Workshop on Seepage Induced Geotechnical Instability

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Visualising internal erosion mechanisms using transparent soil

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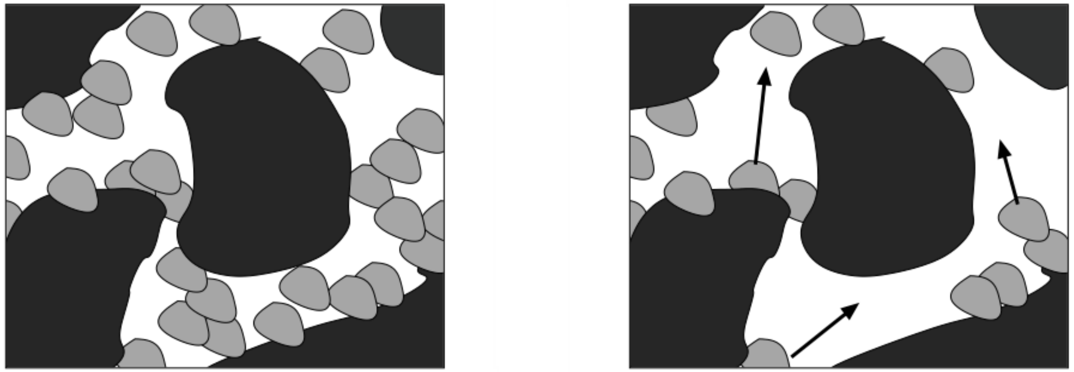
Internal Erosion – dams, canals, dikes & levees

Internal erosion (or suffusion) responsible for ~50 % of embankment dam failures globally

- Predominantly a problem in older or smaller earthworks
- Work focused on establishing erosion criteria
- Work focused on understanding mechanisms of internal erosion



The soil without seepage flow. The pore space is not entirely filled by the fine grains.

Seepage flow mobilises fine grains (particle transport is indicated by arrows).

Gap-graded soil in which fine particles can migrate through voids = suffusion *(Rosenbrand, 2011)*

Skempton & Brogan (1994) experiments

- Performed tests on internally unstable sandy gravels to compare theoretical value of critical hydraulic gradient at which piping occurs i_c under an upward flow (according to Terzaghi, 1925) with the actual hydraulic gradient i_{cr}.

- Proposed that the erodible fine grains carry some (reduced) proportion of the overburden load

- The critical gradient for piping in the fine grains is then:

$$i_{cr} = \alpha \left(\frac{\gamma'}{\gamma_w}\right) \text{ or } i_{cr} = \alpha i_c$$

where i_{cr} is the critical hydraulic gradient observed in the test

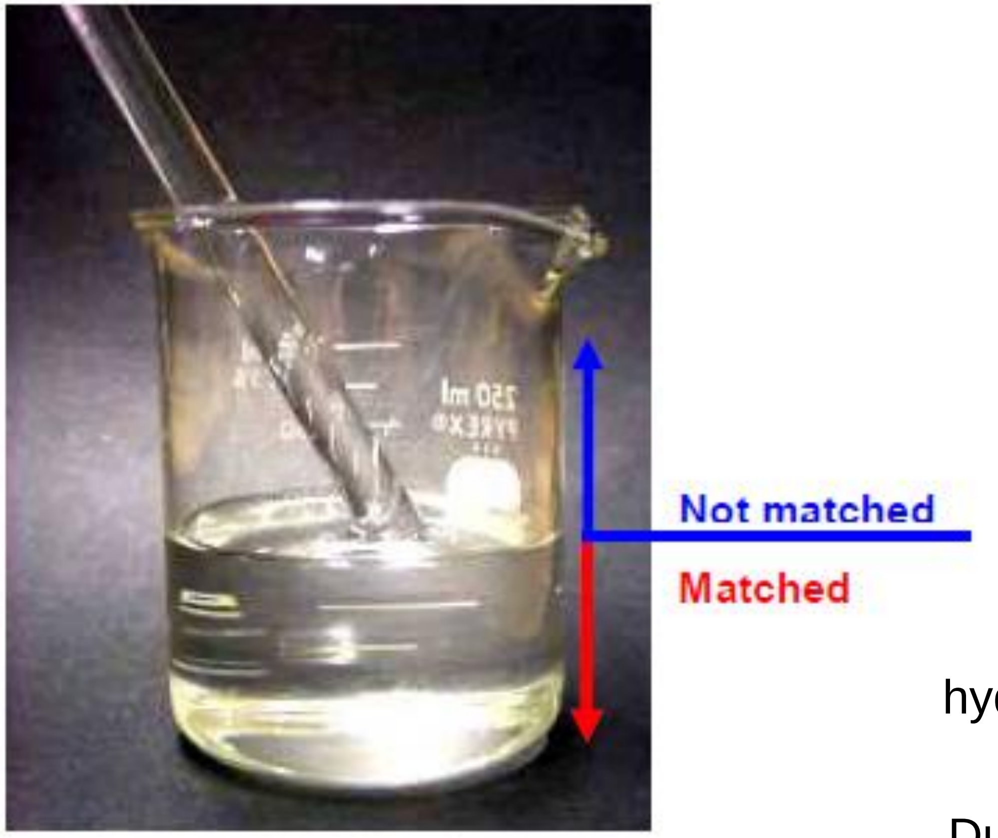
- From this: a larger α will yield a greater resistance to the onset of seepage-induced instability.

Visualising internal erosion

Laboratory based

- Using a box-shaped permeameter
  - Initial experiments based on Skempton & Brogan (1994) design
- Glass particles and optically matched immersion oil
  - Replicating soil and water
- Variable particle grading and hydraulic head
- Refractive index matching (RIM) & planar laser induced fluorescence (PLIF) techniques
- (High) speed imaging
- Image processing

Refractive Index Matching & seepage scaling



Matched! ↑ (Refractive index)

Ratio Gs = 2.65! ↑ (Density)

Scale particles ~4 times up! ↑ (Kinematic viscosity)

	Refractive index at 589.3 nm	Density at 25 °C (g/cm^3)	Kinematic viscosity at 25 °C (cSt)
hydrocarbon oil	**1.4715**	0.846	16
Duran glass	**1.4718**	2.23	-

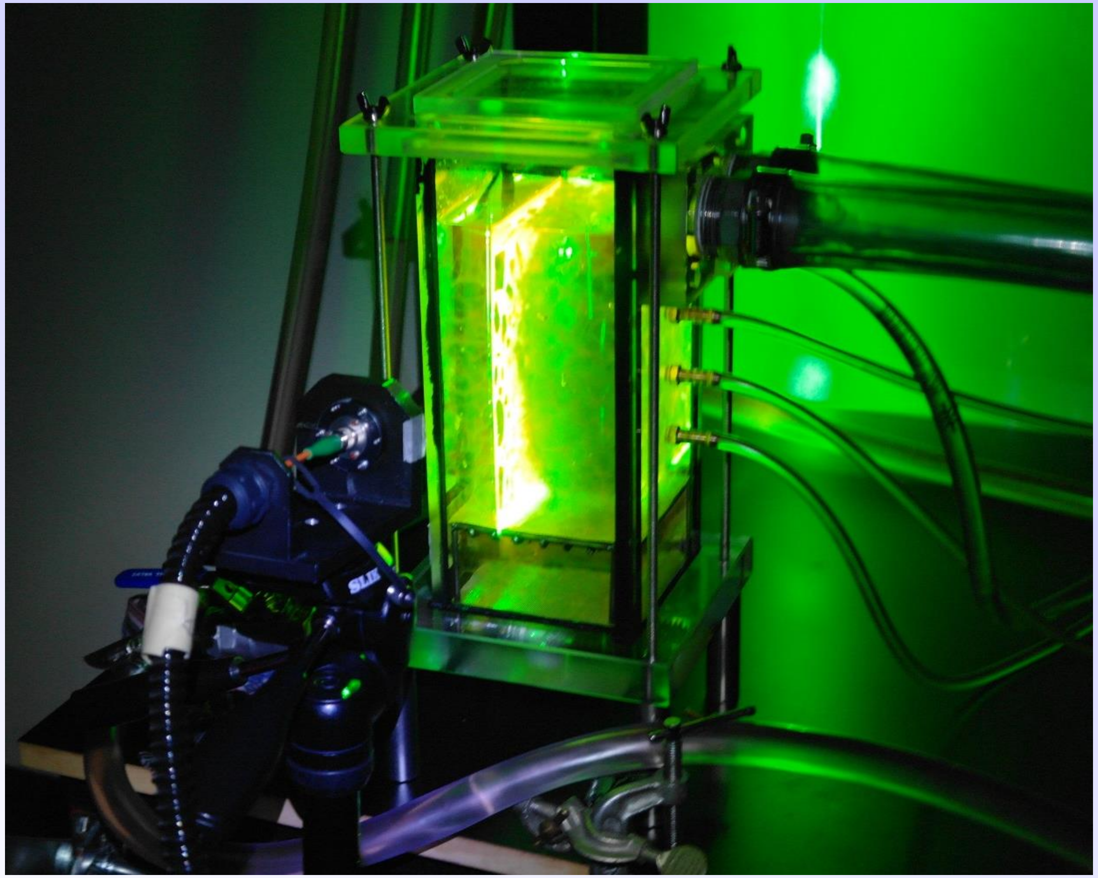
RIM with transparent soil & PLIF

Transparent materials

- Solids & fluid with same refractive index (RIM)

Planar laser induced fluorescence (PLIF)

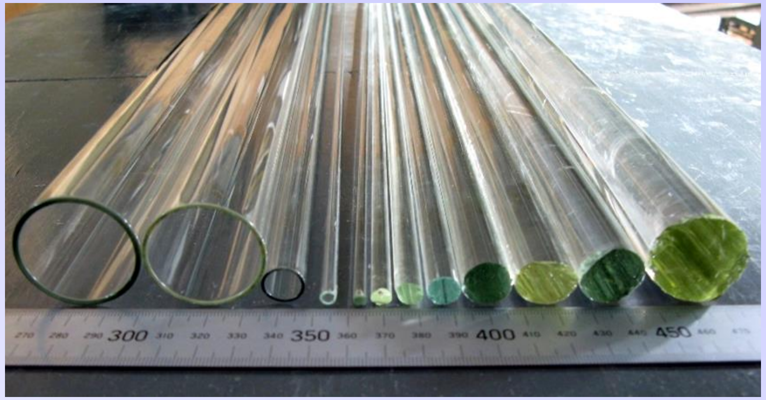
- Fluorescent dye in fluid
- ~1mm thick laser sheet (532nm) to illuminate plane
- Particles appear dark against bright fluid background



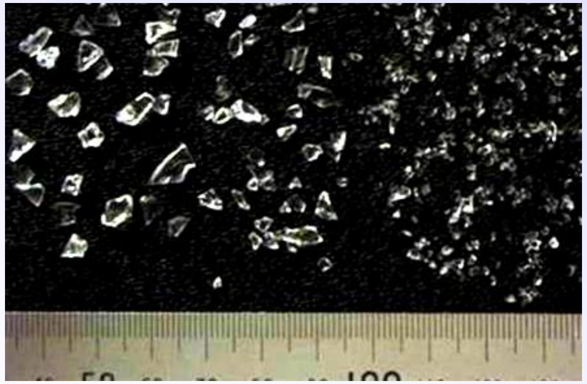
Particles used

Duran® borosilicate glass, irregular shape:

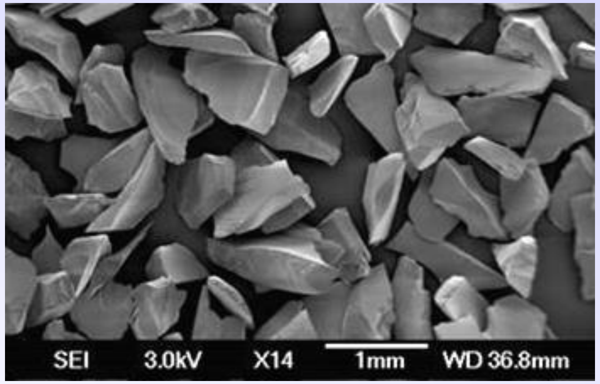
- Cut / crushed rods (4mm to 30mm)
- Crushed tubes (4mm to 150µm)



$d_{particle}$> 4mm



$d_{particle}$< 4mm



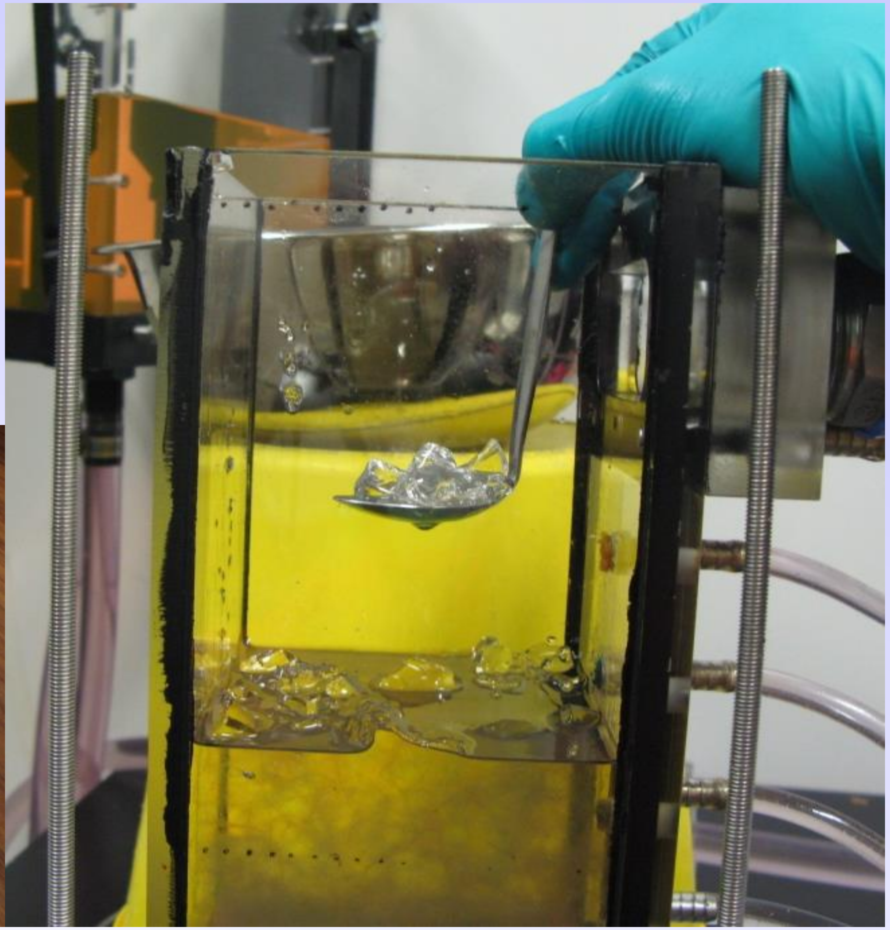
$d_{particle}$= 300µm

Sample preparation

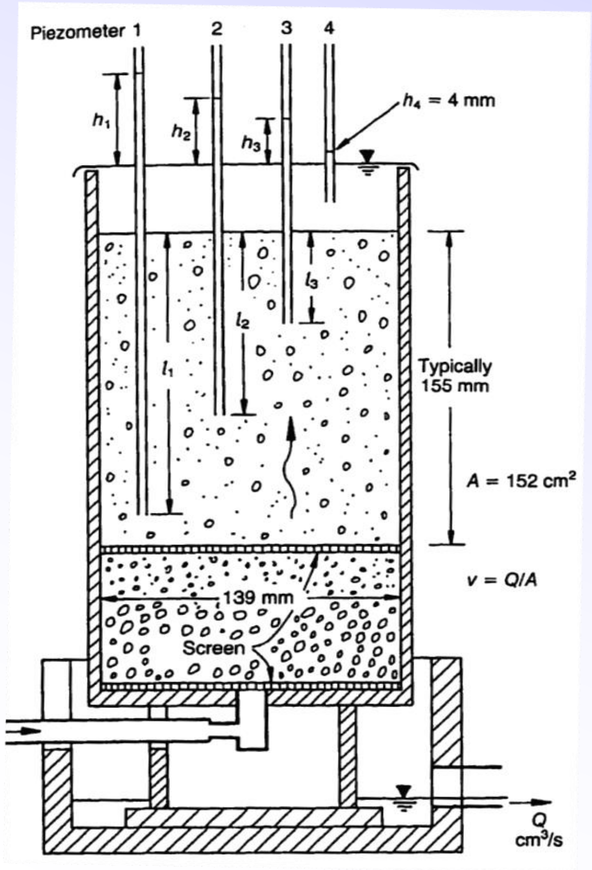
Crushing / breaking & sieving

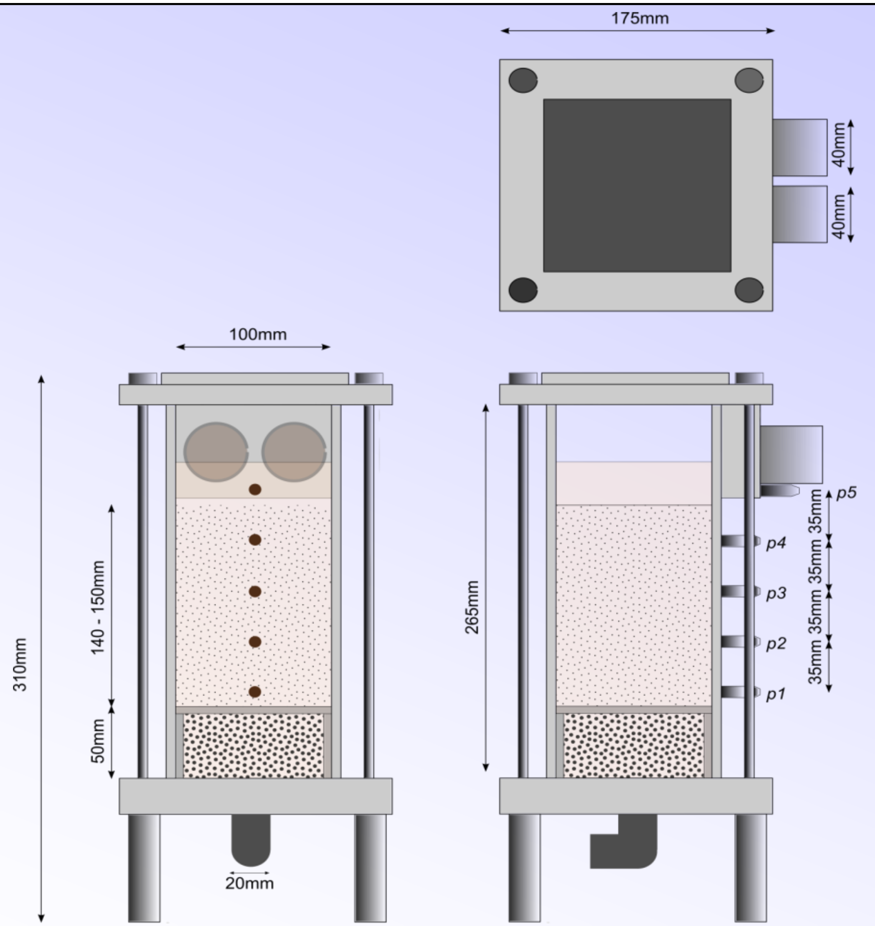
Saturating with immersion oil

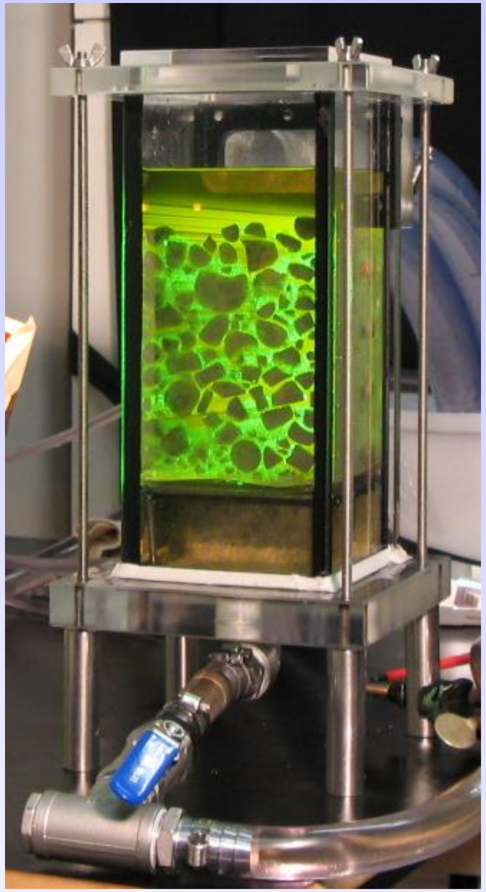
Careful placement into permeameter (no air bubbles!)

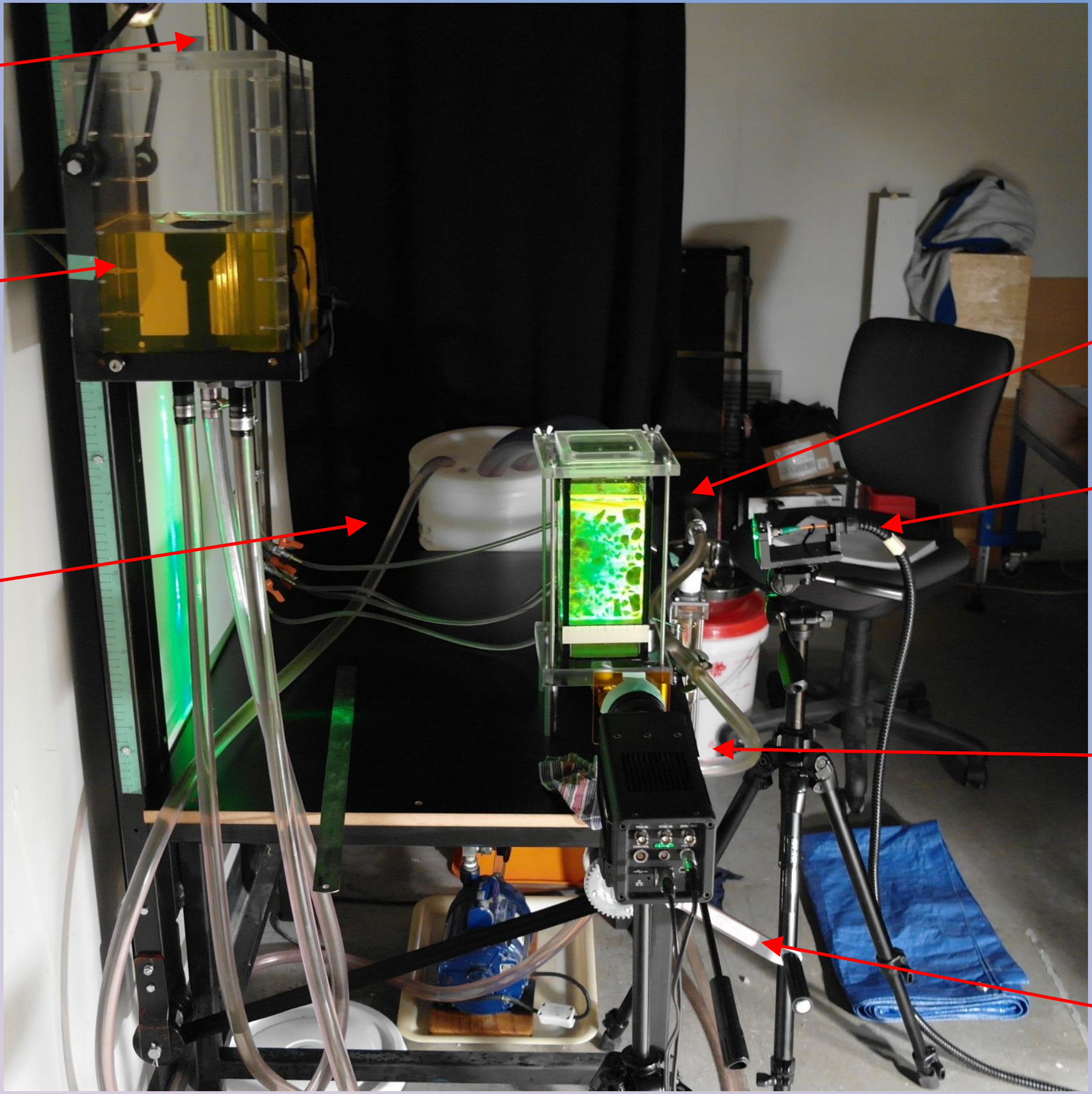


Skempton & Brogan (1994) permeameter method









Manometer rule

Header tank

Fluid recirculation system

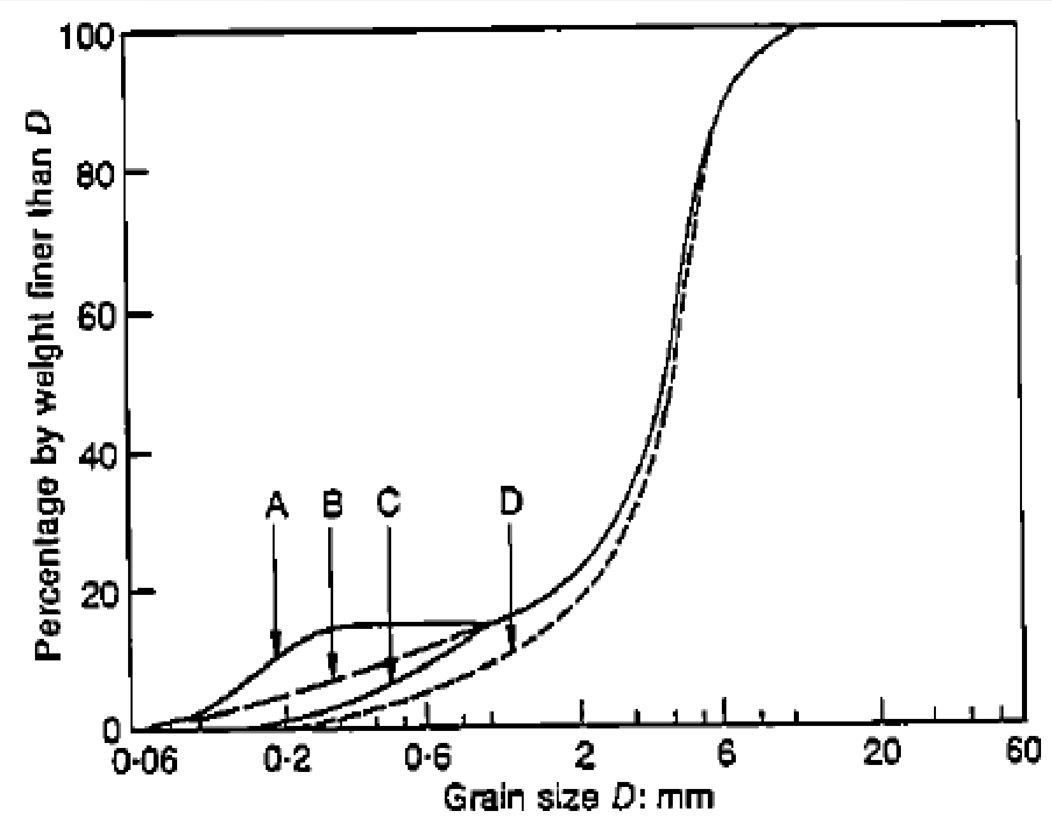
Permeameter

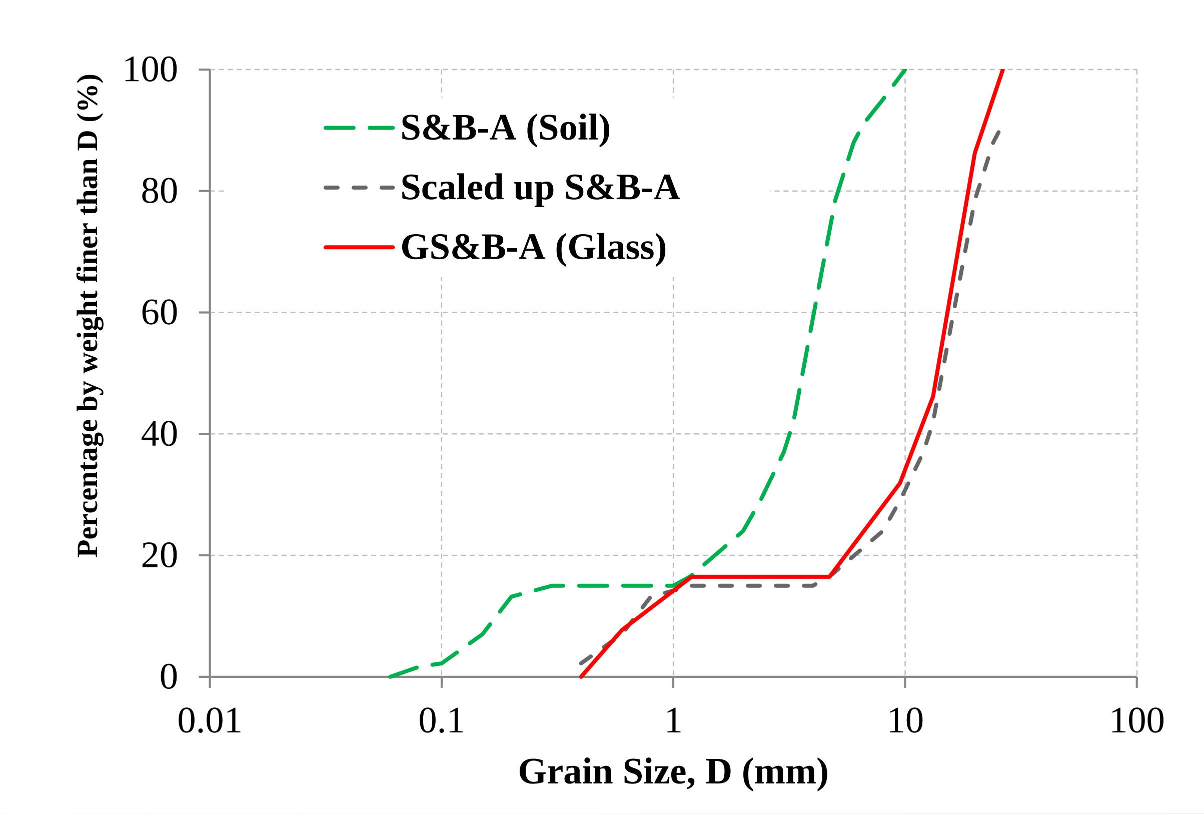
Laser

High speed camera

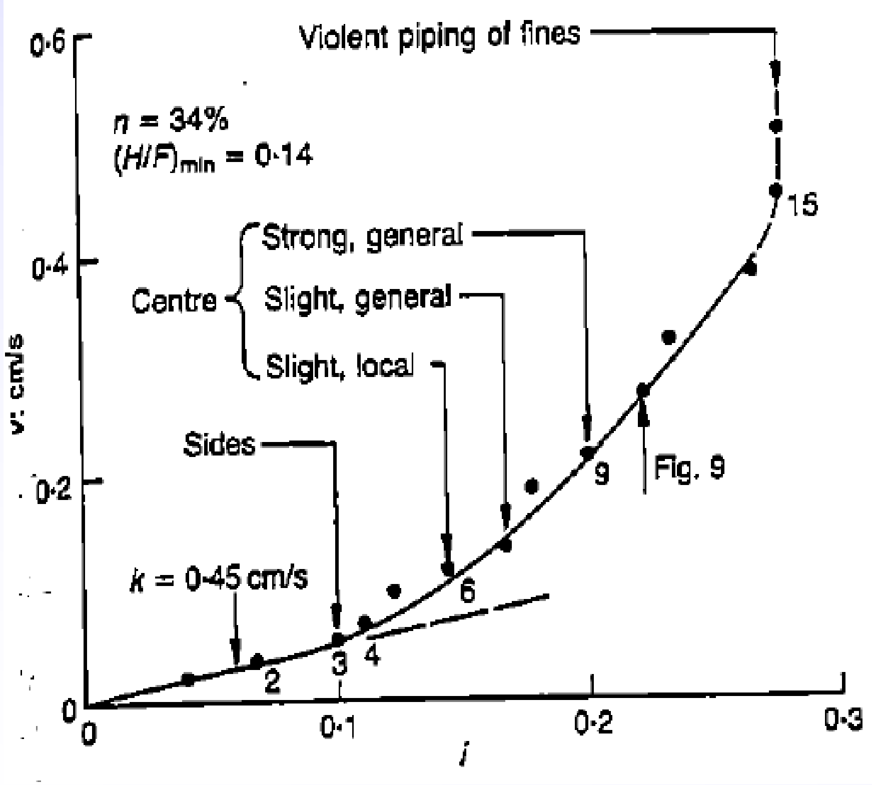
Winch for header tank

Gap graded susceptible soil – Grading “A”

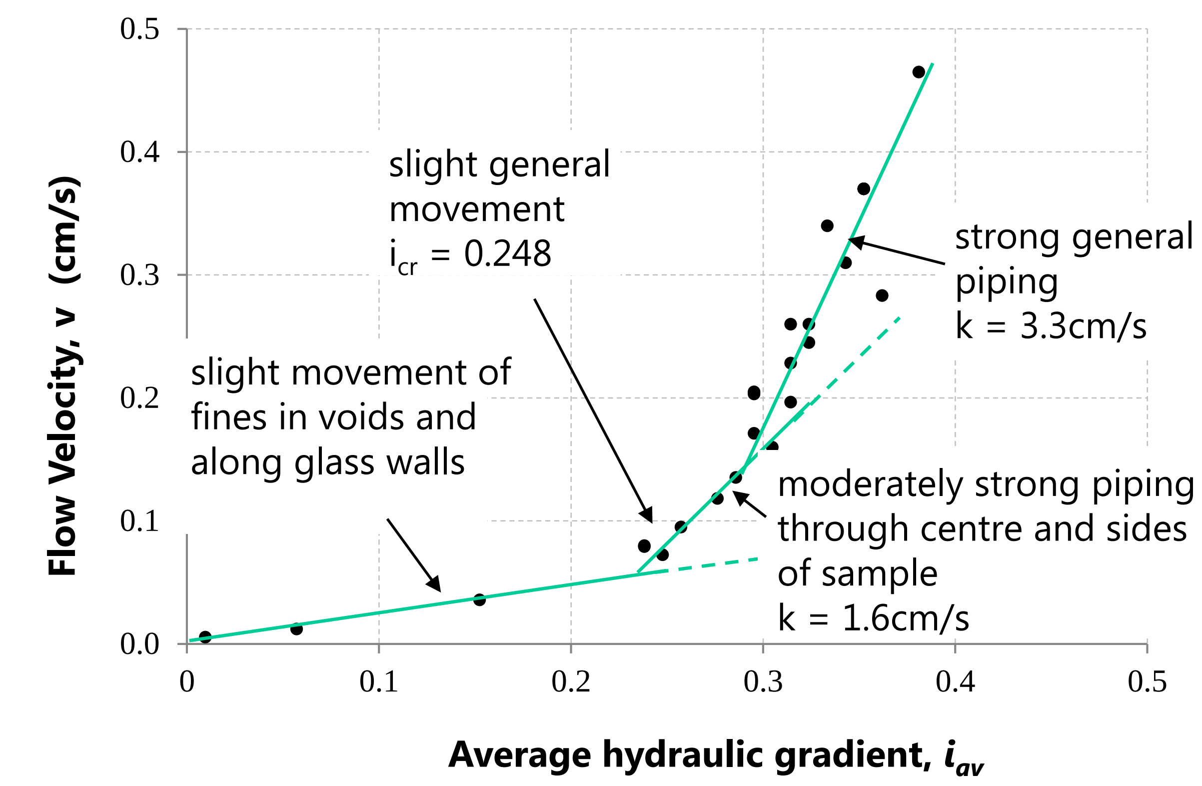




Test results – hydraulic gradient vs seepage velocity

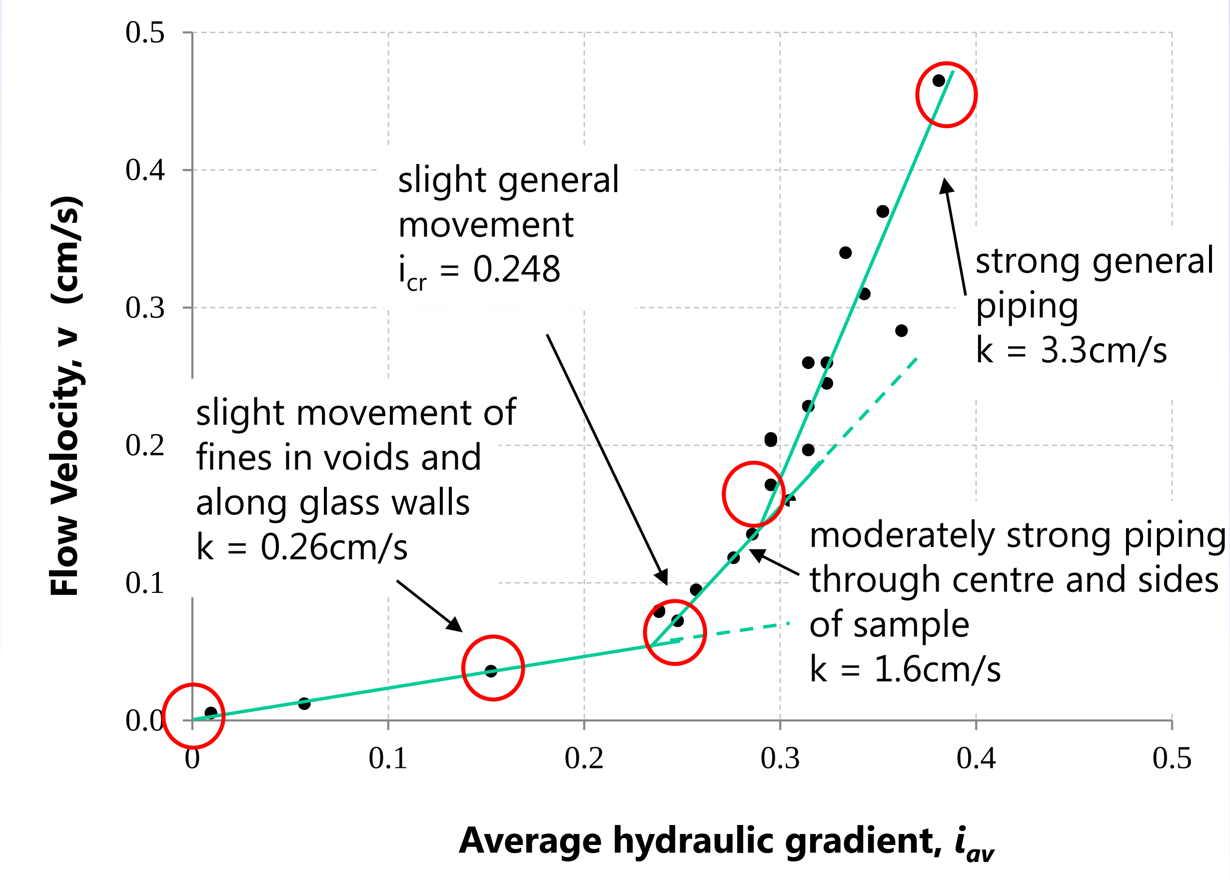


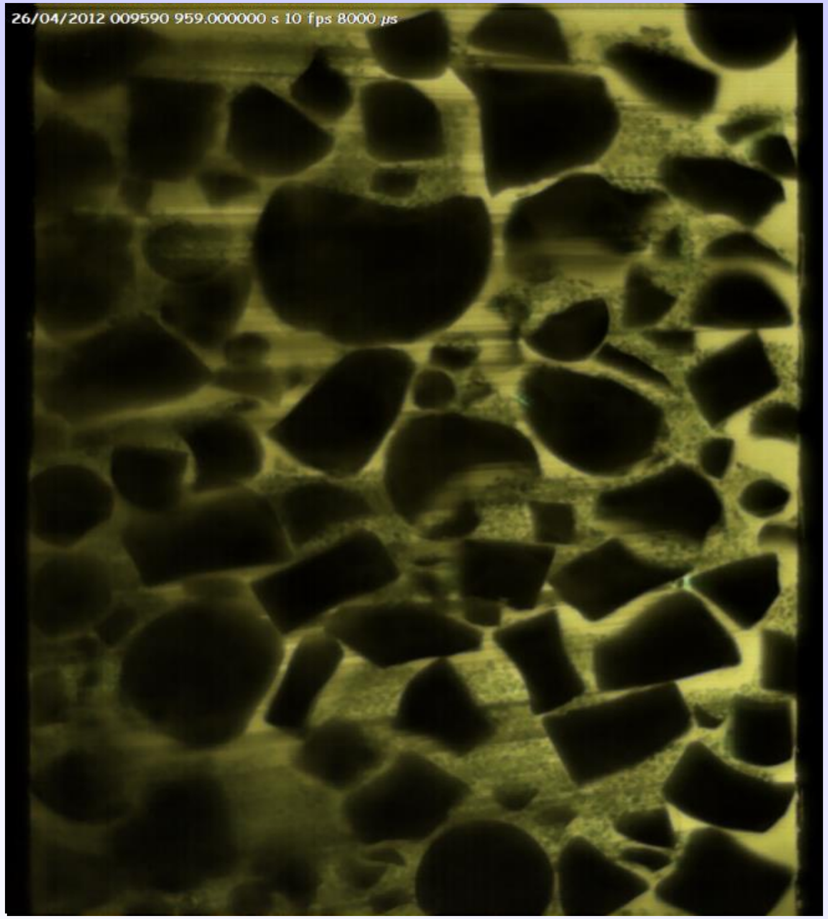
Skempton & Brogan (1994), sample A
Critical hydraulic gradient = 0.2; Alpha factor = 0.18



Critical hydraulic gradient = 0.25; Alpha factor = 0.21

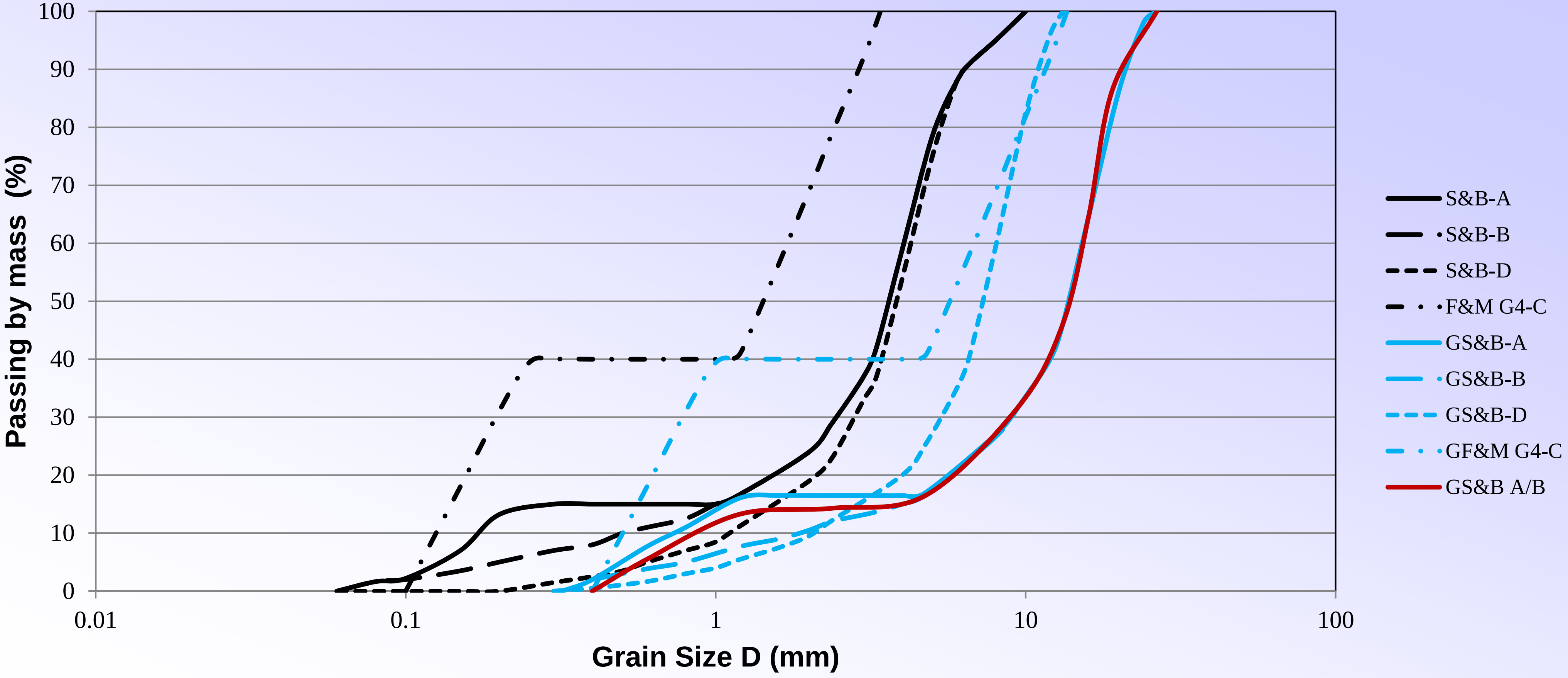
Refractive Index Matching





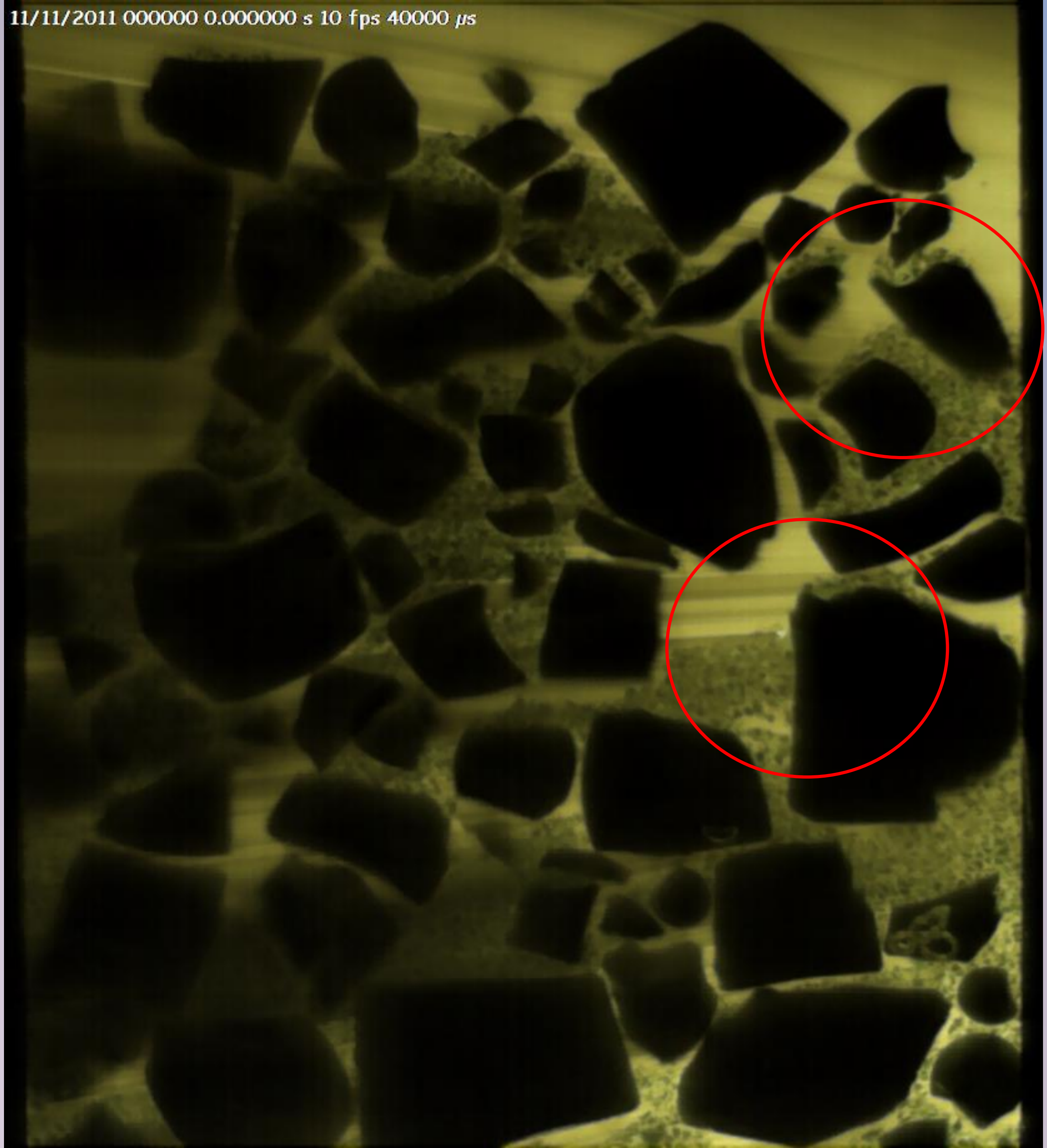
a) $i_{av} = 0$
b) $i_{av} = 0.153$
c) $i_{av} = 0.248$
d) $i_{av} = 0.286.$
e) $i_{av} = 0.381$

Test suite - PSDs



Test results – comparison with soil

Glass – oil tests	GS&B-A	GS&B-B	GS&B-D	G-G4-C
n	0.27	0.27	0.29	0.266
$k_{initial}$ (cm/s)	0.30	1.00	0.18	0.02
i_c	1.19	1.16	1.16	1.20
i_{cr}	0.25	0.300 / 1.01	1.31	0.72
α	0.21	0.26 / 0.85	1.13	0.60
Failure mode	Piping	Piping / heave	Heave	Piping with suffusion / volume change
Soil - water tests	S&B-A	S&B-B	S&B-D	G4-C
n	0.34	0.37	0.365	0.24
$k_{initial}$ (cm/s)	0.45	0.84	1.80	0.022
i_c or i_{gc}	1.09	1.04	1.05	53
i_{cr} or i_{gcr}	0.20	0.34	1.0	9.1, 8.0
α	0.18	0.33	0.95	0.34, 0.30
Failure mode	Piping	Piping	Heave	Piping with suffusion / volume change



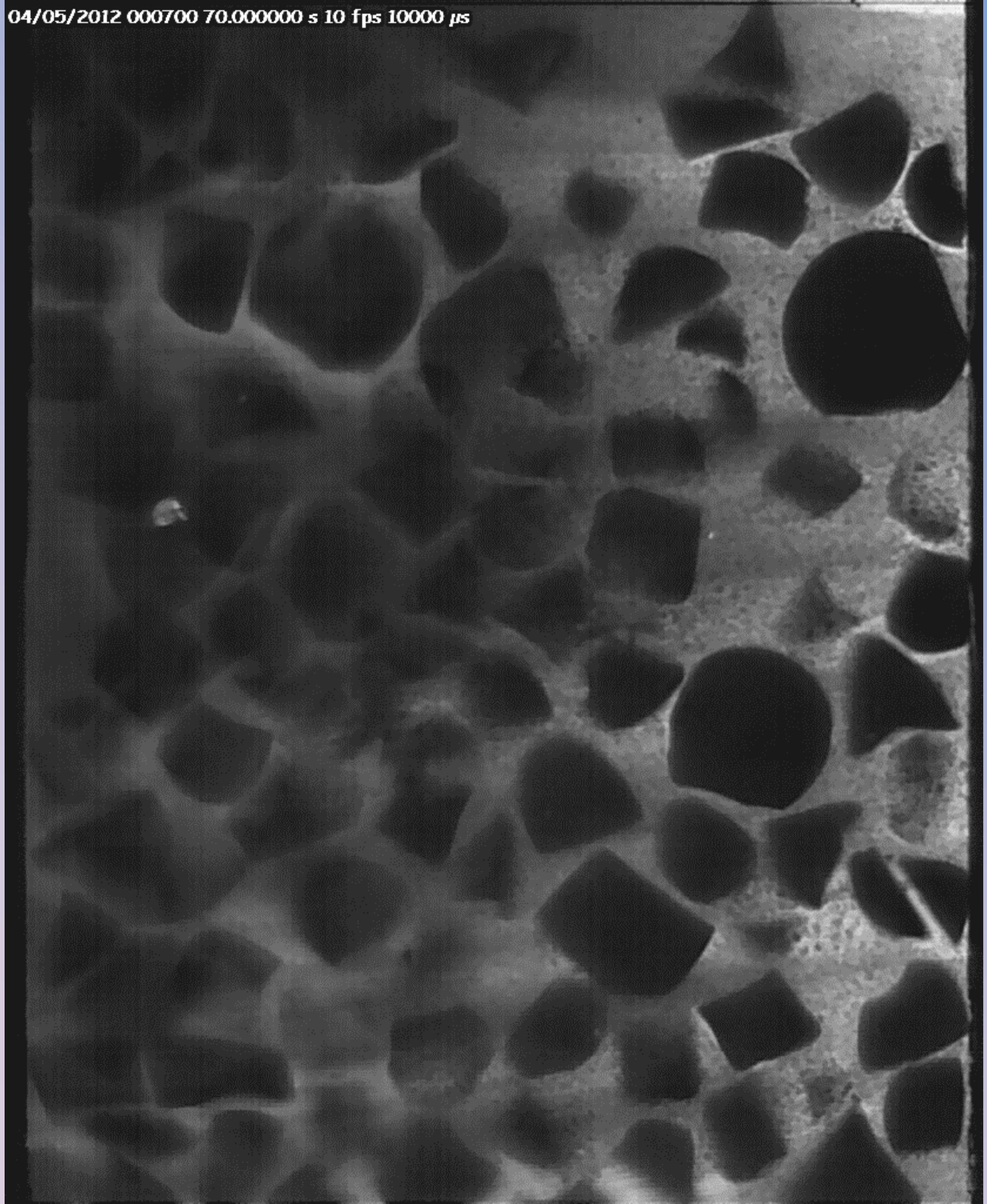
“Suffusion”:

Internal erosion without structure collapse

Internal erosion sequence

Pipe formation:

Glass S&B – grading “A”



“Suffosion”:

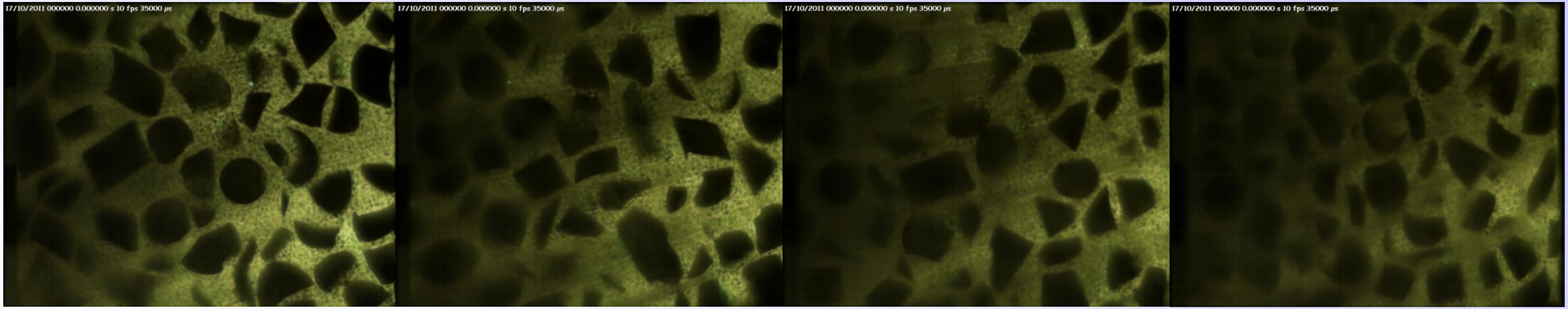
Suffusion leading to structure collapse

Fannin & Moffat (2006)

Material Glass “4C”

Image issues: degradation with laser / image depth

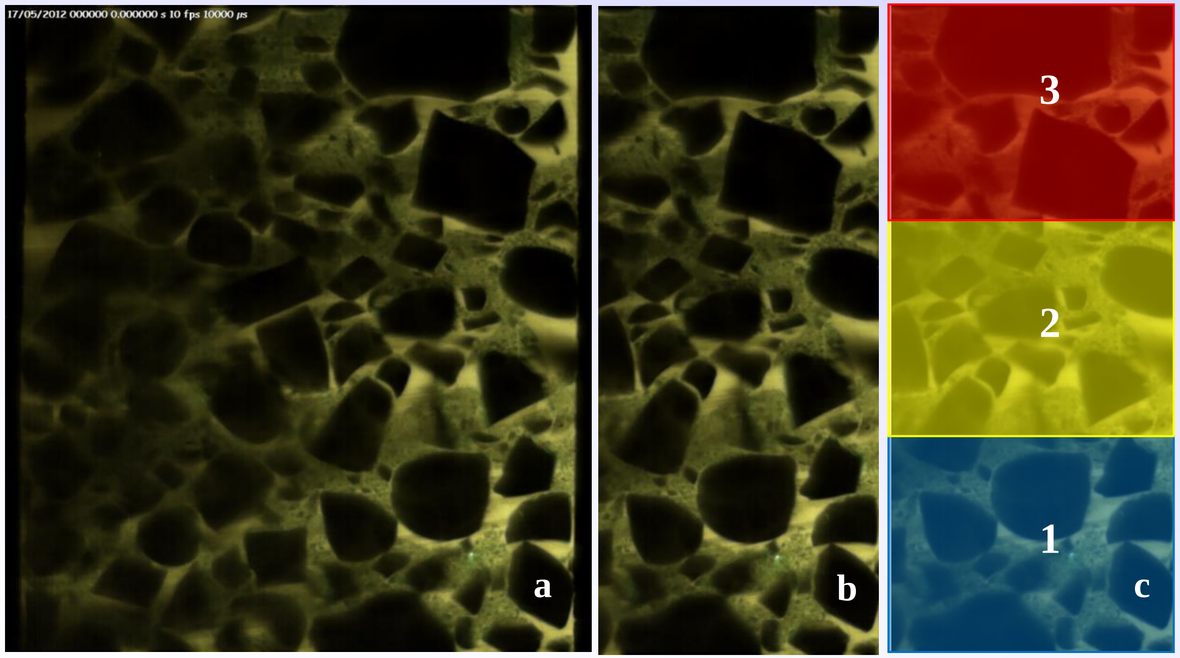
10mm 20mm 30mm 40mm



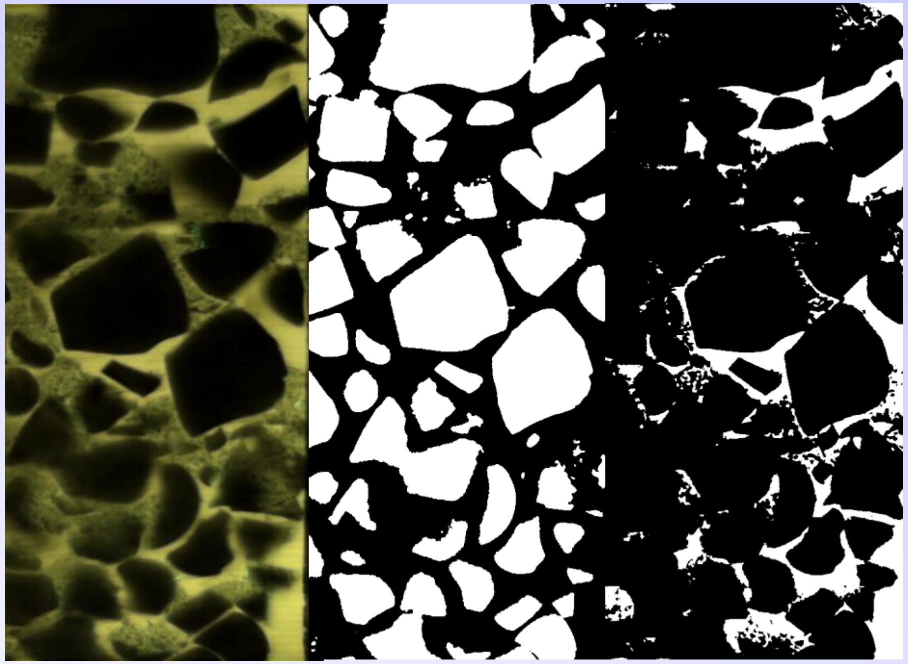
← Loss of brightness along laser due to mismatched RI and impurities

→ Loss of overall clarity with depth due to mismatched RI and impurities (dirt, air bubbles etc)

Quantitative image analysis of “open” void space

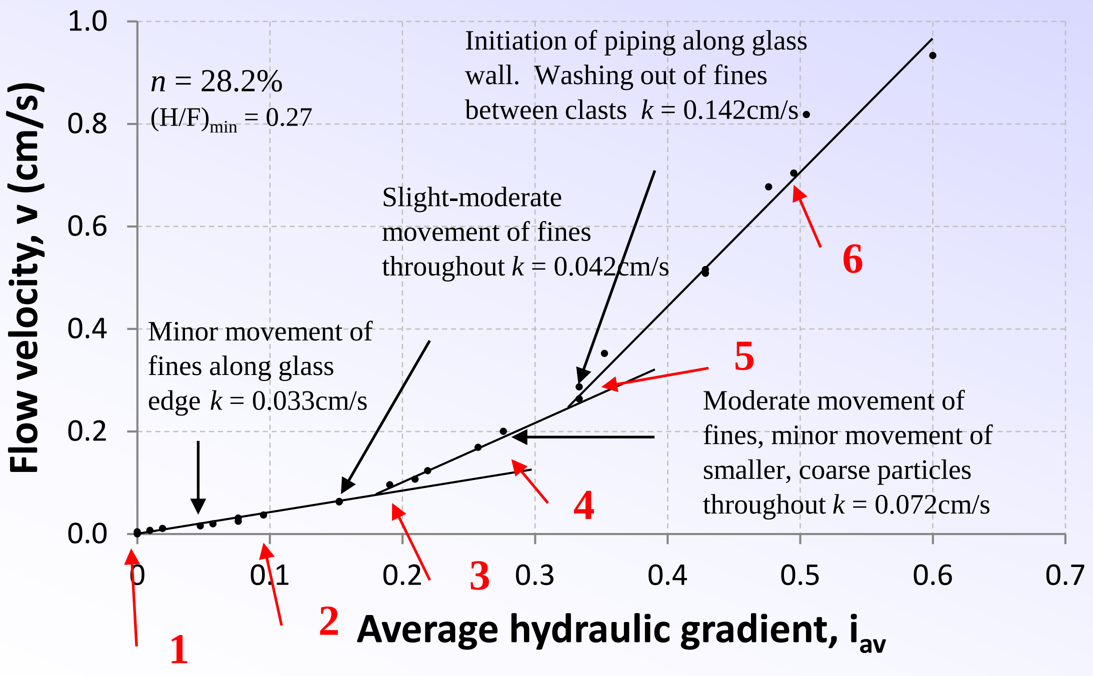


(a) Original image (b) ½ image (c) Divisions

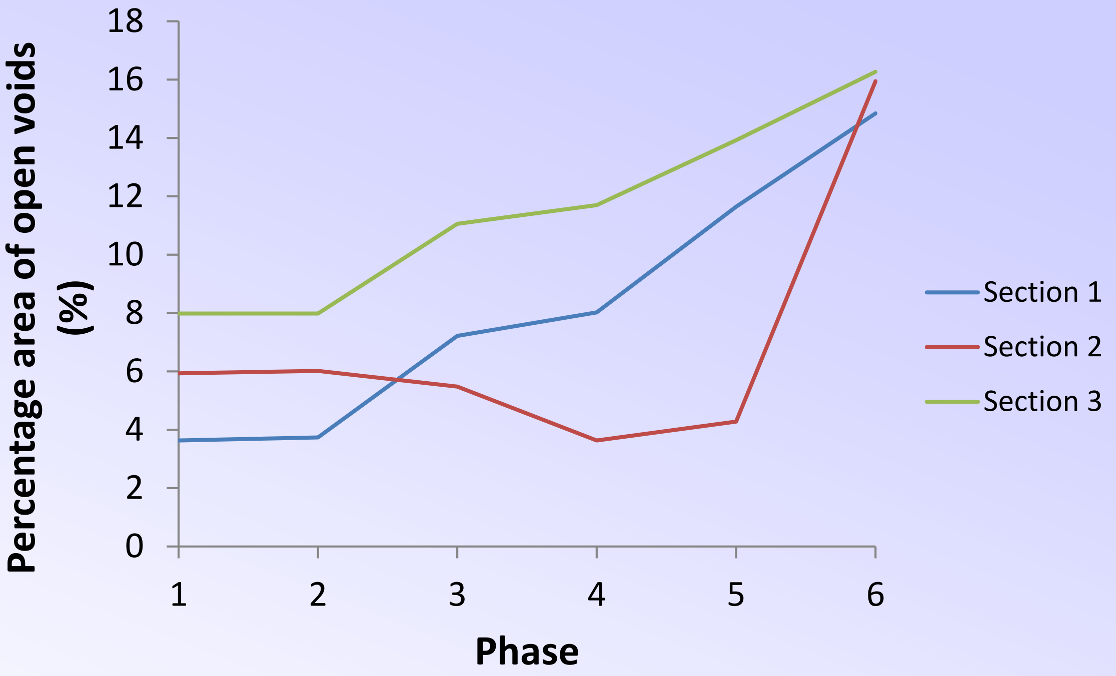


(a) Original image (b) Large particles (c) Large void space

Void space analysis: GS&B – A/B results



Upward seepage velocity vs hydraulic gradient

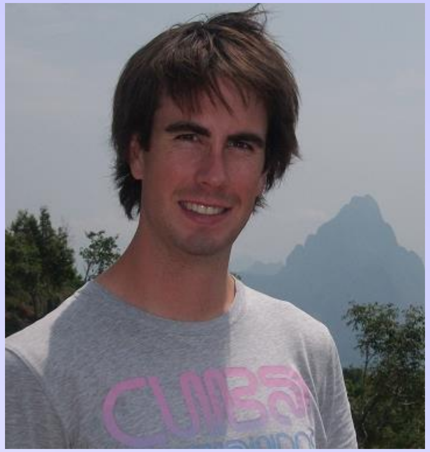


Open void vertical migration with hydraulic gradient

Conclusions => "Seeing is believing"

Transparent soil permeameters

- Allow internal erosion mechanisms to be visualised, internal to the transparent soil
- Similar results to those on real soil
- Image analysis on particle fabric shows fines migration



References

Hunter, RP & Bowman, ET "Visualisation of seepage induced suffusion and suffosion within internally erodible granular media" *submitted to Géotechnique*

Hunter, RP & Bowman, ET (2015) "Visualisation of internal erosion of a granular material via a new transparent soil permeameter" *16th European Conference on Soil Mechanics and Geotechnical Engineering*, 13-17 Sept. 2015, Edinburgh.

Hunter, RP (2012) "Development of Transparent Soil Testing using Planar Laser Induced Fluorescence in the Study of Internal Erosion of Filters in Embankment Dams" *University of Canterbury MSc Thesis*, New Zealand

Future work

Transparent soil **rigid permeameter** (with Jonathan Black and Nicoletta Sanvitale)

- Further work to refine equipment and methods
  - Precision slices using stage micrometer
- Further work on material behaviour
  - Compare behaviour of spherical and angular particles (compare to DEM)
  - Fluid tracking using neutrally buoyant particles (PIV)

Transparent soil **triaxial permeameter** (with Fahed Gaber, Jonathan Black and Nicoletta Sanvitale)

- More complex stress states
  - Influence of erosion on strength / deformation
- Visualisation of erosion

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