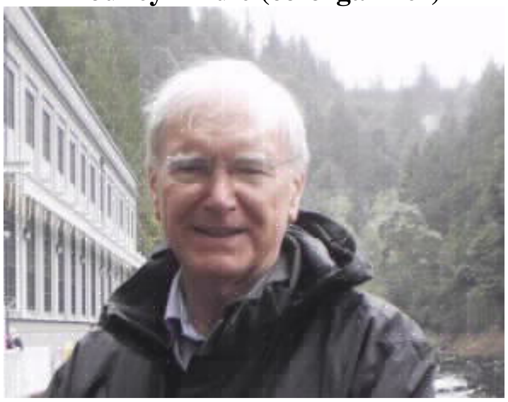
Presenters and Presentations

Rodney Bridle (co-organizer)



Rodney Bridle, Civil engineer, Dam Safety Ltd, specialist consulting engineer in earth and earth-rock dams, internal erosion and risk. UK Member, ICOLD Technical Committee on Embankment Dams. Editor and part-author of the two volumes of ICOLD Bulletin 164 on Internal Erosion. Regular attendee at ICOLD and ICOLD Internal Erosion Working Group (EWGIE) meetings. Former Chair, British Dam Society. More information at www.damsafety.co.uk.

Overview of internal erosion mechanisms

Internal erosion is a process of erosion in which the hydraulic forces imposed by water flowing through openings or seeping through the pores in soils in water-retaining embankments and their foundations are sufficient to overcome the resistance to erosion of those soils. It has parallels to scour and erosion on river beds. The hydraulic forces are usually greatest when water levels are high as floods pass through reservoirs or along waterways, consequently the probability of the water level causing failure can be estimated from the flood hydrology for use in risk analysis (because risk = probability x consequences). If internal erosion initiates, progress to failure will likely be rapid, unless the erosion is stopped by filters – in designed filter zones or in fill zones of a grading capable of filtering - trapping eroded particles and preventing the continuation of erosion after no-, some- or excessive erosion. Unzoned (often called 'homogeneous') embankment dams and levees are more vulnerable to internal erosion than zoned embankments because there are no more-or-less vertical zones that might arrest erosion.

ICOLD Bulletin 164 provides a comprehensive qualitative understanding of internal erosion and the means to quantify the hydraulic forces that will cause failure through the four internal erosion mechanisms: concentrated leak erosion, suffusion, backward erosion and piping, and contact erosion. It gives methods to assess the filtering capability of filters and fills; guidance on investigations and engineering analyses, and on remediation and surveillance. Recent research has added to the usefulness of the Bulletin, notably in backward erosion and piping, as a case history shows. An important conclusion is that it is not possible to anticipate the onset of internal erosion to failure through surveillance and monitoring; and as failure occurs rapidly, the critical hydraulic load, water level, should be predicted by investigations and engineering analysis, and remediation completed if necessary, before large floods occur.

Overview of internal erosion mechanisms

- and how ICOLD worked with others to understand them

Rodney Bridle

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ICOLD Ottawa, Friday 14 June 2019

ICOLD and internal erosion

ICOLD Founded in 1928 to make dams safe – by dam engineers interaction – Meetings - Congresses, issue of guidance (Bulletins) by Technical Committees. Over 100 national committees

ICOLD Bulletin 164 (2017) - international collaboration through ICOLD:

ICOLD European Working Group on Internal Erosion (EWGIE) – participants from all continents welcome!

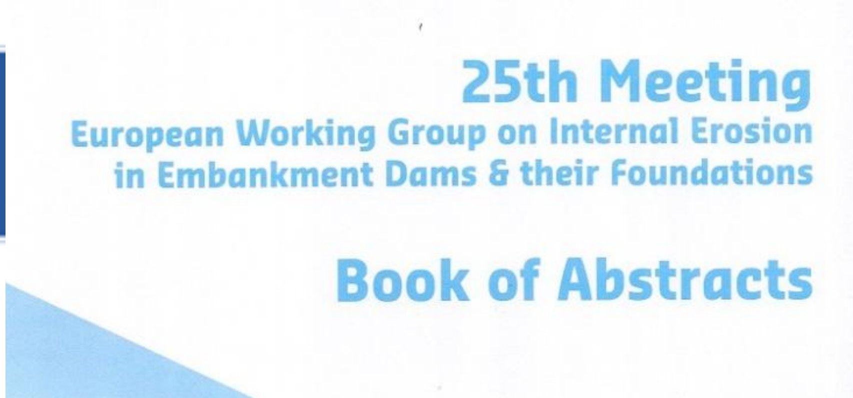
Dr Stephane Bonelli is Chairman, EWGIE

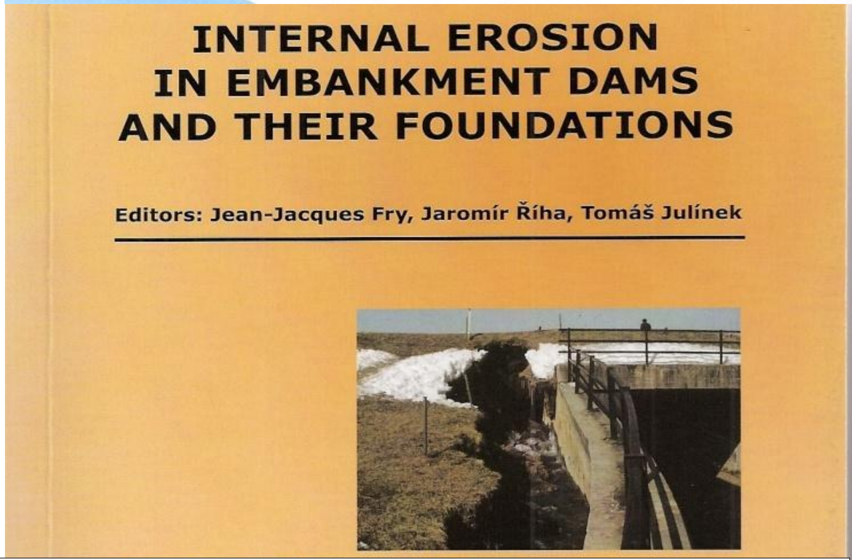
Annual meetings since 1993: Delft (2017) Milan Taiwan (2018) Vancouver (June 18-21 2019) Sheffield Washington DC (2020)

ICOLD Embankment Dams Committee

Dr J-J Fry, Professor Robin Fell

Several young researchers





Internal erosion – caused by flowing water

- Internal erosion initiates when the erosive forces imposed by water flowing through cracks or through the pores in soil fill in a water-retaining earth embankment exceed the ability of the soils in the embankment and its foundation to resist them
- Load > Resistance
- Erosion mechanics – not soil mechanics
- Highest hydraulic loads normally imposed rapidly when water level is high during floods

Internal erosion failures – consequences

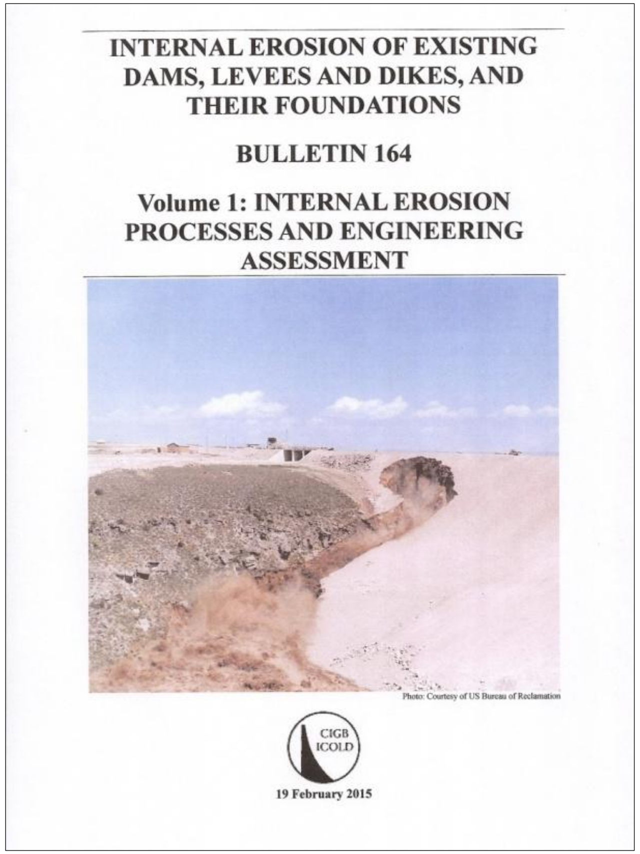
2009 Situ Gintung – Jakarta – 100-200 fatalities – one million m^3 released in ten minutes - 'tsunami'

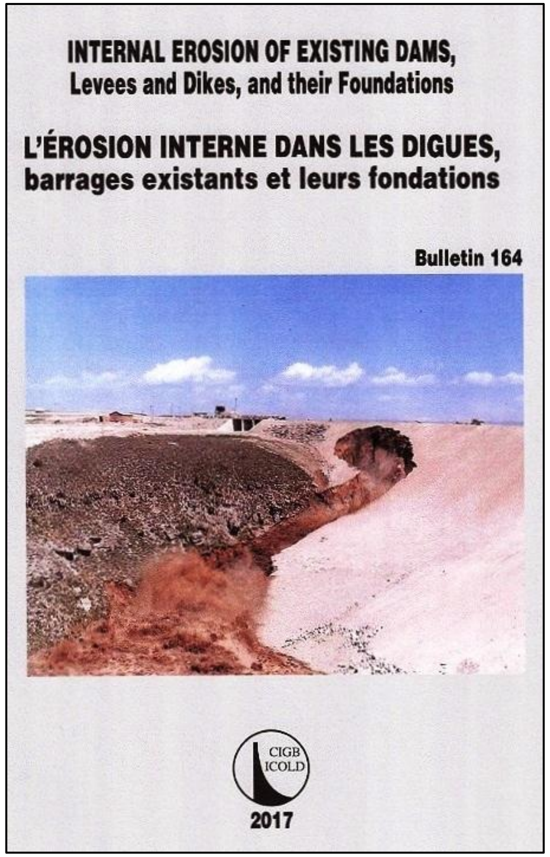
Rapid failures
Fatalities

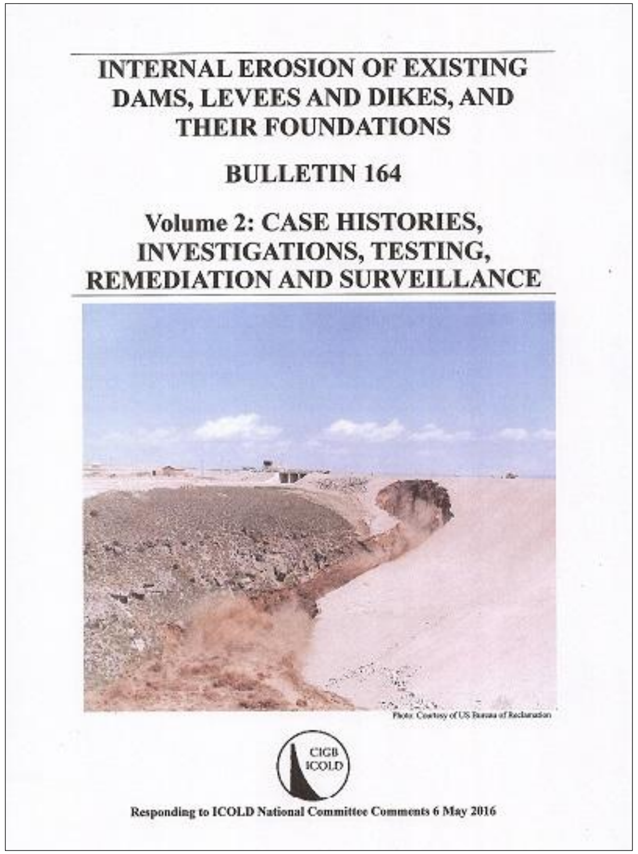
1976 Teton – a few hours – 11 fatalities

46% of earth dam failures, about one-third long after first filling
48% by overtopping – surface erosion
6% by slope instability
Similar proportions of levee failures

ICOLD Bulletin 164 – internal erosion mechanics







First preprint English 2013, final preprint English & French 19 February 2015, final edition 2017

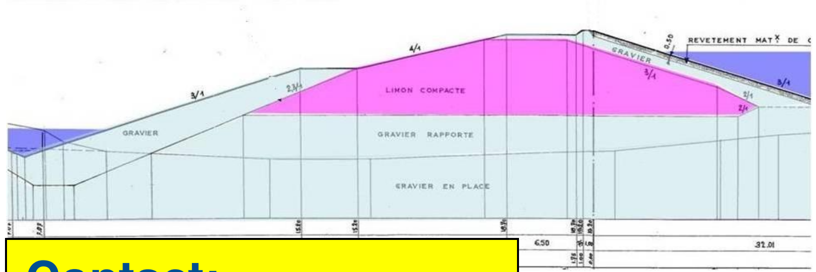
Final preprint English, 6 May 2016, translation to French in progress

Available from ICOLD www.icold-cigb.org; free to ICOLD – national dam society members

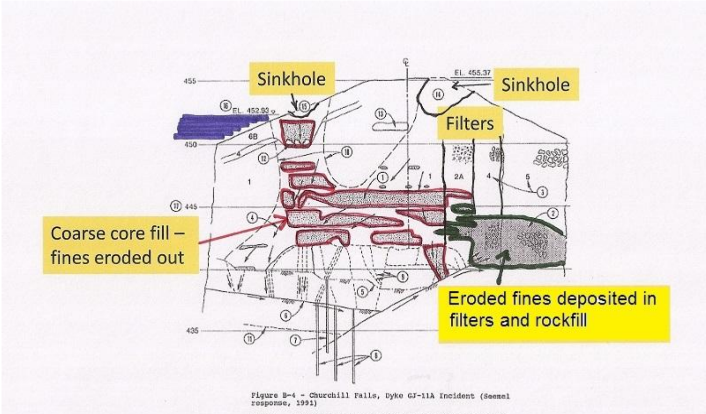
Four internal erosion mechanisms

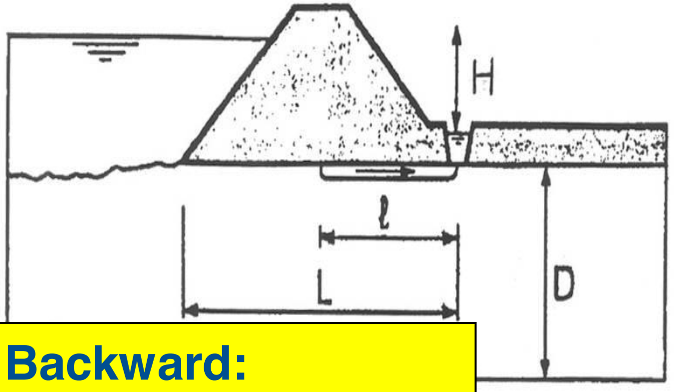
Concentrated leak:

$$\tau = \rho_{\omega} \frac{g H_f d}{4L}$$



Contact:
$v = ki = kH/L$





Backward:
$H/L = 1/c = F_R*F_S*F_G$

Suffusion:
Critical hydraulic gradient can be less than 1

Bulletin makes it possible to estimate H, the water level that causes internal erosion failures

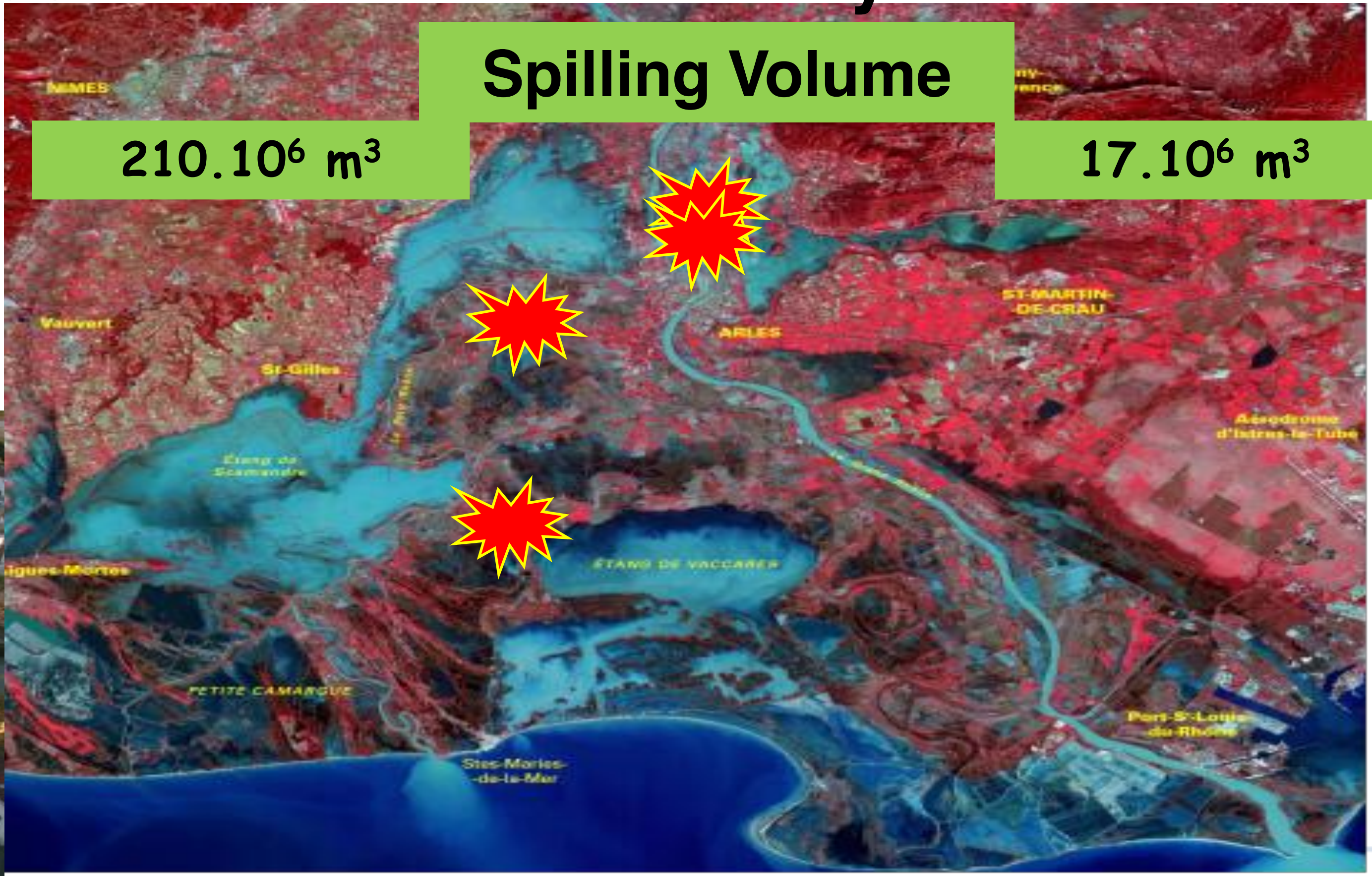
Concentrated leak erosion: quantitative risk assessment

MALLET, T., OUTALMIT, K., FRY, J-J. Probability of failure of an embankment by internal erosion using the Hole Erosion Test. *Proceedings of the Symposium on Dams in Global Environmental Challenges, ICOLD Annual Meeting, Bali, VI 278-VI 287*. 2014.

The last great flood : Dec. 2003 - T≈ 100 years

4 breaches

Damages : 700 Millions €

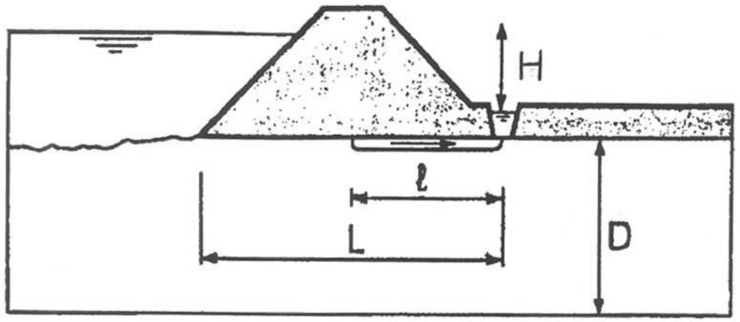


Spilling Volume

210.10^6 m³

17.10^6 m³

Backward erosion and piping – 2D and 3D



2D – initiates at ‘free’ continuous outlet into ditch or where ‘confining layer’ not present.
Formula and diagram (Figure 4.4, 20) in Volume 1 of Bulletin apply to 2D situation.

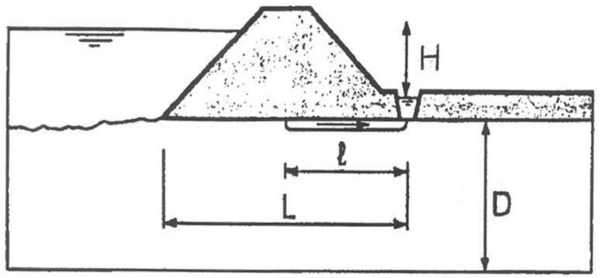
Ref: Van Beek, van Essen, Vandenboer & Bezuijen (2015) Geotechnique

3D – initiates through single openings in confining layer – often forming sand boils.
Not covered by Bulletin.
Fuelled by large 3D aquifers drawing water from wide area towards local openings
Occurs at lower gradient than 2D: higher risk.
A challenge addressed by recent research

Sand boils indicate that BEP is occurring – but not whether it will lead to failure

ICOLD 164 'Sellmeijer 2D' backward erosion

Free outlet - all along toe - no confining layer



H/L = F_R*F_S*F_G

Hans Sellmeijer and
Vera van Beek, Deltares

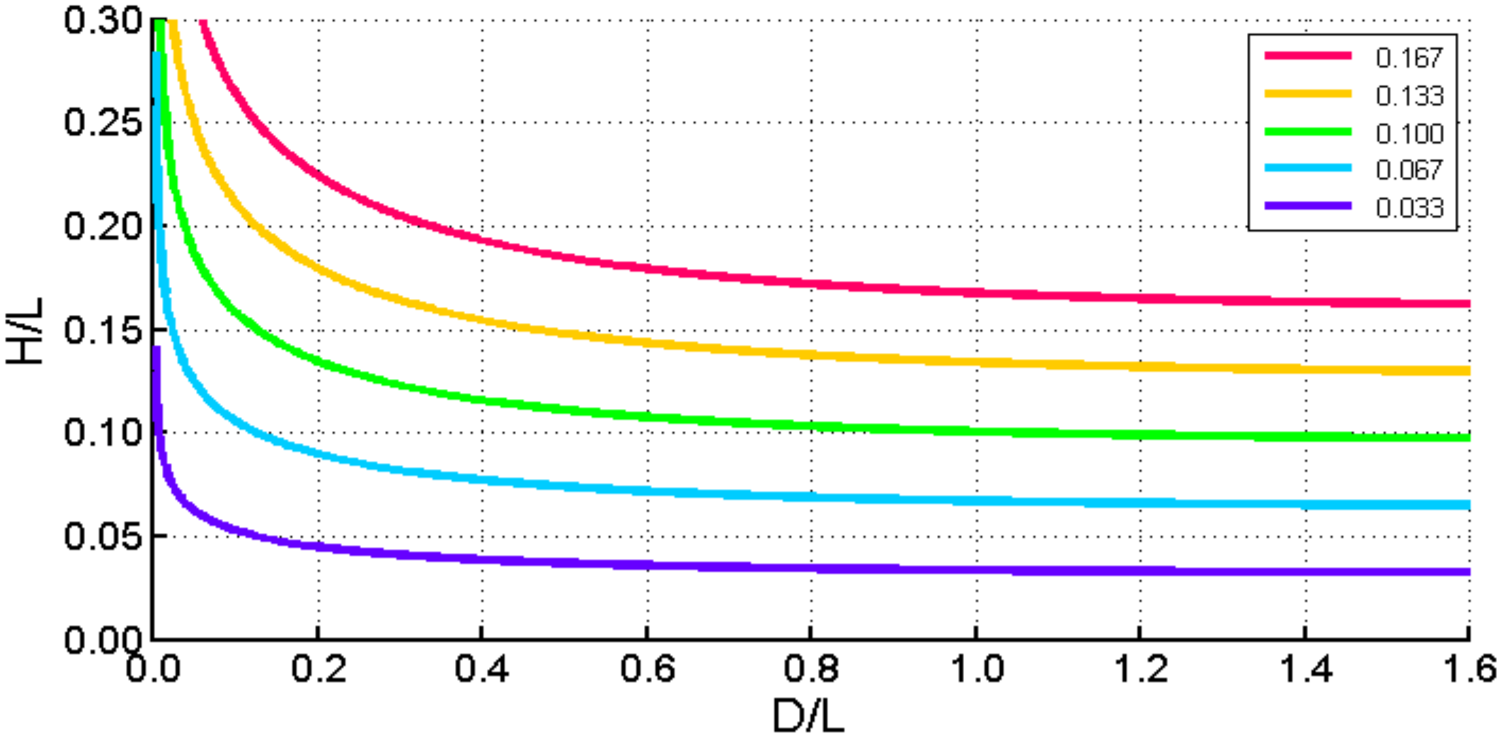


Figure 4.4 (20) Critical gradient to cause failure by BEP for various F_R * F_S values and embankment dimensions. H, D and L are defined in Figure 2.5. As an example, for F_R * F_S = 0.100, D/L = 1.0, critical gradient at which backward erosion will progress to form a pipe back to reservoir is H/L = 0.10.
F_R = Resistance factor F_S = Scale factor F_G = Geometrical shape factor

Sand boil at toe and slide on slope

Sand boil indicates 3D backward erosion

Bliss and Dineen Photograph 2

Using Sellmeijer 2D to estimate 3D critical gradient

Critical gradients:

3D < 2D

3D ≈ 0.5 x 2D Sellmeijer

Van Beek Van Essen Vandenboer and Bezuijen (2015) Developments in modelling of backward erosion. geot.14.P.119

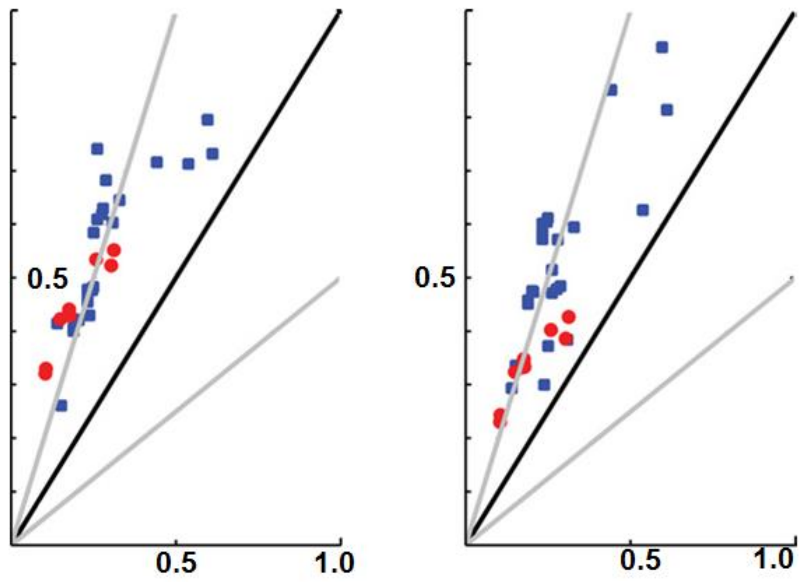
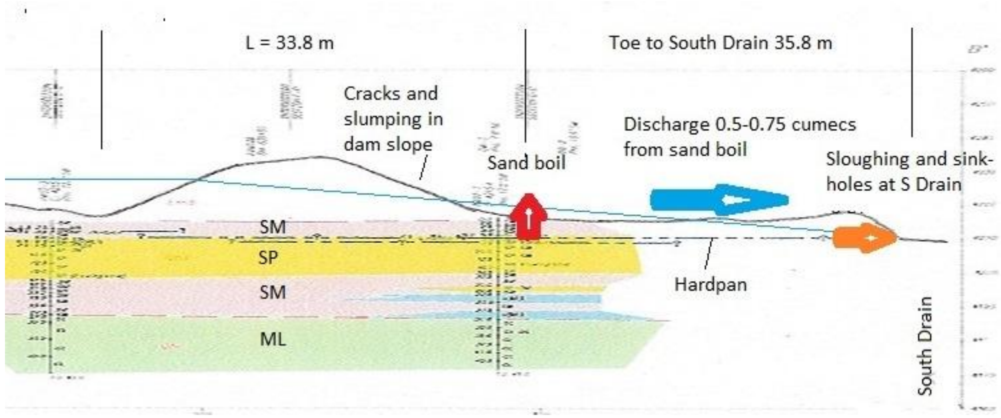
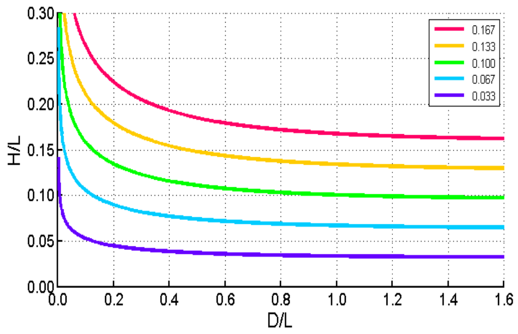


Fig. 7. Experimental (vertical axes) and calculated (by ‘Sellmeijer,’ horizontal axes) critical gradients for all available experiments (lines in black and grey indicate lines where there is no variation (1:1) and variation by a factor of 2 (1:2, 2:1), respectively

AV Watkins - Back analysis using 0.5 Sellmeijer 2D ≈ 3D

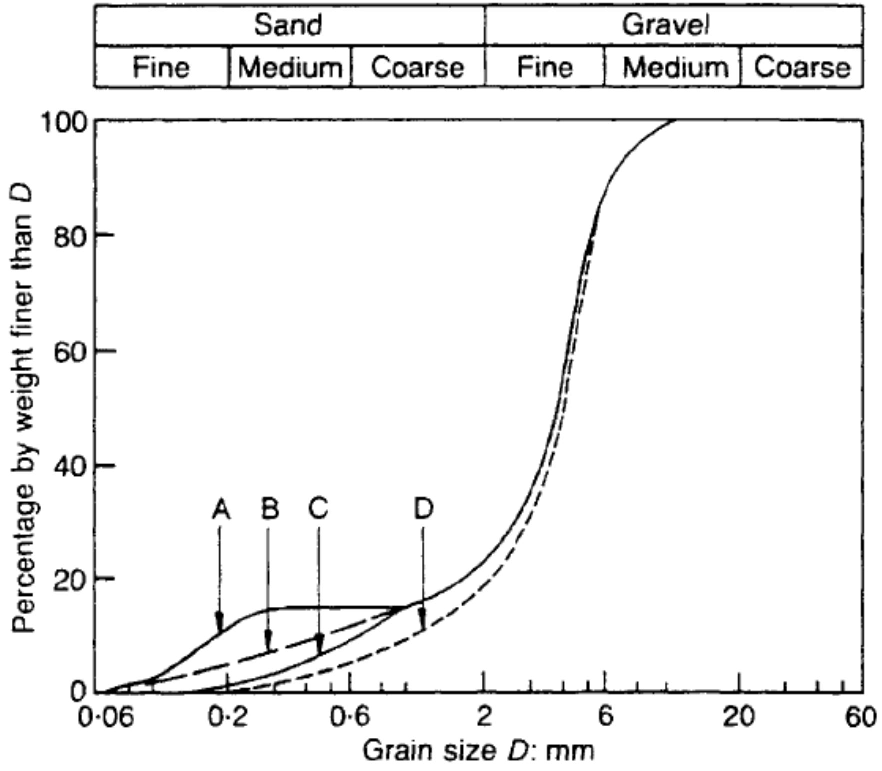




Conclusion: Potential for failure through upper 1.6m deep SM layer

k, perm-eability	F_R*F_S	D, aquifer depth	D/L	2D H_{crit} pre-dicted/L	2D H_{crit} pre-dicted	3D H_{crit} pre-dicted ≈ 0.5 x 2D	H_{actual}	Comments
1.00E-04	0.10	9	0.27	0.13	4.35	2.18	3.2	Highest measured k
1.00E-04	0.10	1.6	0.04	0.19	6.35	3.18	3.2	**H_{calc} 3D ≈ H_{actual}** Shallow SM aquifer above hardpan

Suffusion



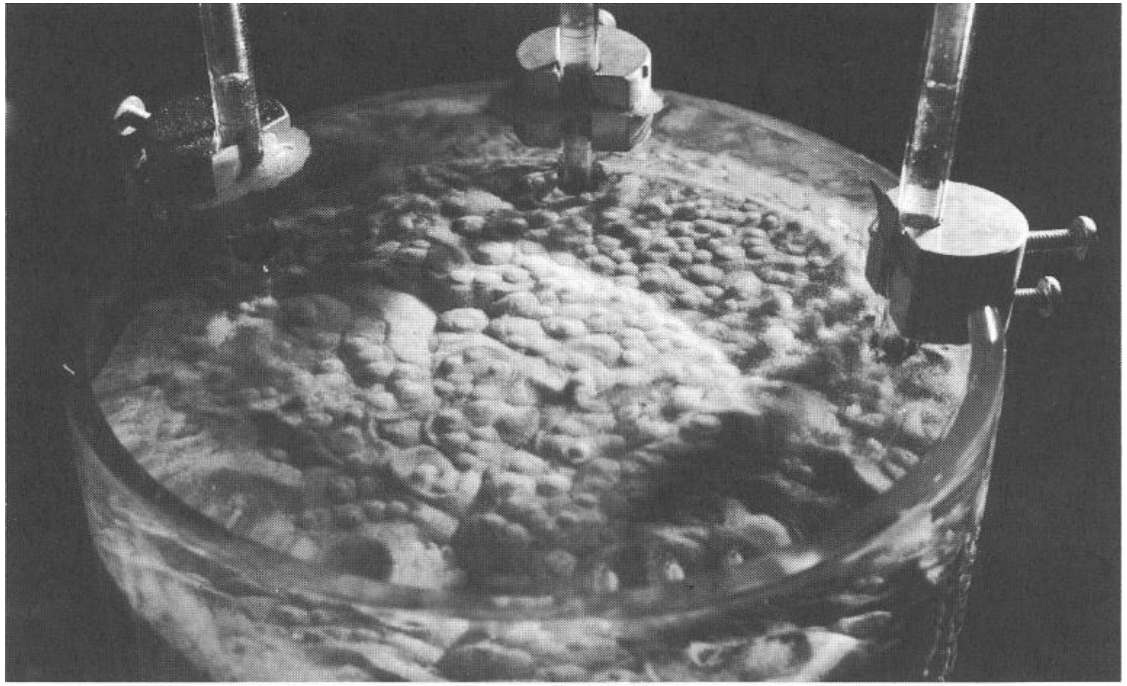


Fig. 9. Material A: strong general piping of fines ($i = 0{\cdot}22$, $v = 0{\cdot}27$ cm/s)

Grain size distribution curves of gap-graded soils in Skempton and Brogan (1994) tests

Samples A and B were suffusive, C and D were not

Suffusion in upward flow initiated at critical hydraulic gradient i_{cr} = 0.2 in A and i_{cr} = 0.34 in B

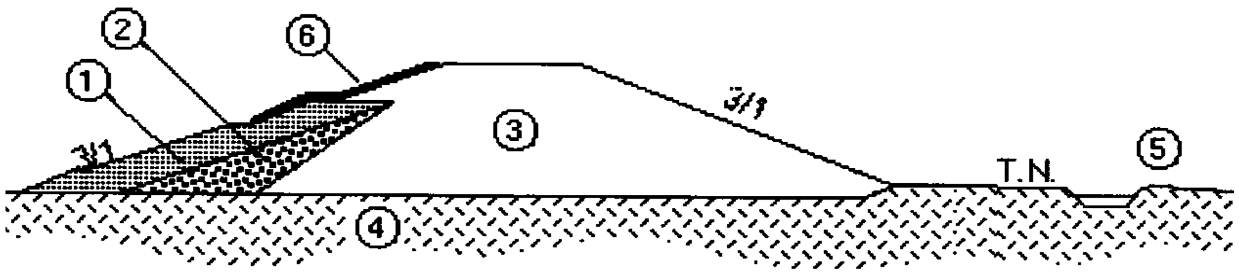
In non-suffusive samples C and D, 'general piping' occurred at i_c ~ 1.0

Identifying potential for suffusion to cause failure

- Many grading criteria to identify potentially suffusive soils: Wan & Fell adaptation of Burenkova (Figures 30, 31 [6.7, 6.8]) uses grading data (only) to give probability of suffusion
- No easy means of assessing hydraulic gradient that would actually cause suffusion: simple and complex tests are available and under development, see Chapter 4 in Volume 2
- Prof Didier Marot (Nantes University) applying Bagnold (1936) energy approach
- Prof Catherine O'Sullivan (Imperial College, London) linking codes DEM+CFD
- Prof Jonathan Fannin (UBC) will say more

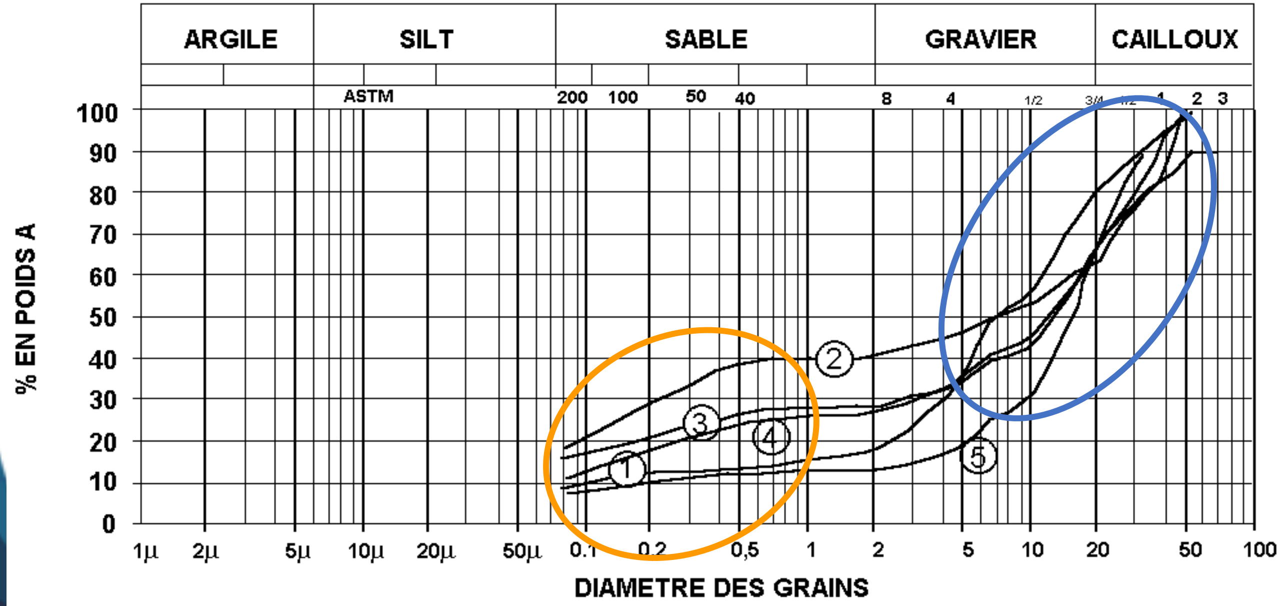
Suffusion on a river dike

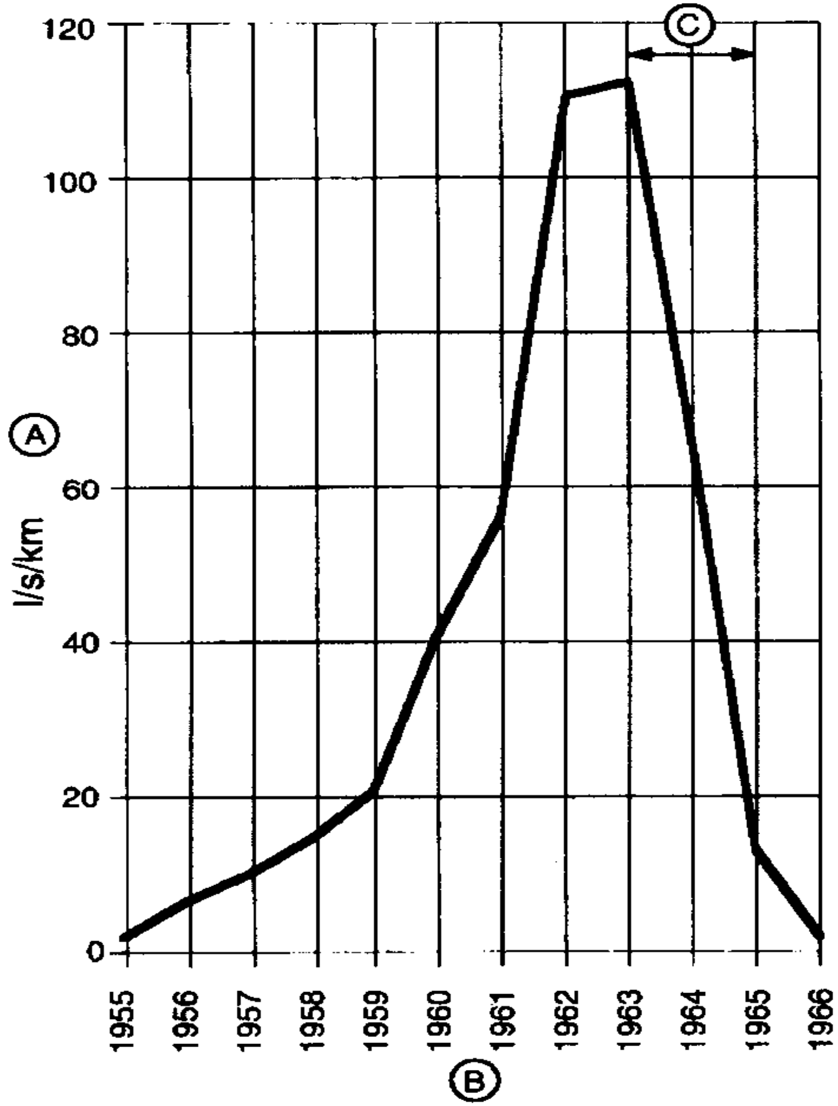
Suffusion in dike



(1) argile corroyée mélangée avec de la chaux
(2) silt
(3) alluvions du canal
(4) alluvions en place
(5) contre canal
(6) dalles en béton

(1) clay mixed with chalk and compacted
(2) silt
(3) alluvium (silt, sand, gravel)
(4) foundation: alluvium
(5) side channel
(6) concrete slabs



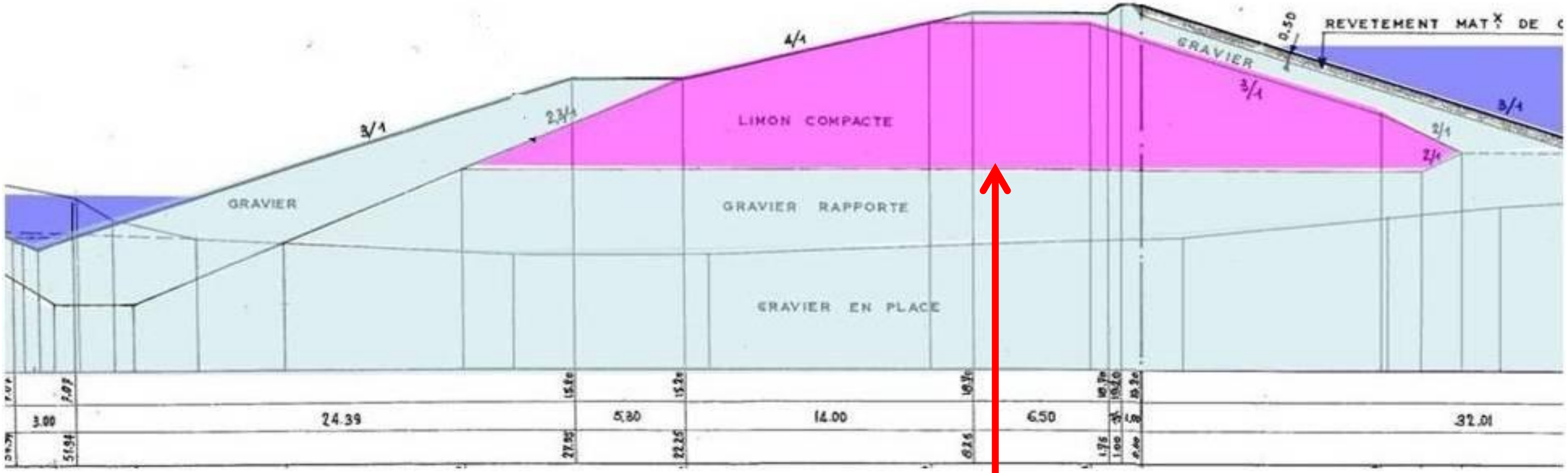


Digue de Cusset - Évolution des fuites au Pk 14.6

Cusset bank - Point 14.6 leakage variation

Ⓐ *Specific leakage (l/s/km)*
Ⓑ *Date*
Ⓒ *Grouting*

Contact erosion



Occurs at interfaces between coarse and fine soils e.g. silt against gravel

Contact erosion – critical Darcy velocity

U = k*H/L

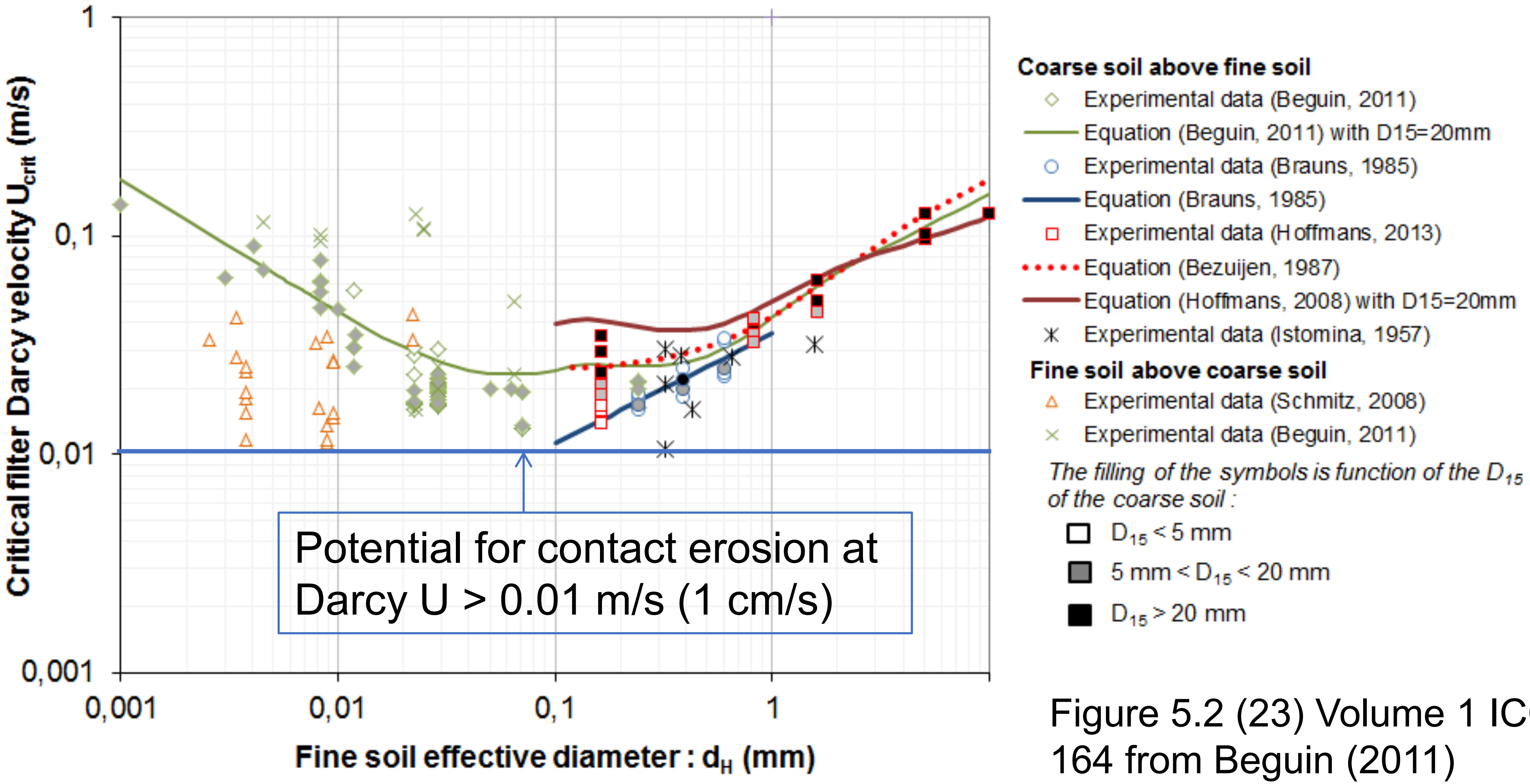


Figure 5.2 (23) Volume 1 ICOLD 164 from Beguin (2011)

Contact erosion - sinkhole developing

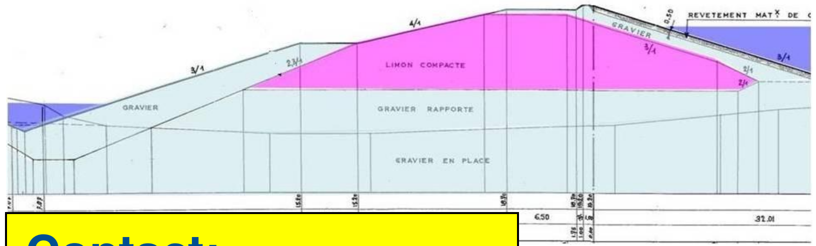
16x

Courtesy Dr Remi Beguin
www.geophyconsult.com

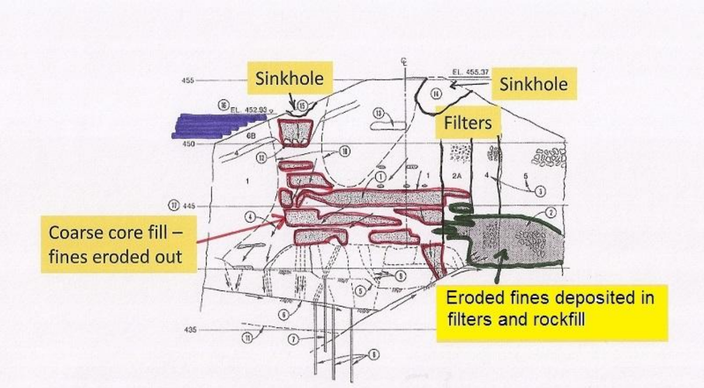
Internal erosion - summary and recommendation

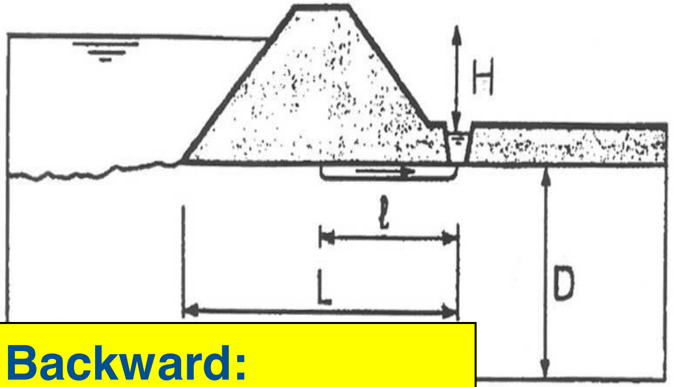
Concentrated leak:

$$\tau = \rho_\omega \frac{gH_f d}{4L}$$



Contact:
v = ki = kH/L





Backward:
$H/L = 1/c = F_R*F_S*F_G$

Suffusion:
Critical hydraulic gradient can be less than 1

1. **H = water level that causes internal erosion**
2. **H_{max} occurs during floods - cannot be reduced**
3. **Investigate potential for IE failure NOW – before a large flood occurs**