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

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Internal erosion – the threat

- Internal erosion causes about one-half of all embankment dam failures
- About one-third are failures of existing embankment dams
- Failures occur rapidly - during floods
- Monitoring and surveillance do not give early enough warnings of the onset of internal erosion leading to failure
Situ Gintung 2009

Rapid failure on rapid refilling after drought.
100-200 people ‘could not escape’
ICOLD Bulletin 164: Mechanics of internal erosion
Internal erosion mechanics

- Internal erosion initiates when the hydraulic forces imposed by water flowing through an earth dam exceed the ability of the soils in dam and foundation to resist them.
- 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
Concentrated leak erosion

Cylindrical pipe

\[ \tau = \rho_w \frac{gH_f d}{4L} \]

Vertical transverse crack

\[ \tau = \frac{\rho_w gH_f^2 W}{2(H_f + W)L} \]

Compare \( \tau \) applied hydraulic shear stress to hydraulic shear strength from HET, JET or soil properties given in Bulletin
Concentrated leak erosion

Cylindrical pipe

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Vertical transverse crack

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Compare \( \tau \) applied hydraulic shear stress to hydraulic shear strength from HET, JET or soil properties given in Bulletin.

Crack dimensions and locations difficult to assess, and vary seasonally and over time. Use ‘filter erosion boundaries concept’ to assess if shoulder fill is able to arrest erosion in cracks. If not, take precautions.
Four phases of internal erosion to failure

INITIATION
Concentrated leak forms, erosion initiates along walls of crack

CONTINUATION OR FILTRATION
Continuation of erosion or
Arrest of erosion by filtration

PROGRESSION
Enlargement of concentrated leak

BREACH
Breach mechanism forms

FOUR PHASES OF INTERNAL EROSION IN THE EMBANKMENT INITIATED BY EROSION IN A CONCENTRATED LEAK

Figure 2.1 Volume 1 ICOLD Bulletin 164
No, some, excessive and continuing erosion

Figure 13.2 Conceptual filter erosion boundaries (Foster, 1999), Foster & Fell (2001)
Filtering by shoulder fill in zoned dam

‘Typical British dam’, Section 2.6.3, Volume 2, ICOLD 164
‘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)
Suffusion

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 suffusive soils: e.g. Ronnqvist’s unified plot

(Ronnqvist, 2015; Ronnqvist et al, 2014)
Hydraulic loads cause suffusion

- Sinkhole
- Sinkhole
- Filters
- Coarse core fill – fines eroded out
- Filters and rockfill clogged with eroded fines
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 $H/L = 0.10$. 
Hauser steel dam, H, water depth ≈ 70-ft, L, bottom width ≈ 70-ft, D, depth of alluvium = 66-ft (H/L, actual ≈ 1, D/L actual ≈ 1) (from video lecture, Dr Ralph Peck, 1995)
Backward erosion

\[ \frac{D}{L} = 1, \quad \frac{H}{L} = 1 = \text{FAILURE} \]

Hans Sellmeijer and Vera van Beek, Deltares

\[ \frac{H}{L} = FR \times FS \times FG \]
Hauser Dam 1907
Hydraulic loads initiate internal erosion

**Contact:**

\[ v = k = k \frac{H}{L} \]

**Backward:**

\[ \frac{H}{L} = 1/c = F_R \ast F_S \ast F_G \]

**Concentrated:**

\[ \tau = \rho \omega g H_f \frac{d}{4L} \]

**Suffusion:**

Critical hydraulic gradient

- In A: \( i_c = 0.2 \)
- In B: \( i_c = 0.34 \)

\[ H = \text{water level that initiates internal erosion} \]
Internal erosion failures - rapid

Monitoring cannot give early warning of onset of internal erosion to failure
Backward erosion – rapid failure

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

From: Marsland & Cooling (1954) ICE
Recommendations – how to deal with the threat of internal erosion

• ICOLD Bulletin 164: mechanics of internal erosion
• New knowledge that can be applied
• To analyse and re-design the dam to protect people from rapid failure occurring during floods
• 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
Mechanics, probability and risk

- Hydraulic load causing failure through the four mechanisms can be estimated as shown.
- Highest hydraulic loads imposed during floods.
- Probability of highest load estimated from flood hydrology.
- Consequences estimated from dambreak study.
- Risk = Probability \times\text{ Consequences}.
Internal erosion risk in UK dams

Estimated annual probability of failure vs Likely loss of life

- High Risk Zone
- Low Risk Zone

- Typical British dam
- Bridle QRAs
- Probability Internal Erosion

Unacceptable above
Acceptable below

Based on Brown & Gosden (2004)
Probability of failure < 1:10,000-yr

Acceptable risk: is 1/10,000 low enough?

- **Typical British dam**
- **Bridle QRAs**
- **Probability Internal Erosion**
- **Unacceptable above**
- **Acceptable below**
- **1 in 10,000-yr probability of failure**
Conclusions

• ICOLD Bulletin 164: mechanics of internal erosion
• New knowledge that can be applied
• To estimate actual hydraulic load (water level) causing internal erosion failure
• Assess whether this water level is high enough to provide an acceptable level of protection to people downstream
• View vulnerability of embankments to internal erosion in context of acceptable risk

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