test program

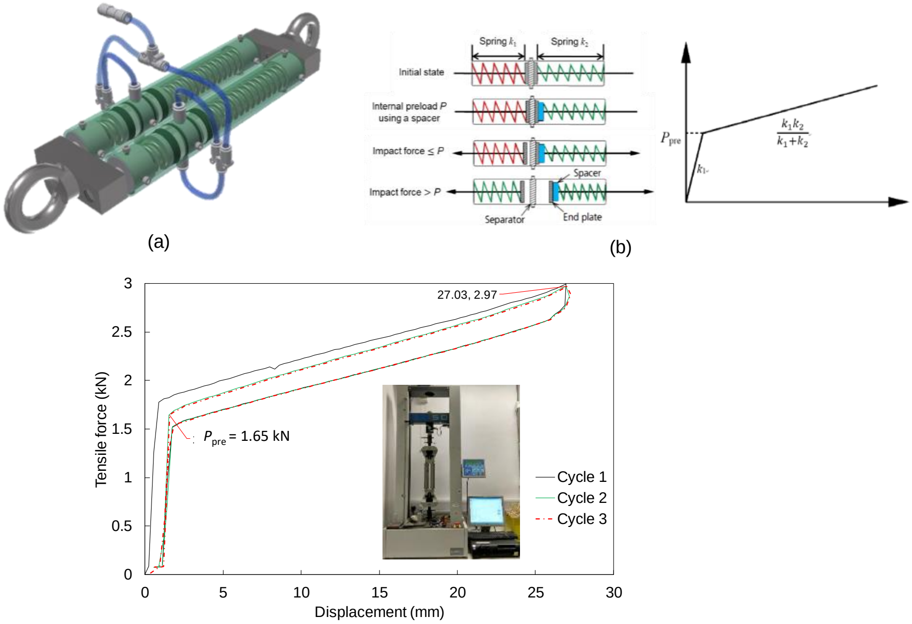
Objective	Test ID	Flow volume (m^3)	Barrier size (m x m)	No. of brake elements per cable
To reveal the fundamental impact dynamics against rigid barrier	R	2.5	-	-
To reveal the fundamental impact dynamics against flexible barriers with and without brake elements	D2NoBr	2.5	2.0 x 0.8	Nil
	D2Br1			1
	D2Br2			2
	D9NoBr	9.0	4.5 x 1.5	Nil
	D9Br1			1
	D9Br2			2

*D2Br2 : **D** (Debris) **2**(volume) **Br** (Brake element**) 2** (Nos. per cable)*
Debris composition in all tests is kept constant with 60% solid concentration

Test setup and instrumentation plan



Newly developed dual bilinear brake elements



(a)

(b)

(c)

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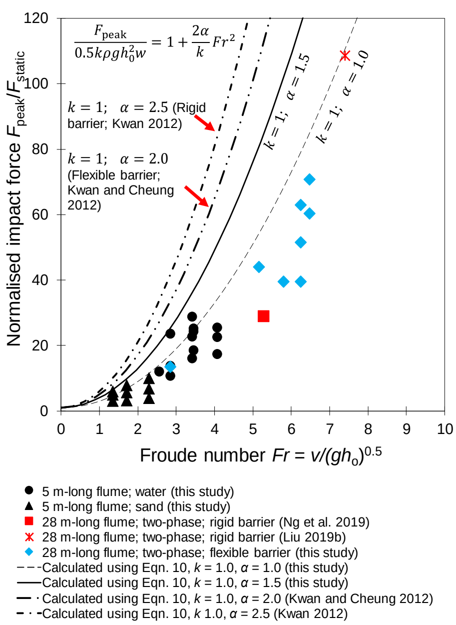
Observed impact kinematics for rigid barrier

Observed impact kinematics for flexible barrier

Front view

Top view

Proposed impact coefficients



Impact coefficient	Barrier type	Original design value	Optimised design value
Dynamic (α)	Rigid	2.5 (GEO270; GEO339)	**1.5** (TGN52 on 30 Dec. 20)
	Flexible	2.0 (GEO270; DN1/2012)	**1.0** (proposed)
Static (k)	-	1.0	


Impact mechanisms of debris flow on barriers: modelling, analysis and design

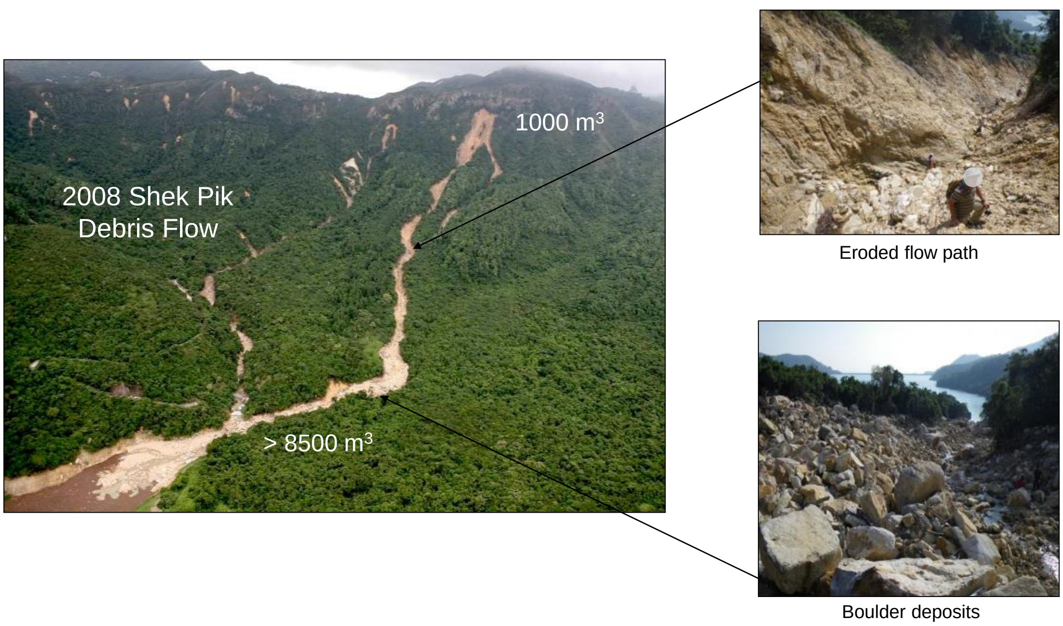

Design Recommendations for Single and Dual Debris Flow Barriers with and Without Basal Clearance

Outline

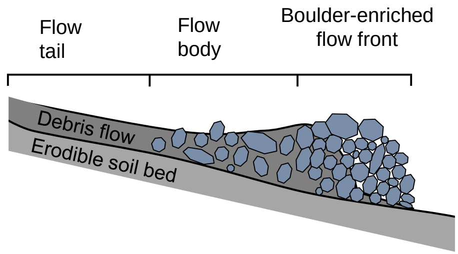
1. Debris flow hazard mitigation
2. Debris flow growth

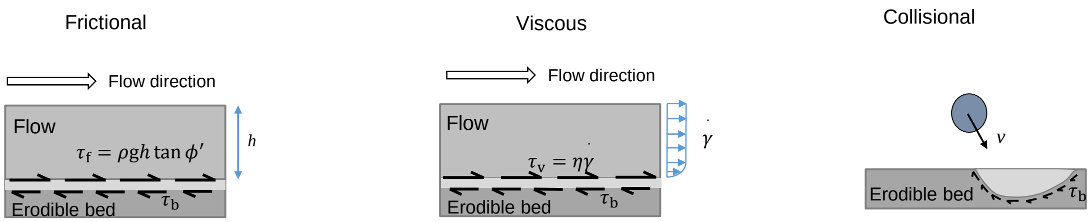
Song, P. & Choi, C.E. (2021) Revealing the Importance of Capillary and Collisional Stresses on Soil Bed Erosion Induced by Debris Flows. *Journal of Geophysical Research: Earth Surface*. https://doi.org/10.1029/2020JF005930

What makes debris flow unique compared to other types of landslides?



Debris Flow Entrainment Mechanics





Existing theoretical entrainment models

Reference	Flow / bed material	Mobilizing stresses	Bed resistance
Fraccarollo & Capart (2002)	Water / soil	Friction (shear) stress	Shear strength of soil
Pitman et al. (2003)	Landslide / soil	Friction (shear) stress	Shear strength of soil
Sovilla et al. (2006)	snow / snow	Friction (shear) stress	Shear strength of snow
Stock & Dietrich (2003)	Debris flow / rock	Collision stresses (point loads)	Tensile strength of rock
Medina et al. (2008)	Debris flow / soil	Friction (shear) stress	Shear strength of soil
Iverson & Ouyang (2015)	Debris flow / soil	Friction (shear) stress	Shear strength of soil

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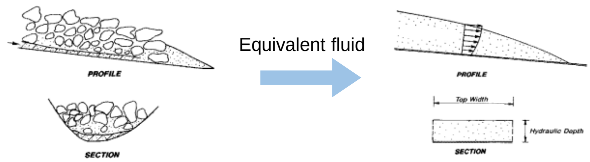
Mechanics of frictional entrainment

- Assume debris flow as an equivalent fluid
- Boulder-enriched front not explicitly considered



External stress > Bed resistance

Interface frictional stress τ_{flow}

Bed shear strength (saturated condition)
$$\tau_{\text{bed}} = (\sigma_{\text{n}} - u_{\text{wb}}) \tan \phi'_{\text{bed}}$$

Entrainment rate: $\dot{e} = \dfrac{\tau_{\text{flow}} - \tau_{\text{bed}}}{\rho_{\text{bed}} U}$

Iverson, R. M. (2012)

U Flow velocity
σ_{n} Normal loading from flow
ρ_{bed} Bed density

ϕ'_{bed} Internal friction angle (bed)
u_{wb} Pore water pressure (in bed)

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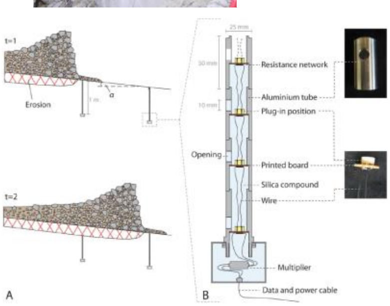
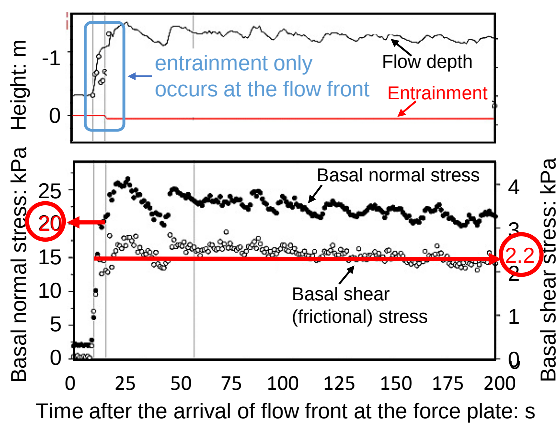
Is entrainment a predominantly frictional process?

Berger et al. (2011)

Unique field measurements from the Illgraben catchment, Switzerland





Estimated shear strength:

$\tau_{\text{bed}} = \sigma_{\text{n}} \tan\phi'_{\text{bed}} = 14\text{kPa}$

$(\phi'_{\text{bed}} = 35^{\circ})$

Estimated shear strength > Applied shear stress
Based on frictional entrainment mechanics, erosion should not have occurred. Importance of collisional flow front?

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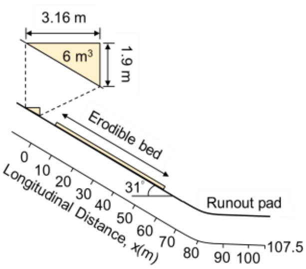
Effects of bed water content on entrainment

Iverson et al. (2011)

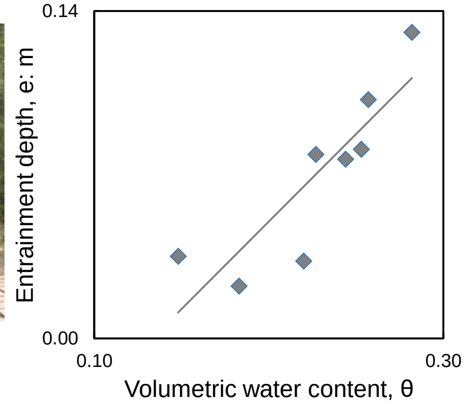


Side view of the USGS flume

Erodible bed
***θ* = 0.22**

Erodible bed
***θ* = 0.25**

Front view USGS flume



Logan, M., Iverson, R.M., and Obryk, M.K., 2018, Video documentation of experiments at the USGS debris-flow flume 1992–2017 (ver 1.4, January 2018): U.S. Geological Survey Open-File Report 2007–1315, https://doi.org/10.3133/ofr20071315.

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Soil beds are rarely saturated when landslides occur

Fredlund et al. (1996)

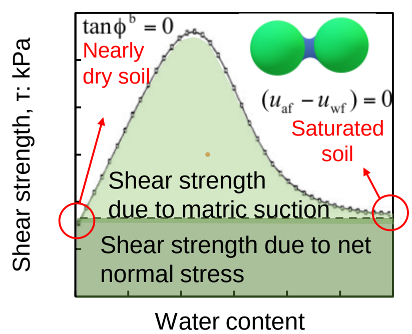
Bed water content when debris flows occur at Chalk Cliff, USA

McCoy, S. W., Kean, J. W., Coe, J. A., Tucker, G. E., Staley, D. M. & Wasklewicz, T. A. (2012). Sediment entrainment by debris flows: In situ measurements from the headwaters of a steep catchment. Journal of Geophysical Research: Earth Surface, 117(F3).

Date	Bed water content
26-July 2011	0
28-June 2010	0.02
15-Sep 2009	0.06
30-Jun 2011	0.06
12-Jun 2010	0.39

$$\tau_{\mathrm{bf}} = \underbrace{(\sigma_{\mathrm{n}} - u_{\mathrm{af}})}_{\text{Net normal stress}} \tan\phi'_{\mathrm{bed}} + \underbrace{(u_{\mathrm{af}} - u_{\mathrm{wf}})}_{\text{Matric suction}} \tan\phi^{b}$$

$u_{\mathrm{wf}} = u_{\mathrm{w0}} + B_{\mathrm{w}}\sigma_{\mathrm{n}}$ $B_{\mathrm{w}} < 1$
$u_{\mathrm{af}} = u_{\mathrm{a0}} + B_{\mathrm{a}}\sigma_{\mathrm{n}}$ $B_{\mathrm{a}} < 1$



τ_{bf} Bed shear strength at failure
σ_{n} Normal loading from flow
ϕ'_{bed} Interface friction angle
B_{a} B_{w} Pore air/water pressure parameter

u_{a0} u_{w0} Initial pore air/water pressure
u_{af} u_{wf} Pore air/water pressure at failure
ϕ^{b} Influence of matric suction on shear strength

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Scientific challenge

What are the effects of collisional stresses and unsaturated soil strength on soil bed entrainment?

Our proposed scaling

- Entrainment is proportional to the collisional stress and unsaturated shear strength
- The N_{soil} considers for the first time the effects of unsaturated soil mechanics and collisional stresses to the entrainment of soil bed

$$N_{\mathrm{soil}} = \frac{\upsilon \rho_{\mathrm{s}} \delta^2 \dot{\gamma}^2}{(\sigma_{\mathrm{n}} - u_{\mathrm{af}})\tan\phi'_{\mathrm{bed}} + (u_{\mathrm{af}} - u_{\mathrm{wf}})\tan\phi^{\mathrm{b}}}$$

Basal collisional stresses (*Bagnold 1954*)

Shear strength of unsaturated soil bed

σ_{n} Normal loading from flow
u_{af} Pore air pressure at failure
u_{wf} Pore water pressure at failure
$\tan\phi^{\mathrm{b}}$ Influence of matric suction on shear strength

ϕ'_{bed} Interface friction angle
υ Solid fraction
ρ_{s} Solid density
δ Particle size
$\dot{\gamma}$ Shear rate

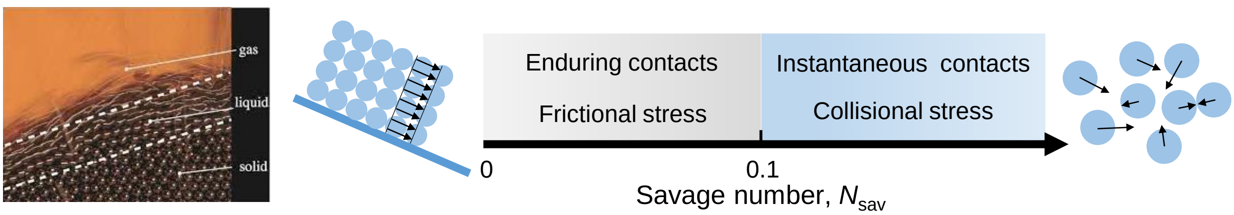
How do we make granular flows predominantly collisional?

Savage & Hutter (1989)

Savage number: $$N_{\text{sav}} = \frac{\nu \rho_s \boldsymbol{\delta}^2 \dot{\boldsymbol{\gamma}}^2}{\rho g h \tan \phi_f'}$$

$\nu \rho_s \delta^2 \dot{\gamma}^2$ ← Collisional stress

$\rho g h \tan \phi_f'$ ← Frictional stress



υ solid fraction
ρ_s solid density
$\boldsymbol{\delta}$ particle size
g gravitational acceleration
h flow depth
$\dot{\boldsymbol{\gamma}}$ shear rate
ϕ_f' effective friction angle of flow material

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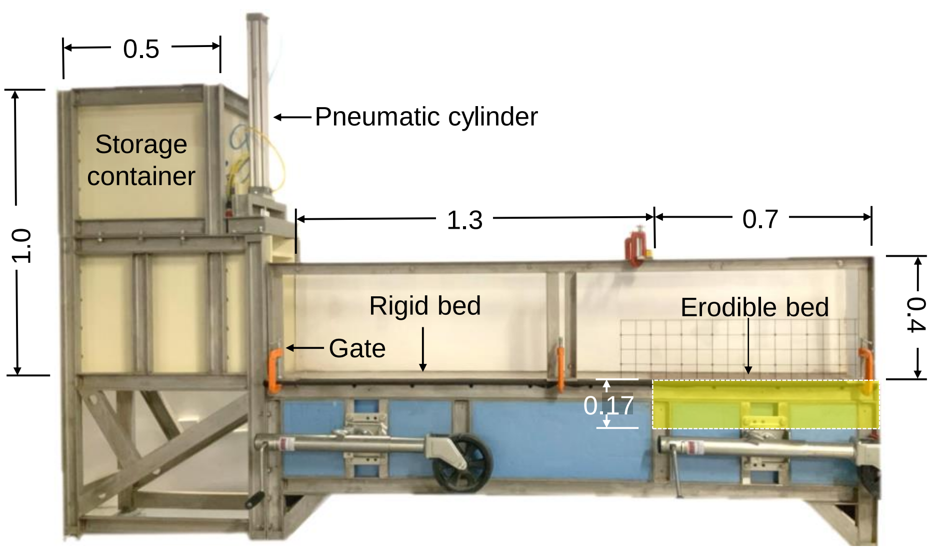
Flume model



(Side view of the flume, all dimensions in meters)

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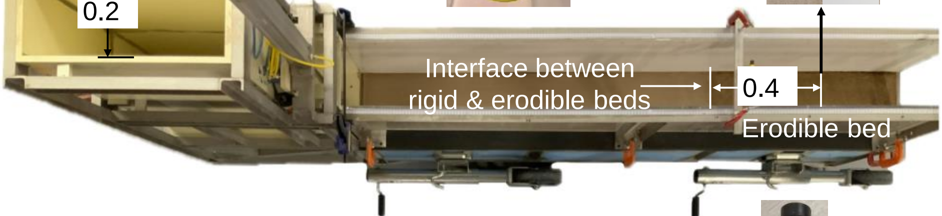
Instrumentation

Ultrasonic sensor (mounted on top of erodible bed)

Pore pressure transducer (buried at a depth of 0.12 m along the centreline)



Images captured are analysed with Particle Image Velocimetry (PIV) (*Thielicke & Stamhuis 2014*)

High-speed camera

(All dimensions in meters)

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Test materials

Soil bed:

Completely decomposed granite (D_{50} = 0.75 mm)

Dry density: 1322±18kg/m^3 (within 2% error)

Flow material:

Gravel (equivalent diameter of 12 mm; 70 kg)

CDG

Gravel

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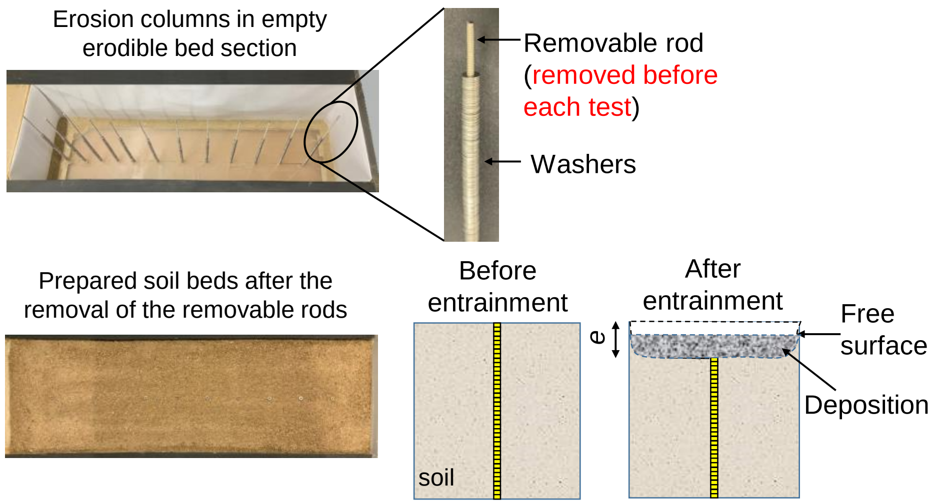
Measurement of entrainment depth

Erosion columns (*Berger et al. 2010*) are used to deduce the entrainment depth of soil bed to exclude the influence of the deposition layer



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Test program

Test ID	Volumetric water content, θ	Initial matric suction[1], (u_{a0}-u_{w0}) (kPa)	Pore pressure parameter[2], B_w & B_a	Shear strength, τ (kPa)
θ_0	0.00	-	0.48	0.62
θ_006	0.06	97.8	0.51	1.10
θ_011	0.11	79.5	0.54	5.60
θ_013	0.13	68.0	0.55	7.38
θ_016	0.16	26.0	0.58	6.74
θ_018a	0.18	14.0	0.59	4.12
θ_018b	0.18	10.8	0.59	3.24
θ_020	0.20	5.0	0.60	1.93
θ_021	0.21	1.7	0.61	0.95
θ_022	0.22	1.3	0.63	0.85
θ_024	0.24	0.9	0.64	0.71
θ_028	0.28	0.4	0.68	0.53
θ_030	0.30	0.1	0.71	0.37

[1] Initial matric suction is measured with a tensiometer

[2] B_w & B_a are calculated with equation proposed by Hilf (1948):

$$B_a = B_w = 1/\left[1 + \frac{(1 - S_0)n_0}{(u_{a0} + \Delta u_a)m_v}\right]$$

S_0 Initial saturation of soil
m_v Compressibility of soil
n_0 Initial void ratio
u_{a0} Initial pore air pressure

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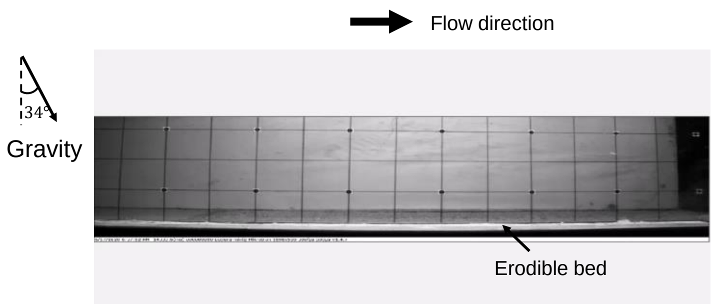
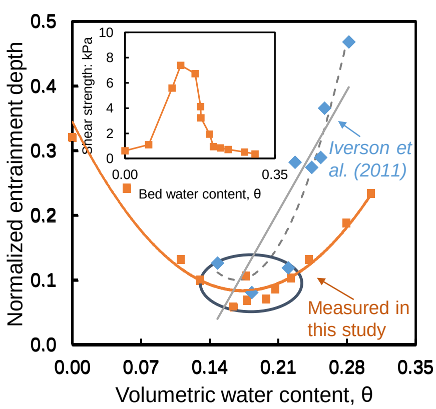
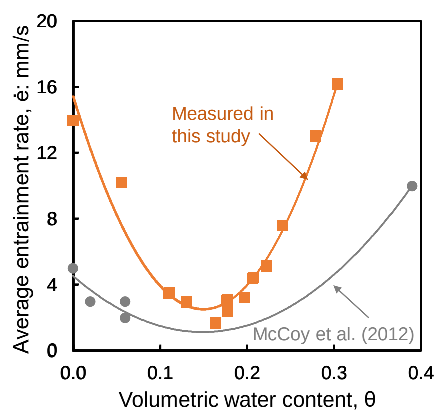
Observed kinematics from high-speed camera with Particle Image Velocimetry (PIV)



Comparison of measured data with USGS and the field: effects of water content on entrainment





Unsaturated strength plays an important role in the entrainment of a soil bed

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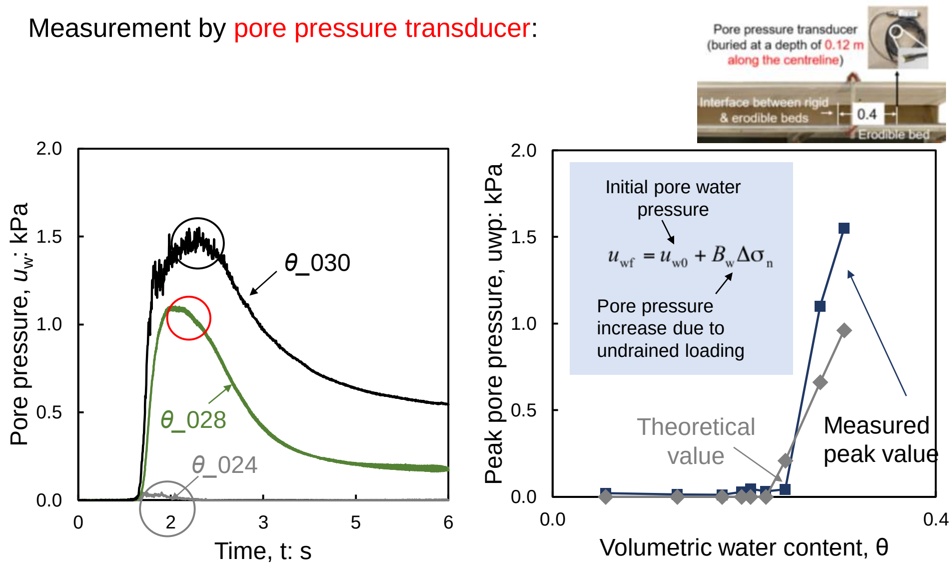
Pore pressure response of soil bed to undrained loading

Measurement by pore pressure transducer:



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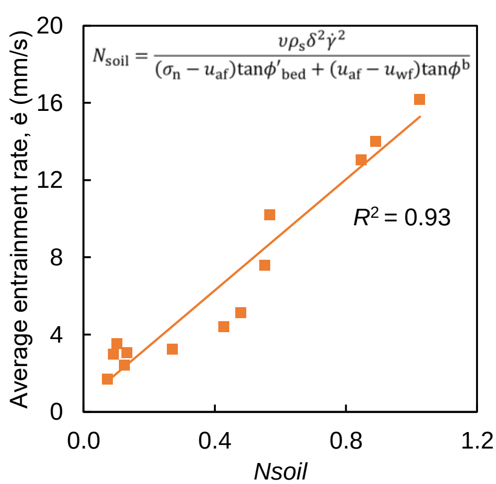
Evaluation of N_{soil} to evaluate our proposed scaling

Our hypothesis :

$\dot{e} \propto N_{soil}$



τ_{bf} Bed shear strength at failure
σ_n Normal loading from flow
ϕ'_{bed} Interface friction angle
u_{af} Pore air pressure at failure
u_{wf} Pore air pressure at failure
ϕ^b Influence of matric suction on shear strength
υ Solid fraction
ρ_s Solid density
δ Particle size
$\dot{\gamma}$ Shear rate

Collisional stresses plays an important role in the entrainment of a soil bed

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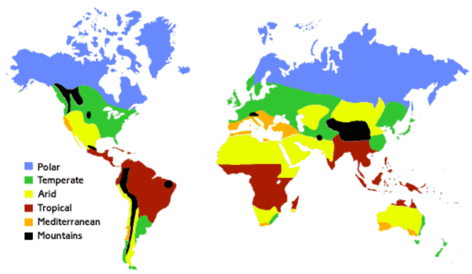
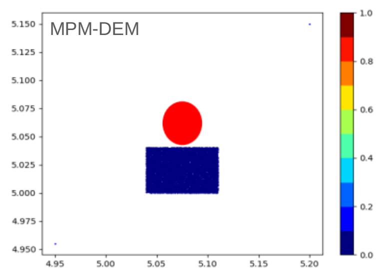
Summary: debris flow growth

- Soil-atmospheric interaction is very much relevant for landslide growth
  - What are the competing roles of rainfall and humidity on landslide growth in different climates?
- Collisions are more dominant in the entrainment of soil than initially perceived
  - Is there a need for improved entrainment and numerical models?





In collaboration with Dr. Choo, Dr. Jiang, and Mr. Zhao at HKU

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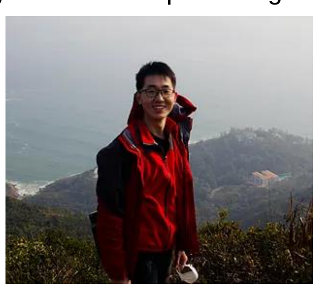
1. Colleagues at HKU and HKUST
2. Collaborators in industry
3. Research Grants Council of Hong Kong (16209717; 16212618; 16210219; 27205320; AoE/E-603/18; T22-603/15N); The National Natural Science Foundation (NSFC) of China (51709052); The Hong Kong Jockey Club Disaster Preparedness and Response Institute (HKJCDPRI17; HKJCDPRI18)
4. Mr. Pengjia Song for advancing the research pertaining to entrainment



Thank you

www.cechoi.org
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Reference

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