ICOLD Bulletin 164 on internal erosion of dams, dikes and levees and their foundations

Rodney Bridle
UK Member, ICOLD Technical Committee on Embankment Dams
rodney.bridle@damsafety.co.uk

Workshop on seepage-induced geotechnical instability
Imperial College, London
31 August and 01 September 2017

Internal erosion – the threat

2005 Katrina – New Orleans – 1,500 fatalities

2009 Situ Gintung – Jakarta – 100-200 fatalities

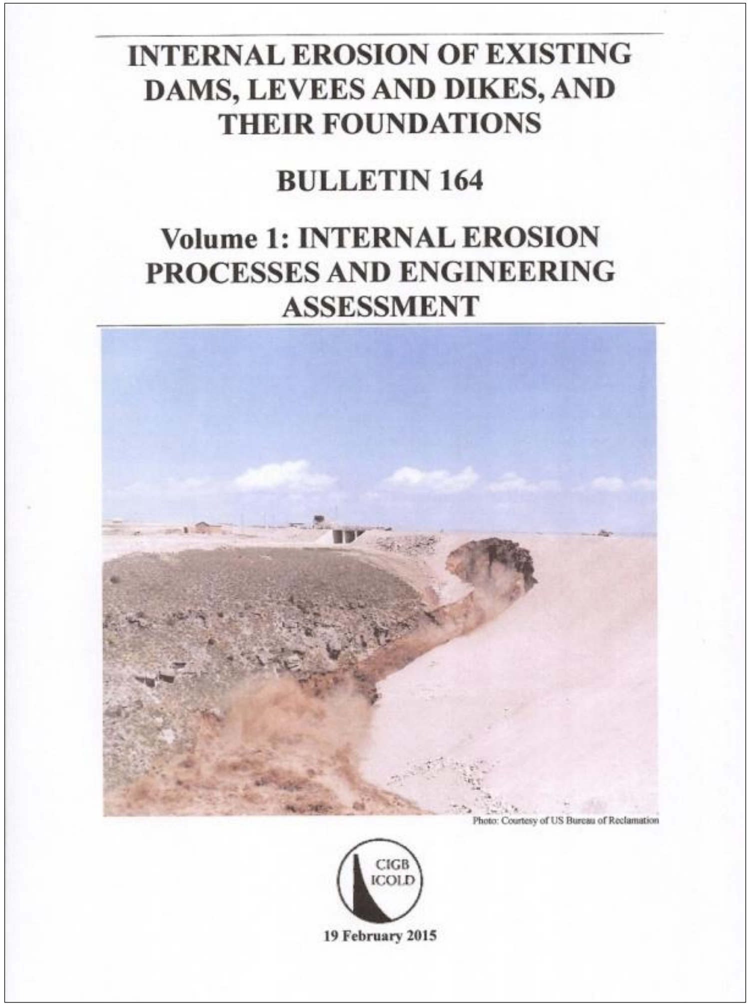
1976 Teton – a few hours

Fatalities

Rapidity of failure

50% of earth dam failures

ICOLD Bulletin 164:
Mechanics of internal erosion



INTERNAL EROSION OF EXISTING
DAMS, LEVEES AND DIKES, AND
THEIR FOUNDATIONS

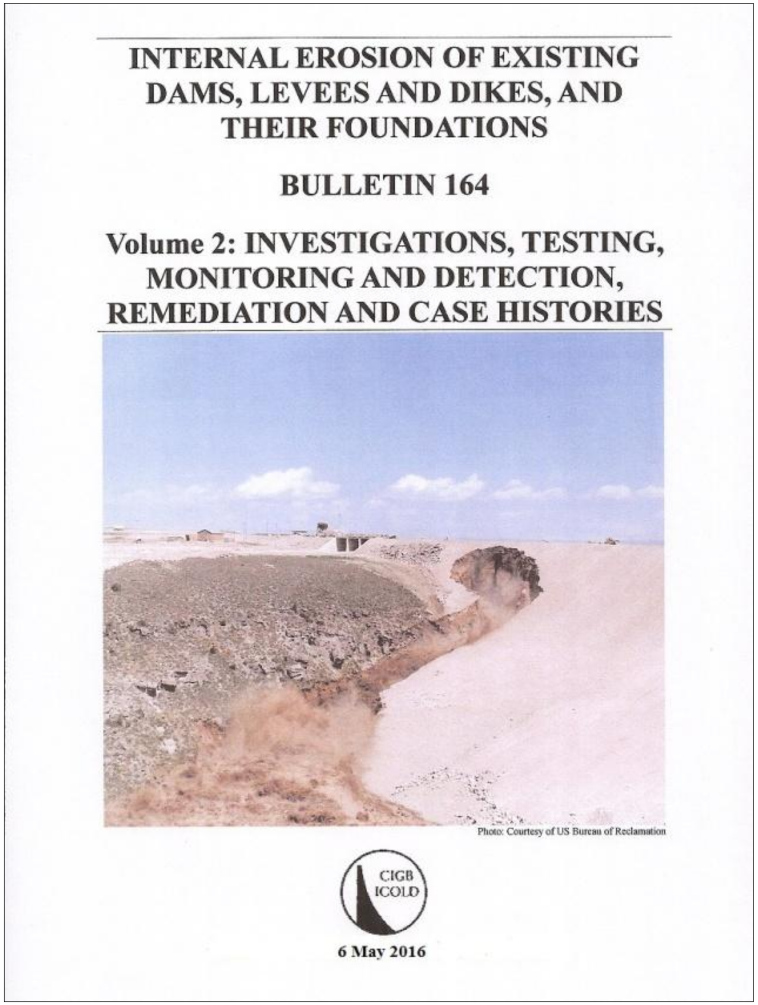
BULLETIN 164

Volume 1: INTERNAL EROSION
PROCESSES AND ENGINEERING
ASSESSMENT

Photo: Courtesy of US Bureau of Reclamation

CIGB
ICOLD

19 February 2015



INTERNAL EROSION OF EXISTING
DAMS, LEVEES AND DIKES, AND
THEIR FOUNDATIONS

BULLETIN 164

Volume 2: INVESTIGATIONS, TESTING,
MONITORING AND DETECTION,
REMEDIATION AND CASE HISTORIES

Photo: Courtesy of US Bureau of Reclamation

CIGB
ICOLD

6 May 2016

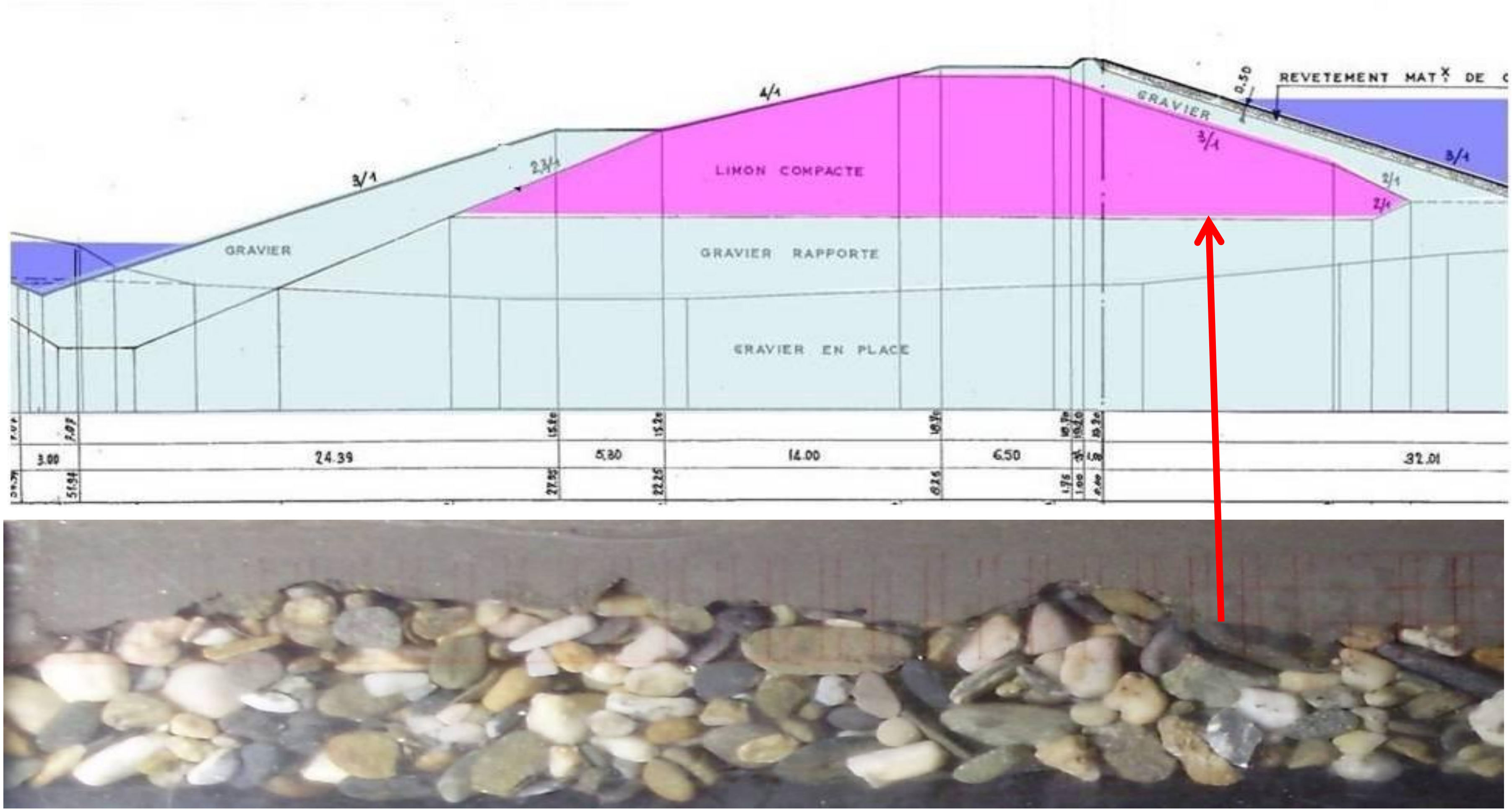
Internal erosion mechanics

- Internal erosion initiates when the hydraulic forces imposed by water flowing or seeping through a water-retaining earth embankment exceed the ability of the soils in the embankment and its foundation to resist them
- Load > Resistance
- Highest hydraulic loads normally occur during floods

Four internal erosion mechanisms

- Bulletin makes it possible to estimate water level at which internal erosion will initiate for the four internal erosion mechanisms:
  - Contact erosion
  - Concentrated leak erosion
  - Suffusion
  - Backward erosion

Contact erosion



Contact erosion – critical hydraulic load

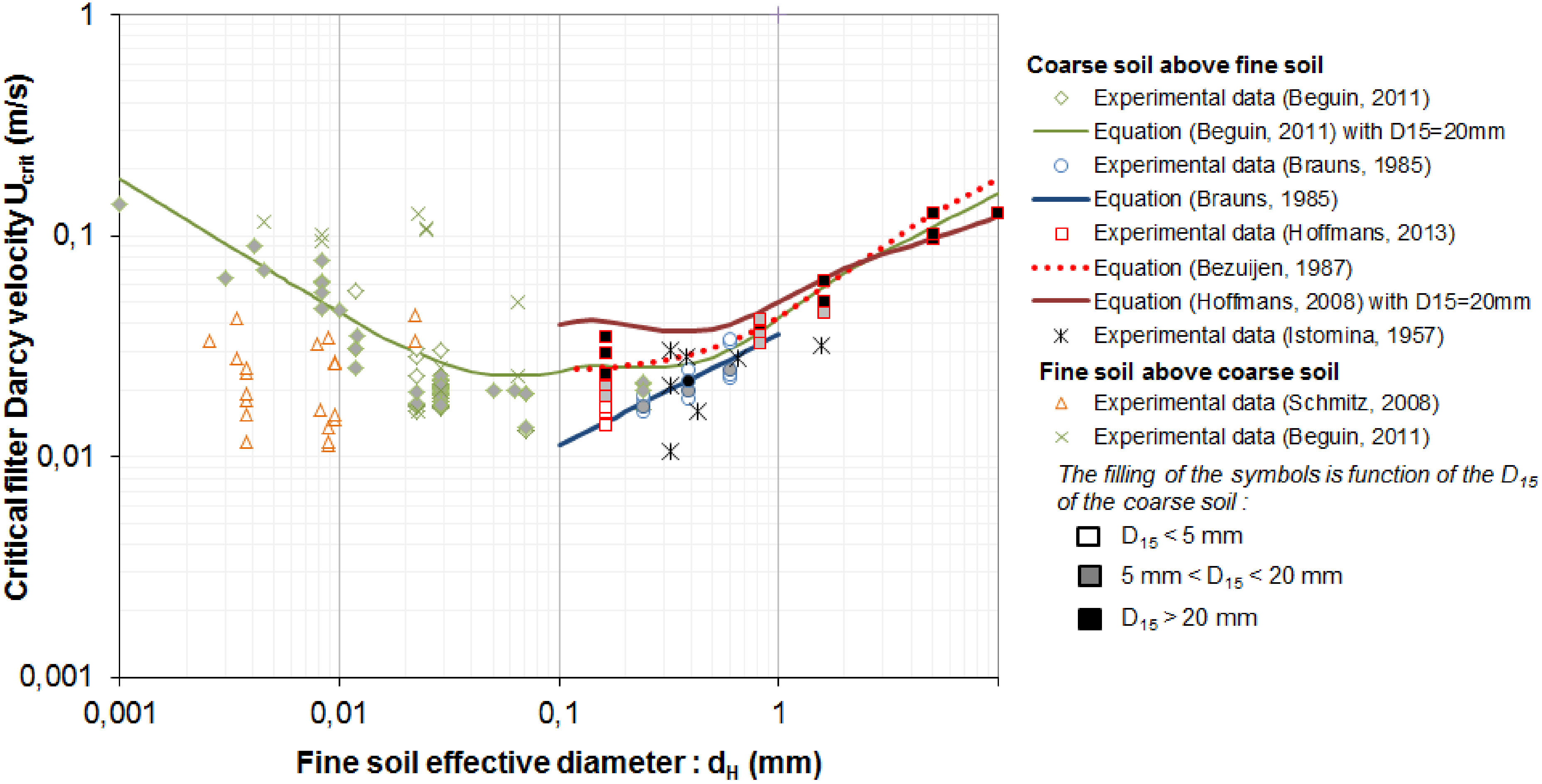
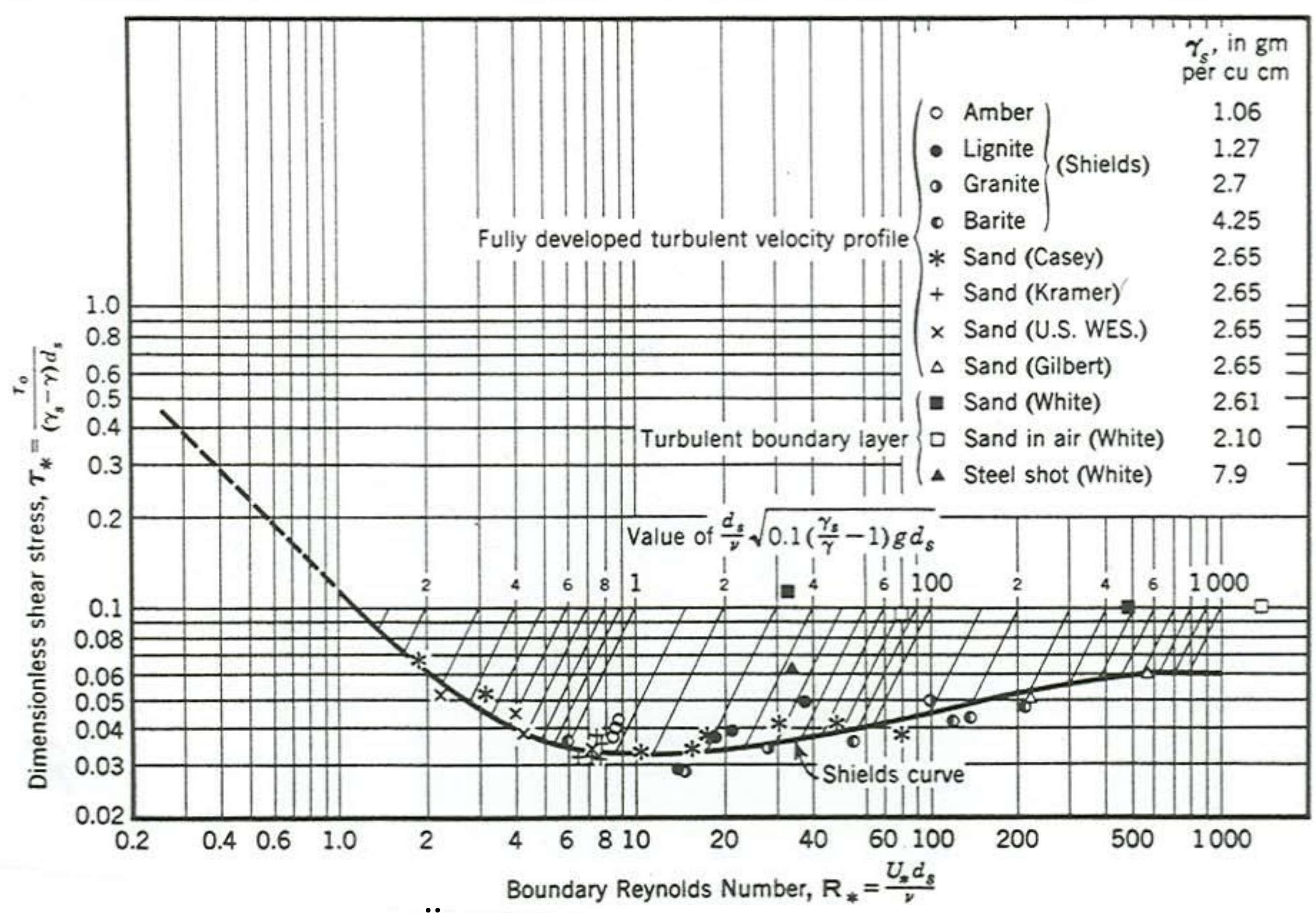


Figure 5.2 Volume 1 ICOLD 164 from Beguin (2011)

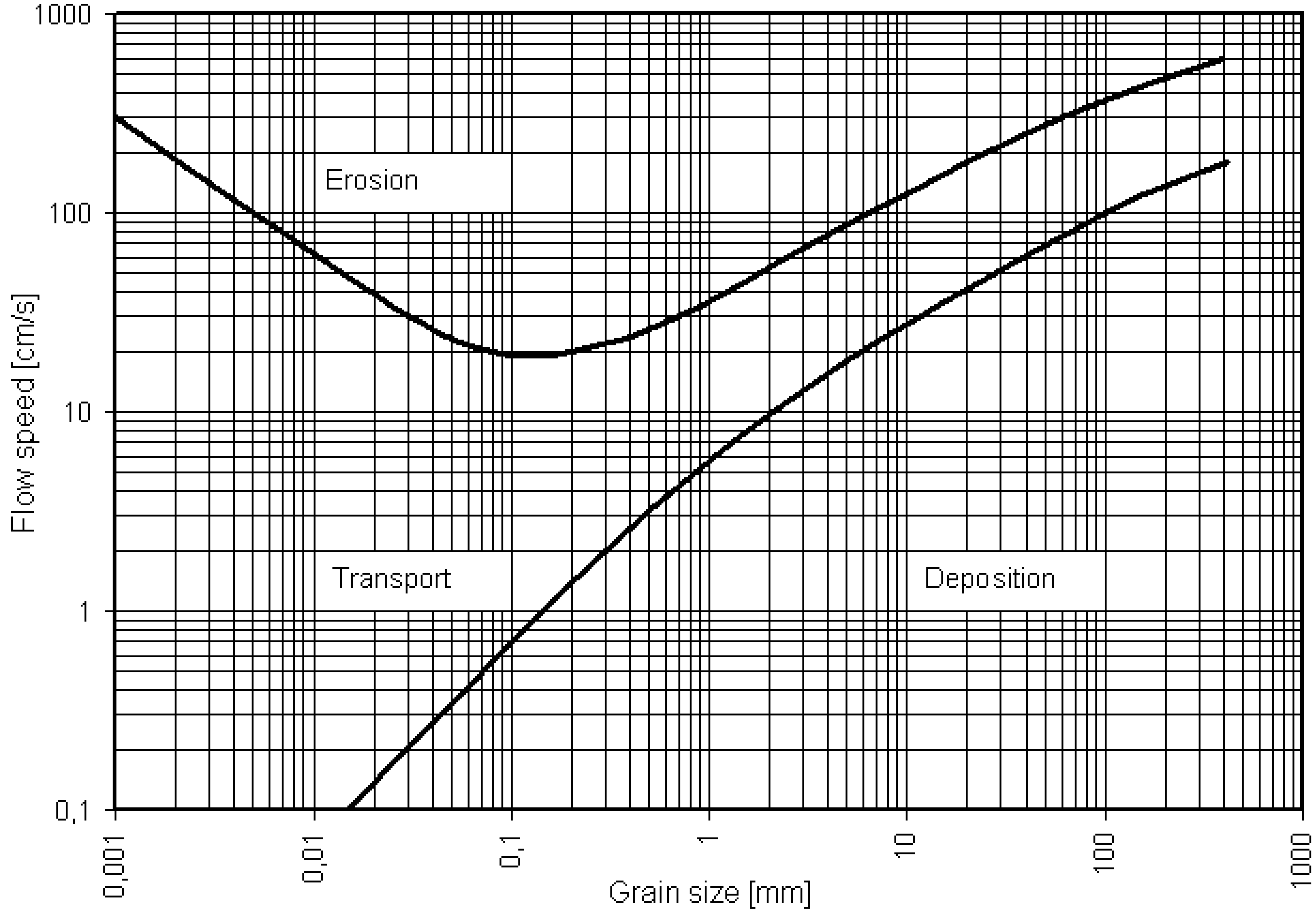
Internal erosion: between hydraulics and soil mechanics

Bed-load transport - Shields diagram



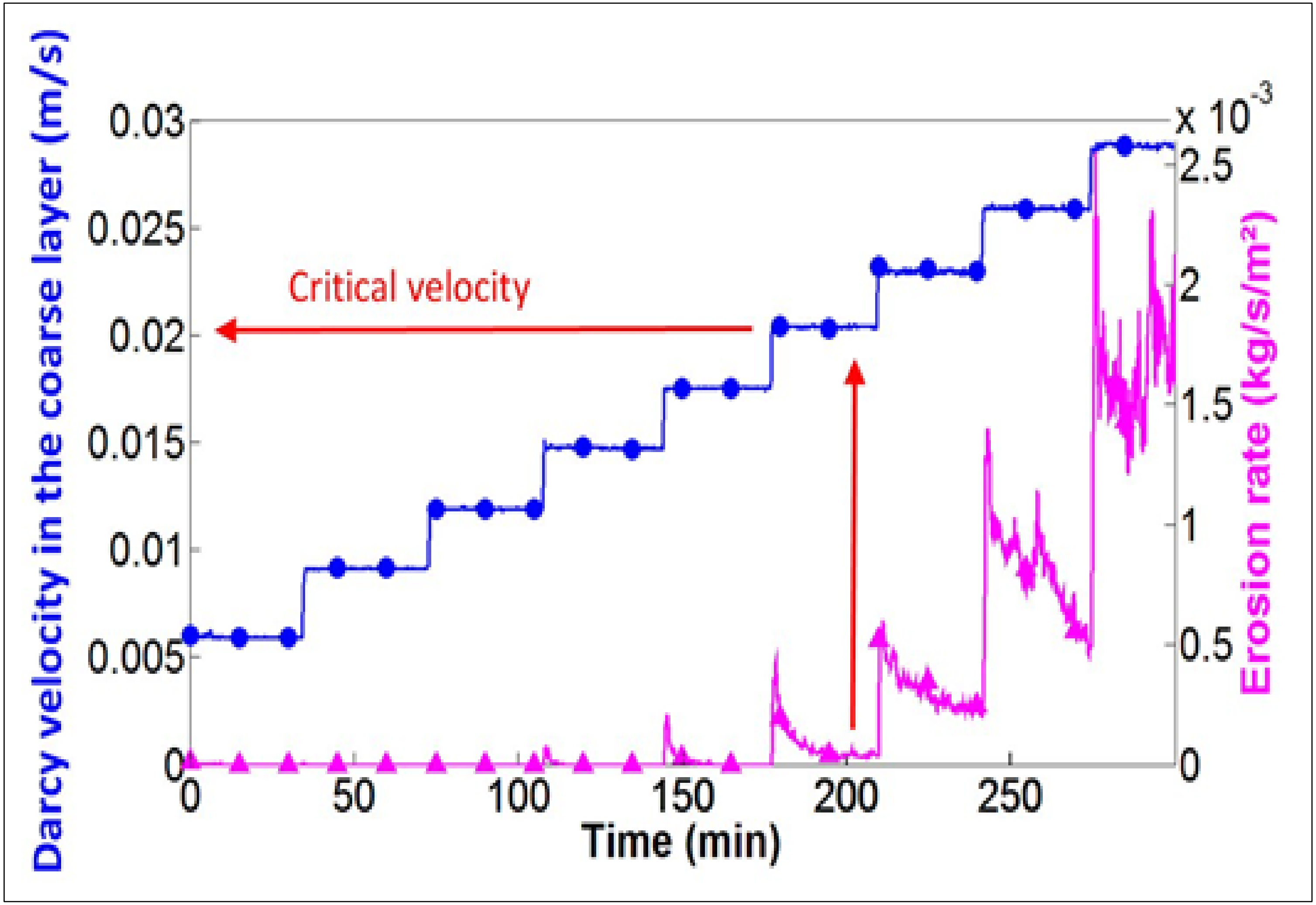
Shields, A., 1936, Anwendung der Ähnlichkeitsmechanik auf die Geschiebebewegung: Berlin, Preussische Versuchanstalt für Wasserbau und Schiffbau, Mitteilungen, no. 26, 25 p.

Bed-load transport - Hjulström diagram



Hjulström, F. "Transportation of Debris by Moving Water." In *Recent Marine Sediments. Edited by P. D. Trask, 1939; Tulsa, Oklahoma. "A Symposium." American Association of Petroleum Geologists. pp. 5-31*

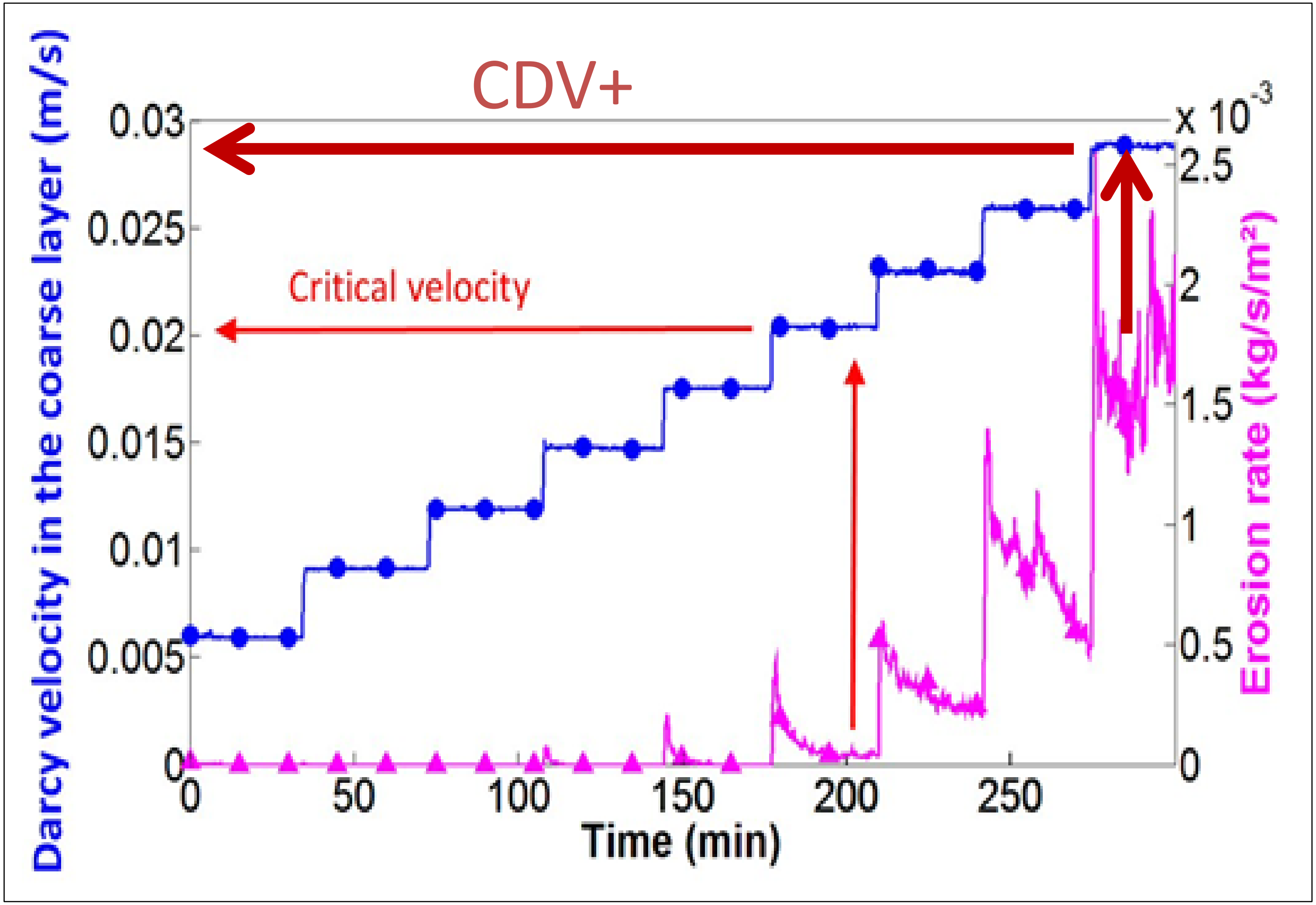
Continuous contact erosion - determining critical Darcy velocity



Remi Beguin & Pierre Philippe presentations at EWGIE Vienna, 2013

Sinkholes from slow contact erosion at sub-critical Darcy velocity

Continuous contact erosion at critical Darcy velocity – rapid failure at CDV+



Remi Beguin & Pierre Philippe presentations at EWGIE Vienna, 2013

Concentrated leak erosion

Cylindrical pipe

$$\tau = \rho_w \frac{gH_f d}{4L}$$

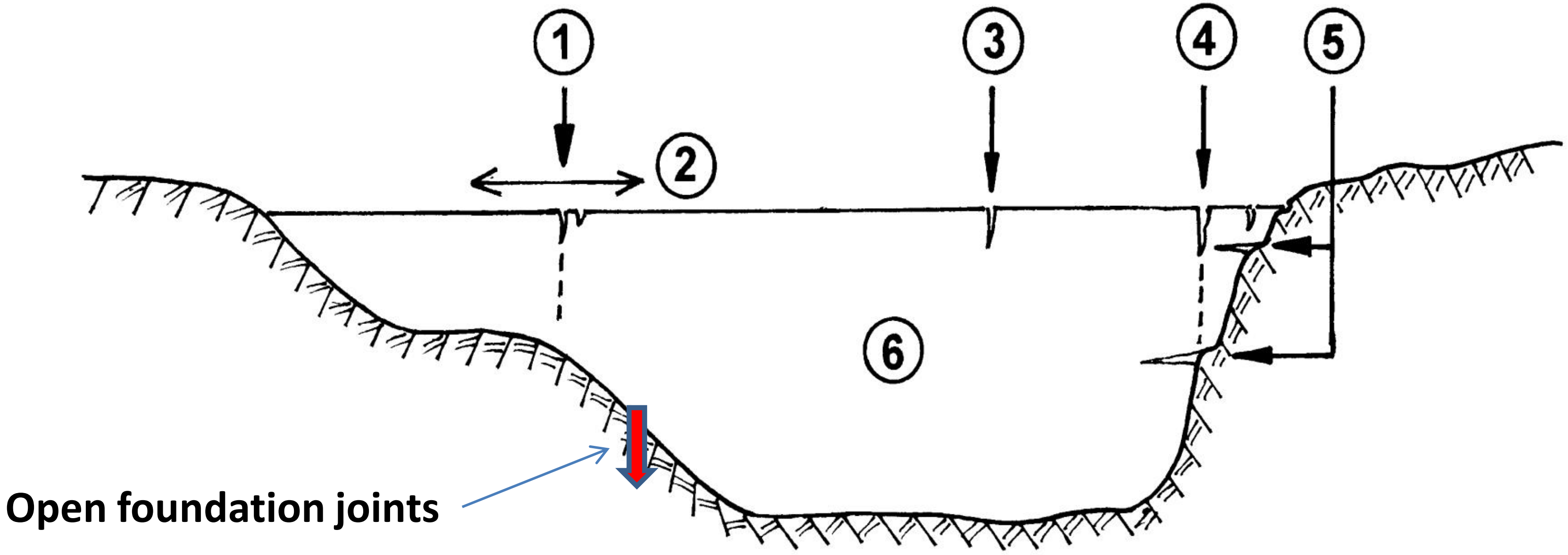
Vertical transverse crack

$$\tau = \frac{\rho_w g H_f^2 W}{2(H_f + W)L}$$

Compare τ applied hydraulic shear stress to hydraulic shear strength from HET, JET or soil properties given in Bulletin

Concentrated Leak Erosion

Figure 2.2 Examples of possible locations of initiation of internal erosion in concentrated leaks



Open foundation joints

1 Vertical crack due to lateral straining
2 Lateral straining caused by differential settlement
3 Vertical crack due to desiccation
4 Vertical crack due to sliding of core along steep abutment wall with steps (protrusions)
5 Horizontal cracks due to sliding of core along steep abutment wall with steps (protrusions)
6 Dam core

Cracks may be opened/enlarged by hydraulic fracture as water level rises, $u>\sigma_3$

Hydraulic forces causing 'segregation piping'
Skempton-Brogan (1994)

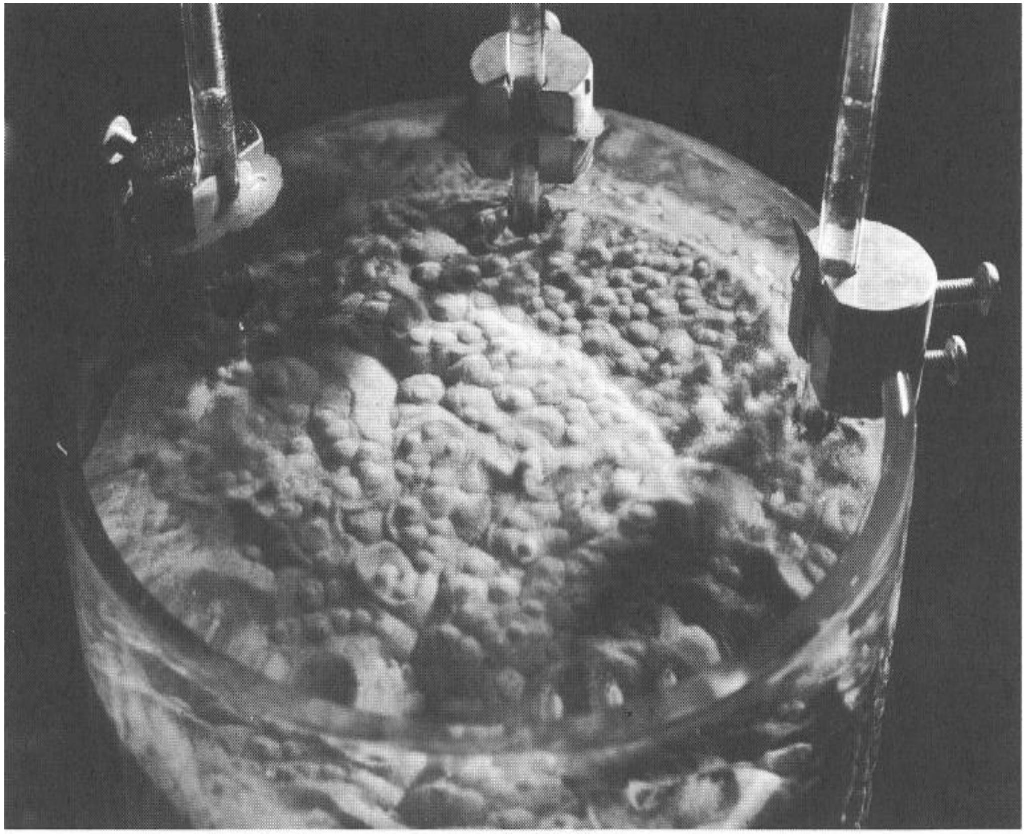


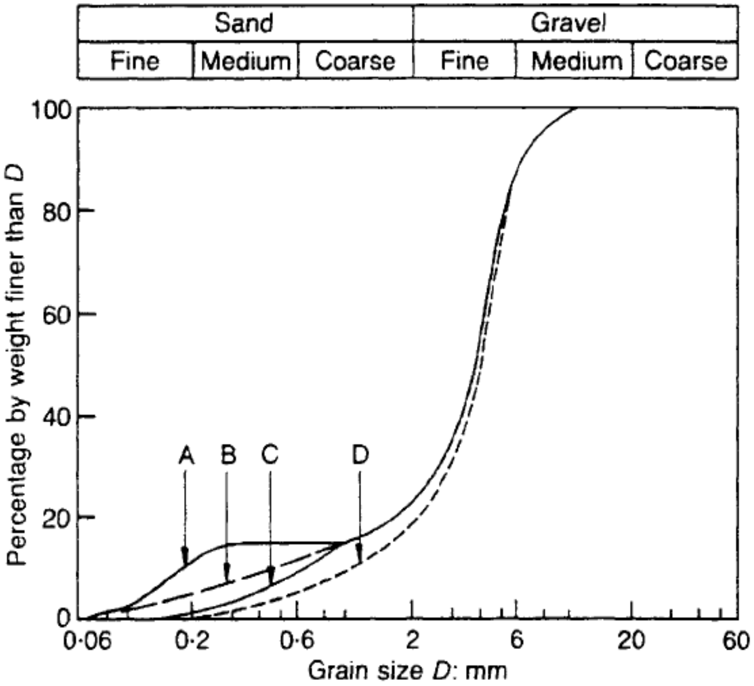
Fig. 9. Material A: strong general piping of fines ($i = 0{\cdot}22$, $v = 0{\cdot}27$ cm/s)

$$i_{cr} = \alpha i_c$$

"… for unstable materials, the critical hydraulic gradient could be roughly 1/3 to 1/5 of the normal threshold of 1.0."

From J Fannin EWGIE 2010 - Hydraulic gradient

Suffusion



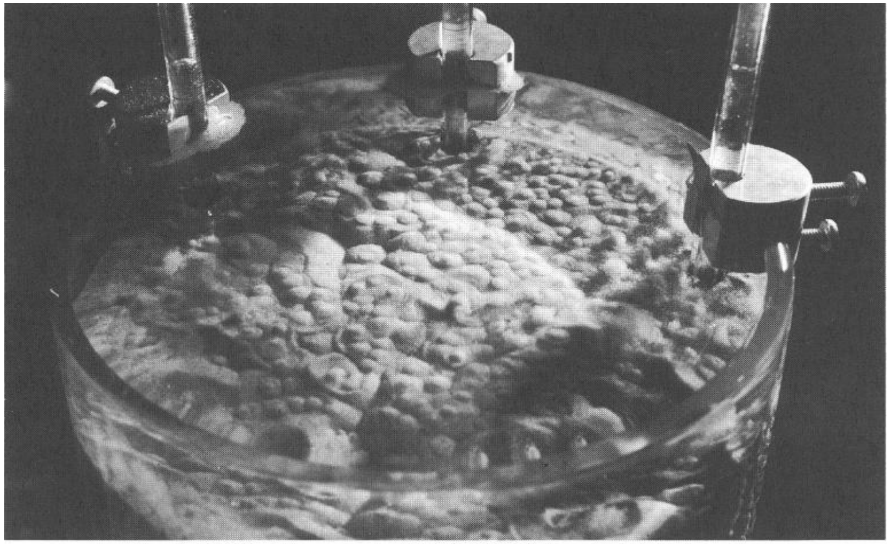
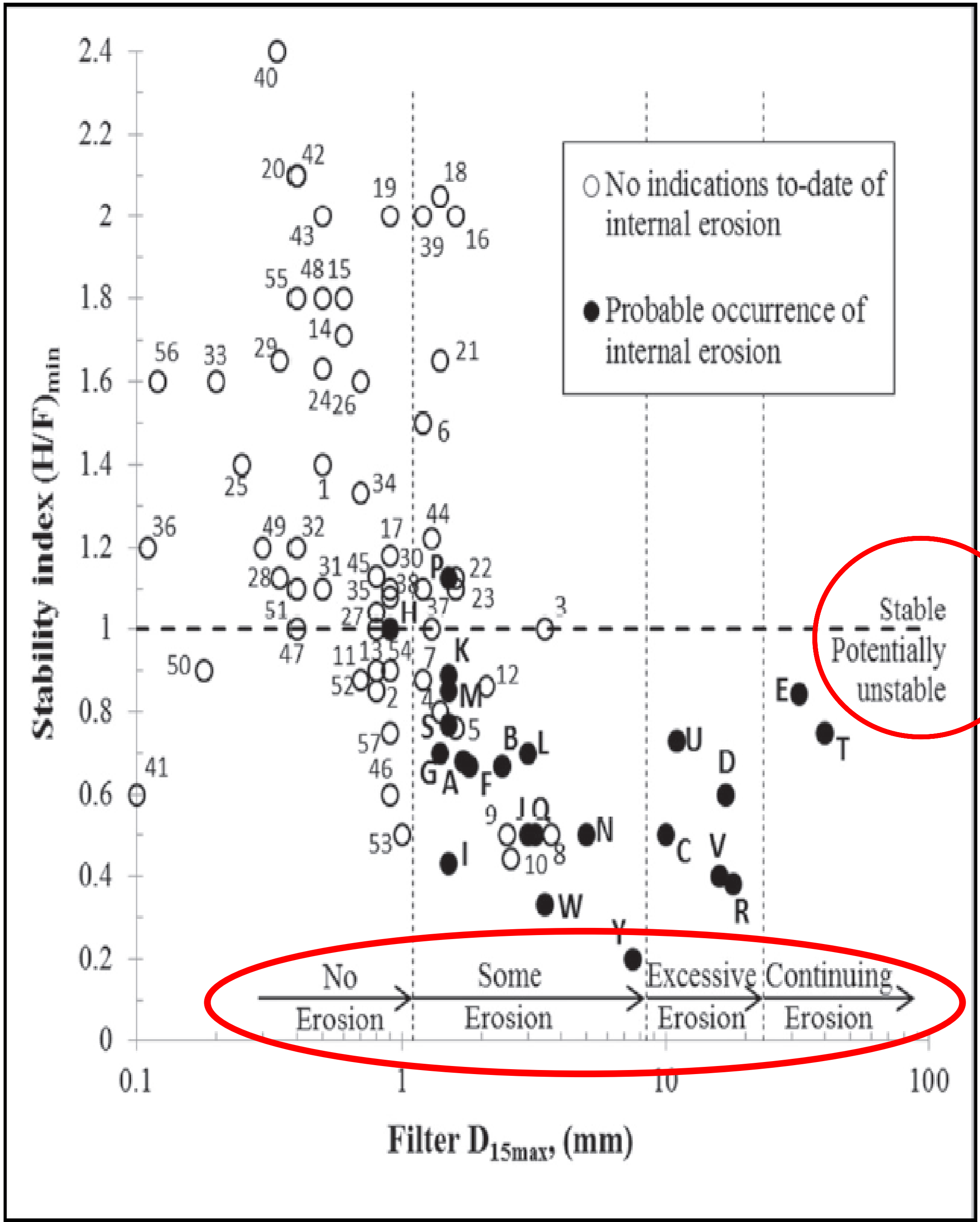


Fig. 9. Material A: strong general piping of fines ($i = 0{\cdot}22$, $v = 0{\cdot}27$ cm/s)

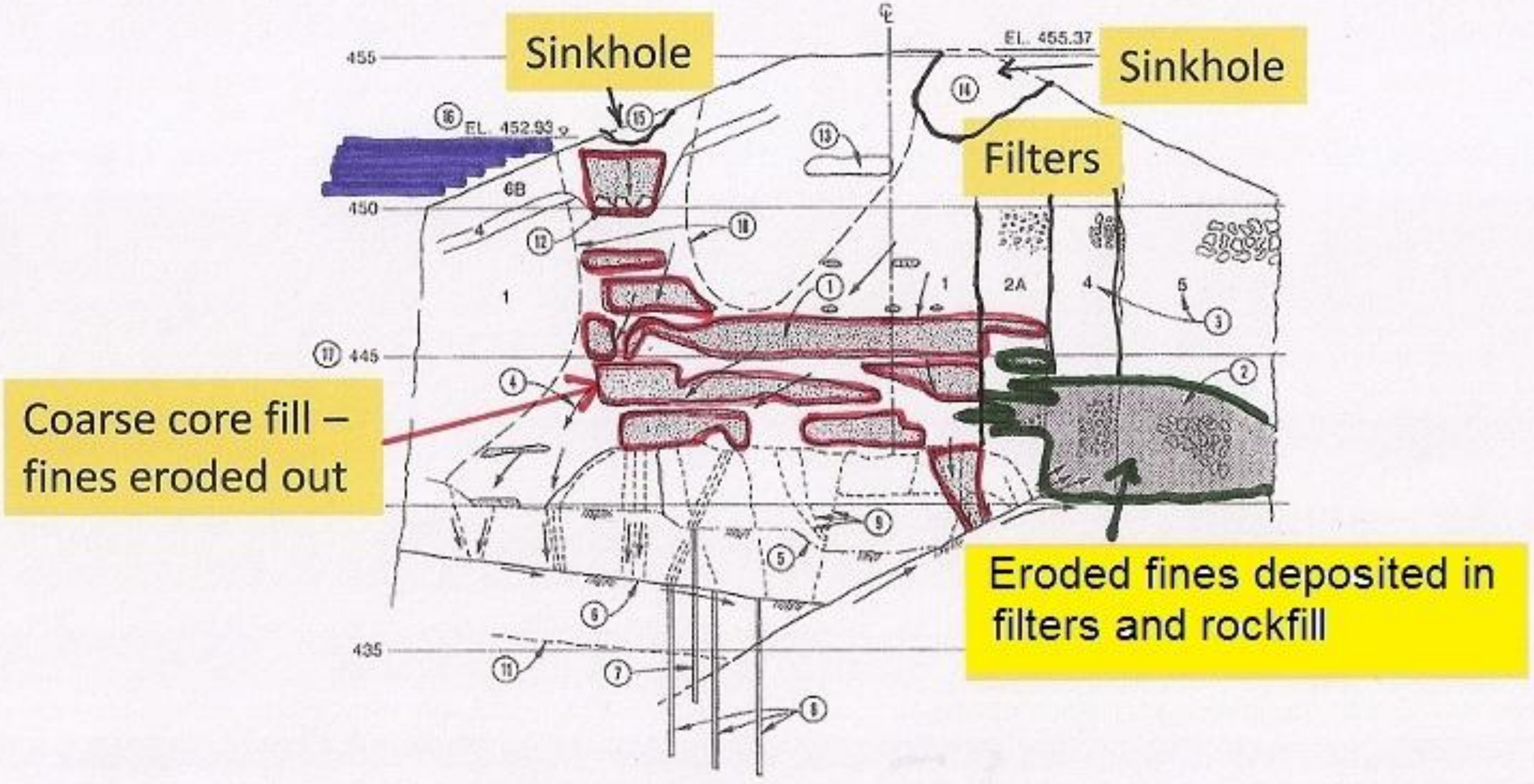
Grain size distribution curves of soils in Skempton and Brogan (1994) tests.
Samples A and B were suffusive, C and D were not.
Suffusion in upward flow initiated at critical hydraulic gradient $i_{cr} = 0.2$ in A and $i_{cr} = 0.34$ in B
In non-suffusive samples C and D, 'general piping' occurred at $i_c \sim 1.0$



Identifying potentially suffusive soils: Ronnqvist's unified plot

(Ronnqvist, 2015; Ronnqvist et al, 2014)

Hydraulic loads cause suffusion



Sinkhole

Sinkhole

Filters

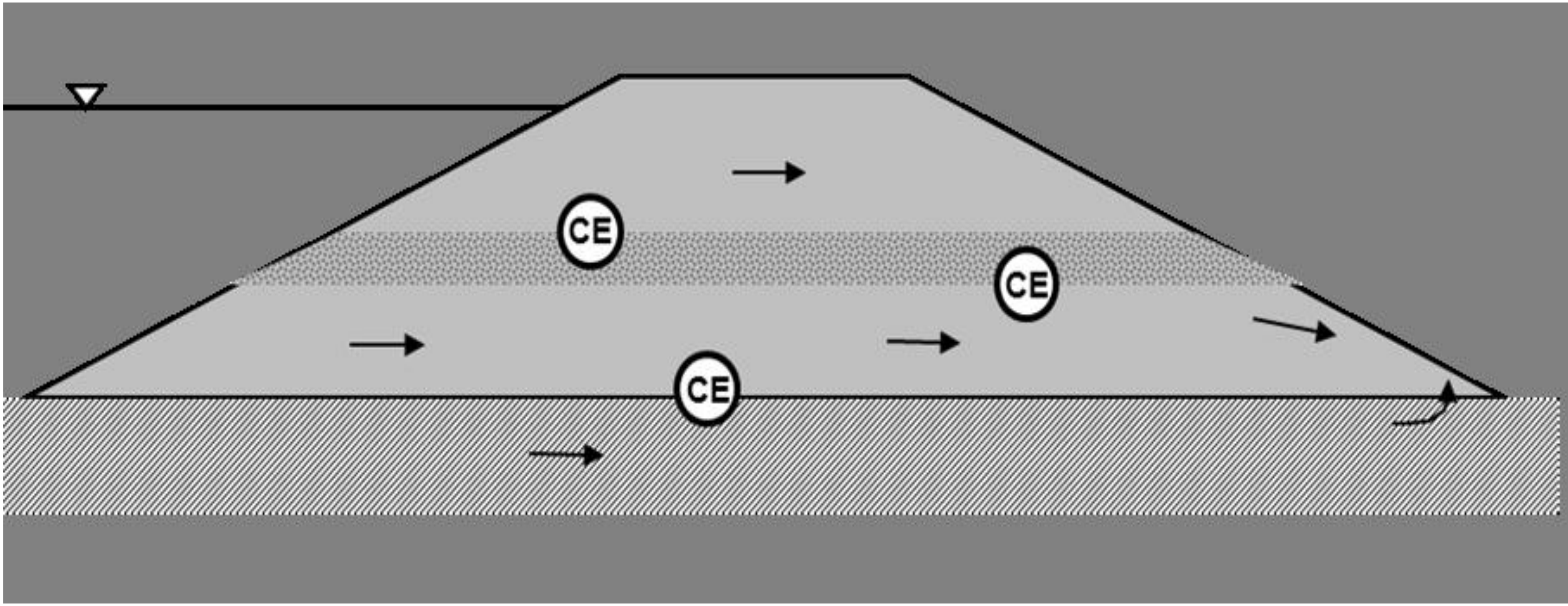
Coarse core fill – fines eroded out

Eroded fines deposited in filters and rockfill

Figure B-4 - Churchill Falls, Dyke GJ-11A Incident (Seemel response, 1991)

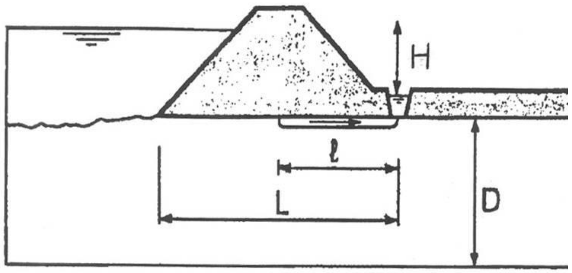
Note: The figure is a pictorial representation of the deterioration process at Sta. 15+07

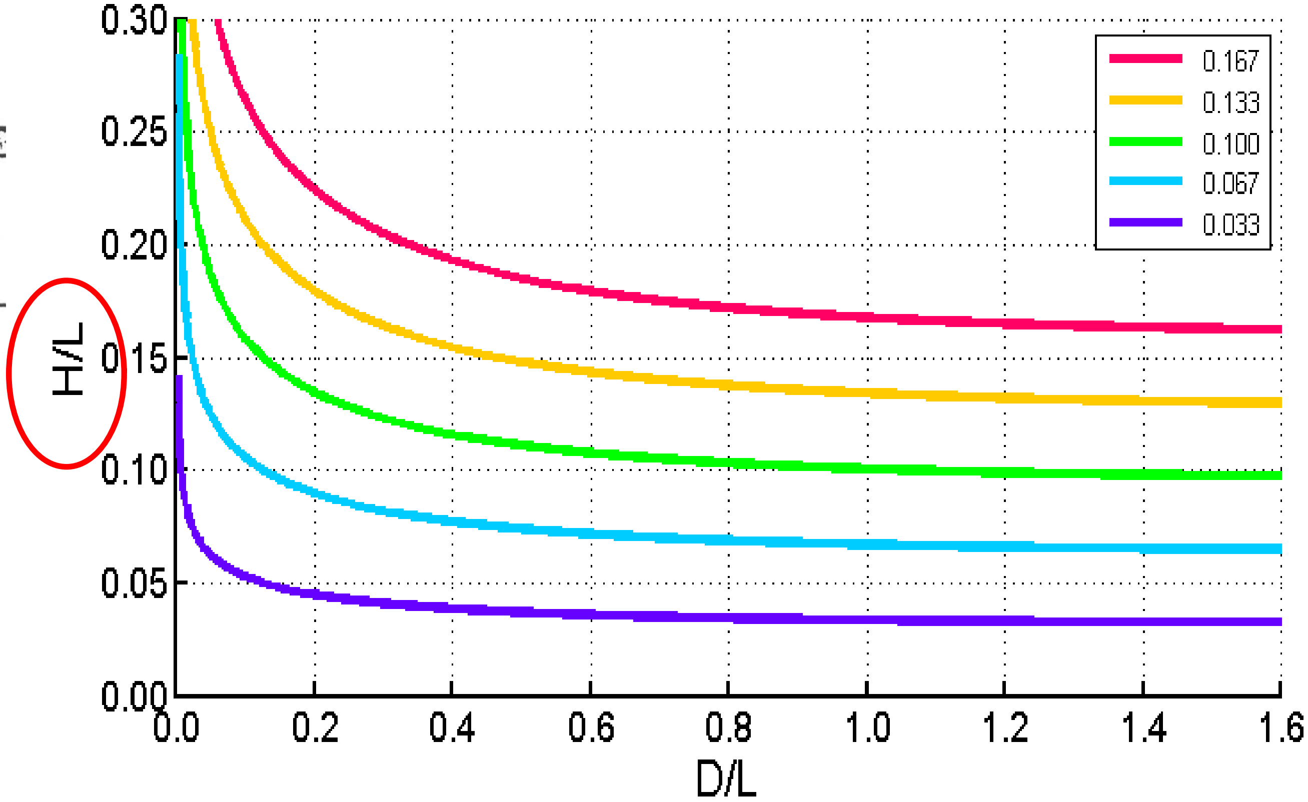
‘Homogeneous’ (unzoned) dams cannot arrest erosion if it initiates



Possible locations of contact erosion initiation in homogeneous dam with layered fill and a coarse foundation soil (Beguin et al, 2009)

Backward erosion





$$H/L = F_R * F_S * F_G$$

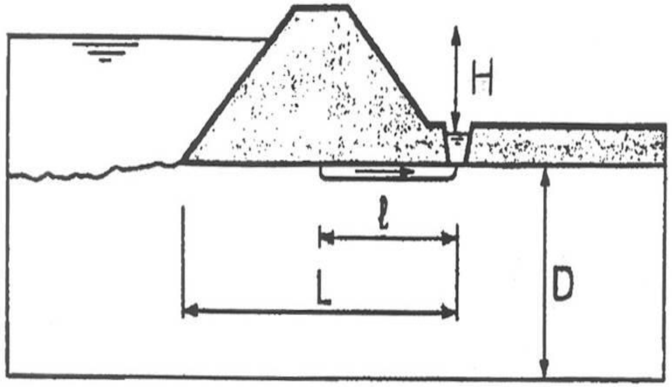
Hans Sellmeijer and Vera van Beek, Deltares

Figure 4.4 Critical gradient 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 $H/L = 0.10$.

Backward erosion 2D & 3D

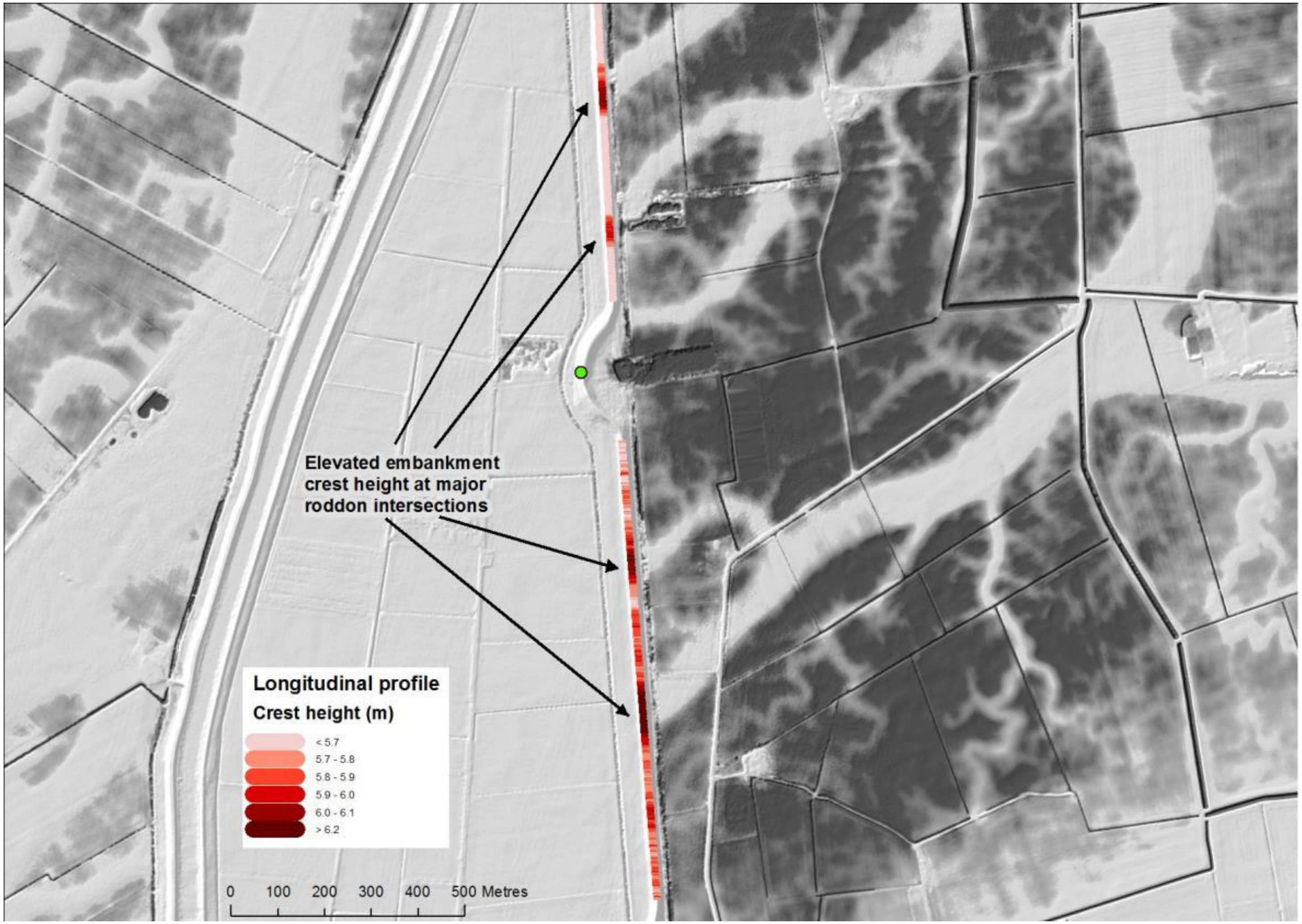


3D – initiates through single openings in confining layer – often forming sand boils.
Not covered by Bulletin.
Occurs at lower gradient than 2D: higher risk.
A challenge to be addressed – by application of geophysics, geomorphology and hydrogeology perhaps.

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

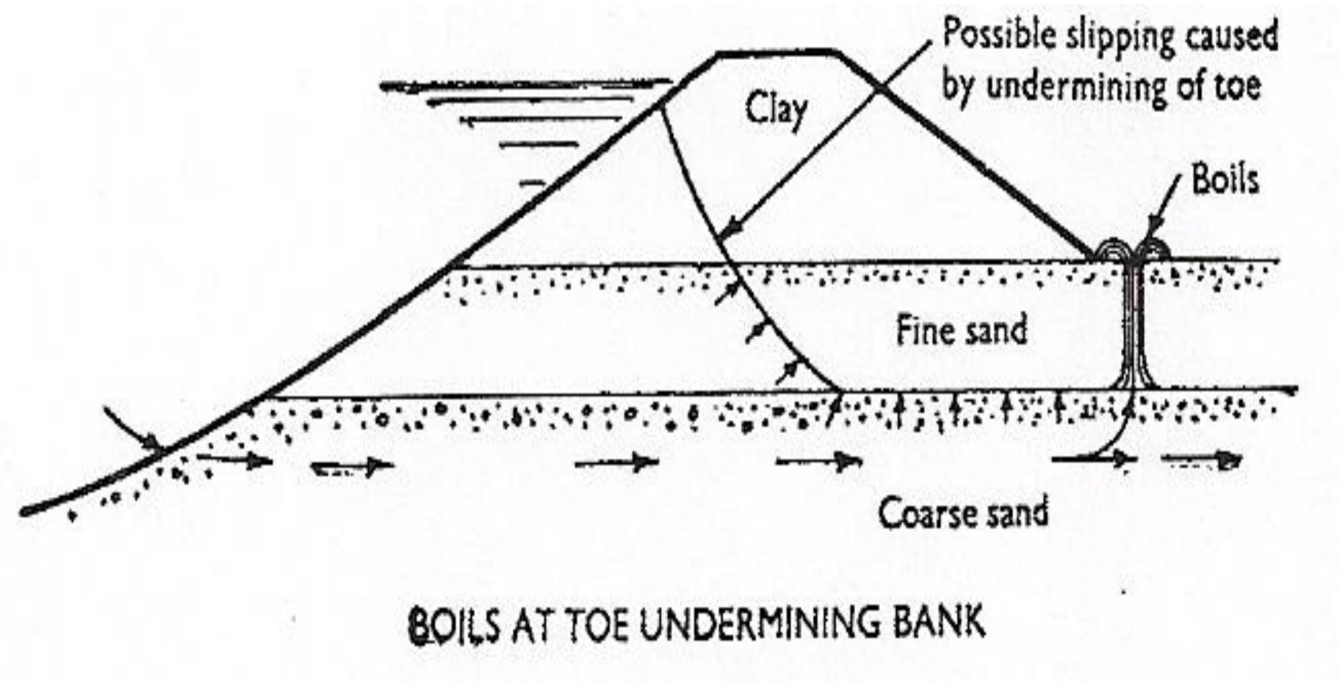
Ref: Van Beek, van Essen, Vandenboer & Bezuijen (2015) Geotechnique

River morphology
Paleo-channels revealed by LIDAR



Research News Issue 28 Flood and Coastal Erosion Risk Management

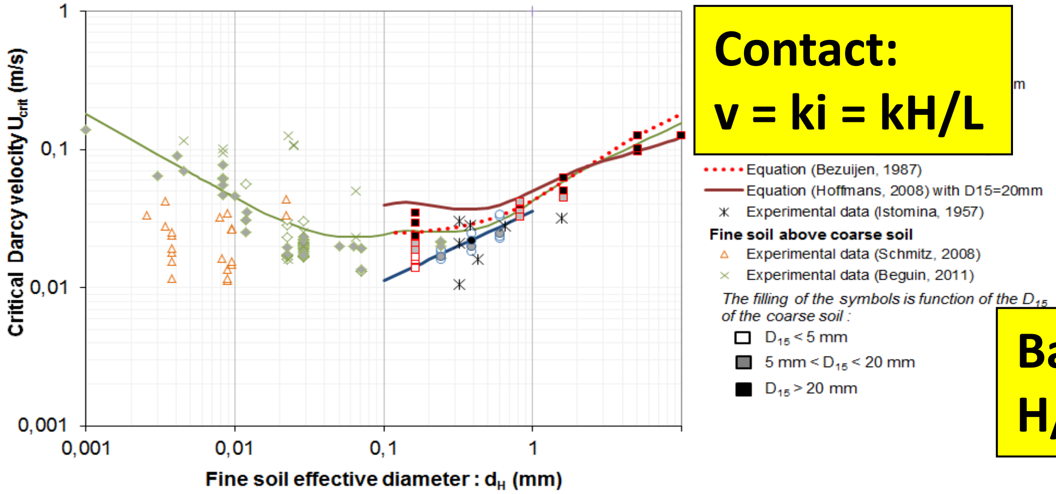
Backward erosion – rapid failure



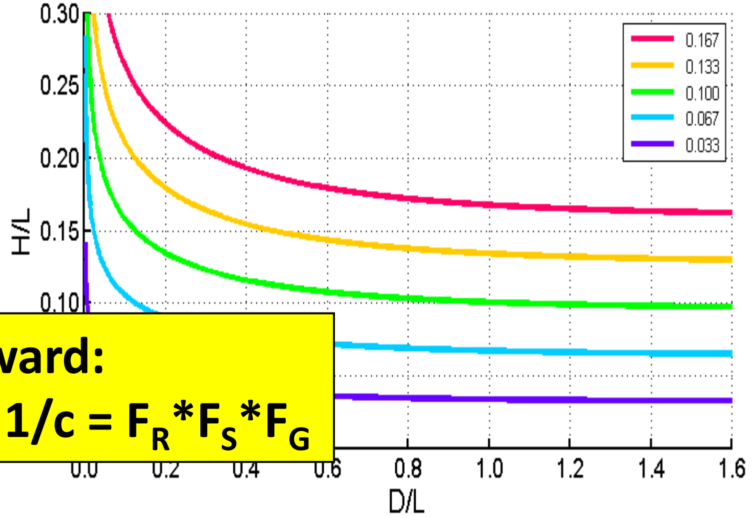
North Sea Coastal Dike: failed during 2-3 hour peak of 1953 storm surge

From: Marsland & Cooling (1954) ICE

Hydraulic loads initiate internal erosion



Contact:
$v = ki = kH/L$



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

Suffusion:
Critical hydraulic gradient
$i_c = 0.2$ **in A and** $i_c = 0.34$ **in B**

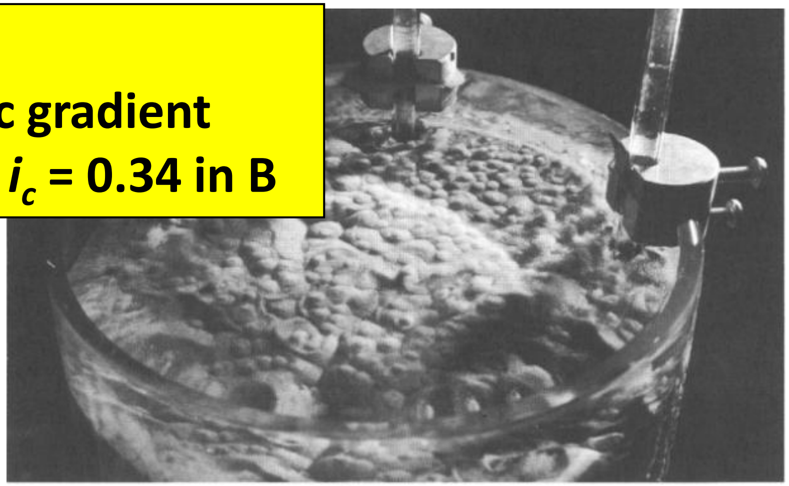


Fig. 9 Material A: strong general piping of fines ($i = 0{\cdot}22$, $v = 0{\cdot}27$ cm/s)

Concentrated:

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

H = water level that initiates internal erosion

Recommendations to engineers: Addressing the threat of internal erosion

- ICOLD Bulletin 164: mechanics of internal erosion
- New knowledge that can be applied
- To carry out investigations and analyses to estimate actual hydraulic load (water level) causing internal erosion failure
- Remediate, if necessary, to provide an acceptable level of protection to people downstream
- Maintain dam in post-remediation condition, confirmed by routine surveillance and monitoring

Conclusions

- The four internal erosion processes are caused by the hydraulic forces imposed by seepage or flow through soils
- The challenge is to estimate the hydraulic forces causing internal erosion in vulnerable soils
- ICOLD Bulletin 164 collects much current knowledge, provides guidance for engineers
- More to research and learn (e.g. Bridle, research suggestions, ICSE8, Oxford, 2016)

www.icold-cigb.org rodney.bridle@damsafety.co.uk