Internal Erosion Risks for Embankments and Foundations

Best Practices in Dam and Levee Safety Risk Analysis

Part D – Embankments and Foundations

Chapter D-6

Last modified June 2017, presented July 2019

Outline of Presentation

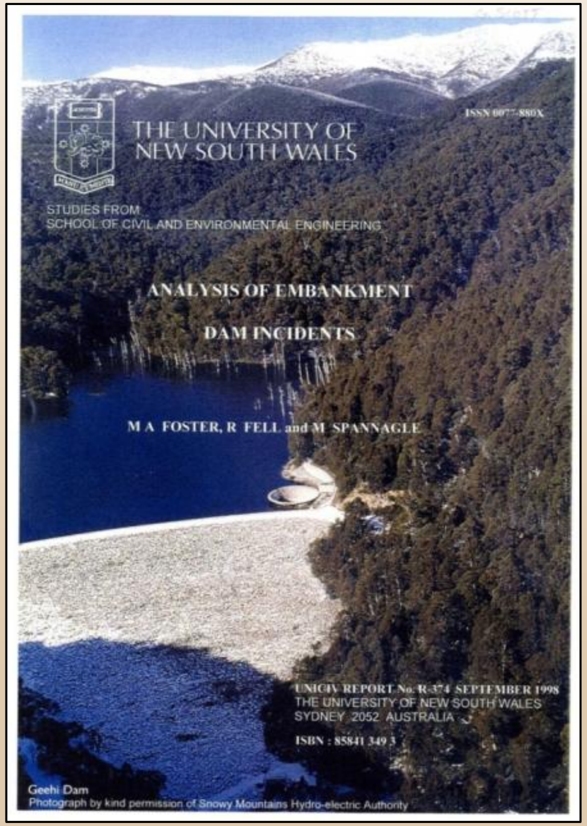
- Historical Significance
- Objectives
  - Understand
    - Mechanisms that affect internal erosion and where they occurs
    - How we construct an event tree to represent internal erosion
    - Keys to estimate the probability of failure
- Many Case Histories will be included throughout

Key Concepts in Chapter

- Understand case histories – most common failure mode
- Gradient versus critical gradient – selecting the correct model
- Geometry and physical constraints/characteristics that promote erosion
- Understand the different mechanisms
- The use of seepage analysis
- Understanding the basic mechanics of seepage and leakage
- Understand the susceptibilities and vulnerabilities
- Average versus local gradients
- How to consider performance history
- Limits of physical and mathematical models
- Critical shear stress concepts
- Intervention and Breach

UNSW Statistics on Embankment Dam Failures

- UNSW (Foster et al., 1998, 2000) historical frequencies of failures and accidents in embankments of large dams constructed from 1800 to 1986:
  - 47% of failures due to internal erosion
  - Can occur at normal loading, later due to degradation over time, or when record levels are reached.



Current Information from Levee and Dam Incidents

199 Levee segments

- 894 Internal Erosion (IE) incidents
- 450 Significant IE incidents
- 39 Breaches prior to overtopping
    - 29 attributed to Internal Erosion

Embankment dams - about 120 internal erosion incidents in USACE and about 100 in Reclamation

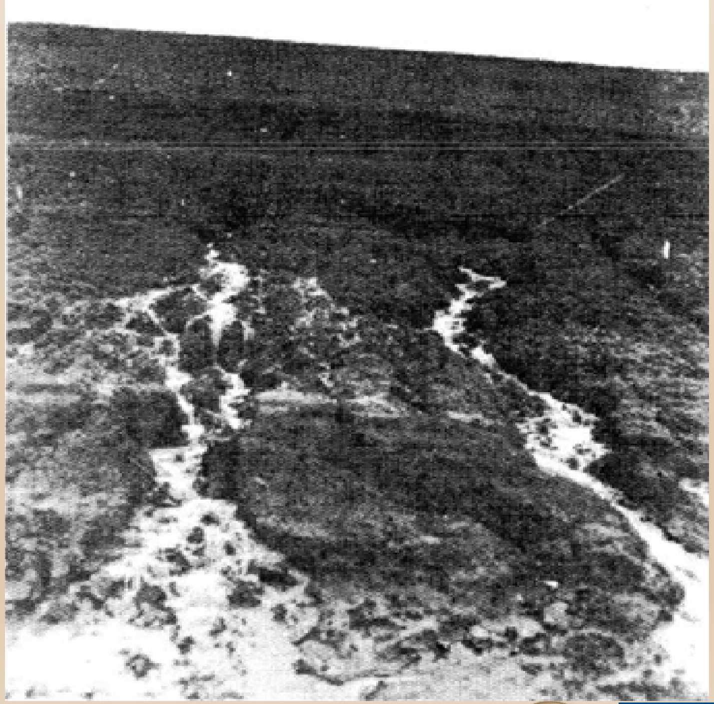
MECHANISMS

- Backward Erosion Piping (BEP)
- Scour or Concentrated Leak Erosion (CLE)
  - Soil Contact Erosion*
- Internal Instability (Suffusion/Suffosion)**
- Internal Migration (Stoping) ***

*USACE considers this a separate mechanism

**USACE considers a secondary mechanism of BEP or CLE

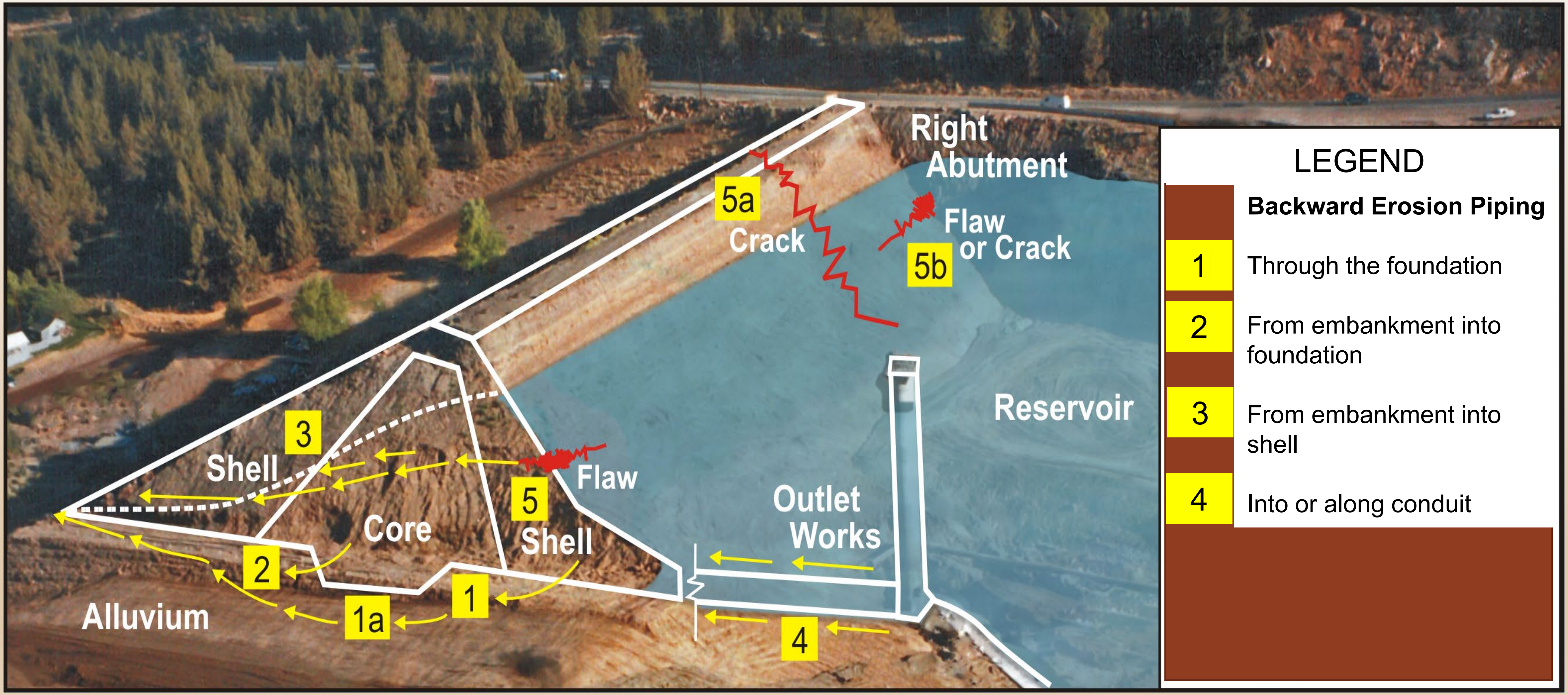
*** ICOLD includes stoping with global backwards erosion



General Categories of Internal Erosion

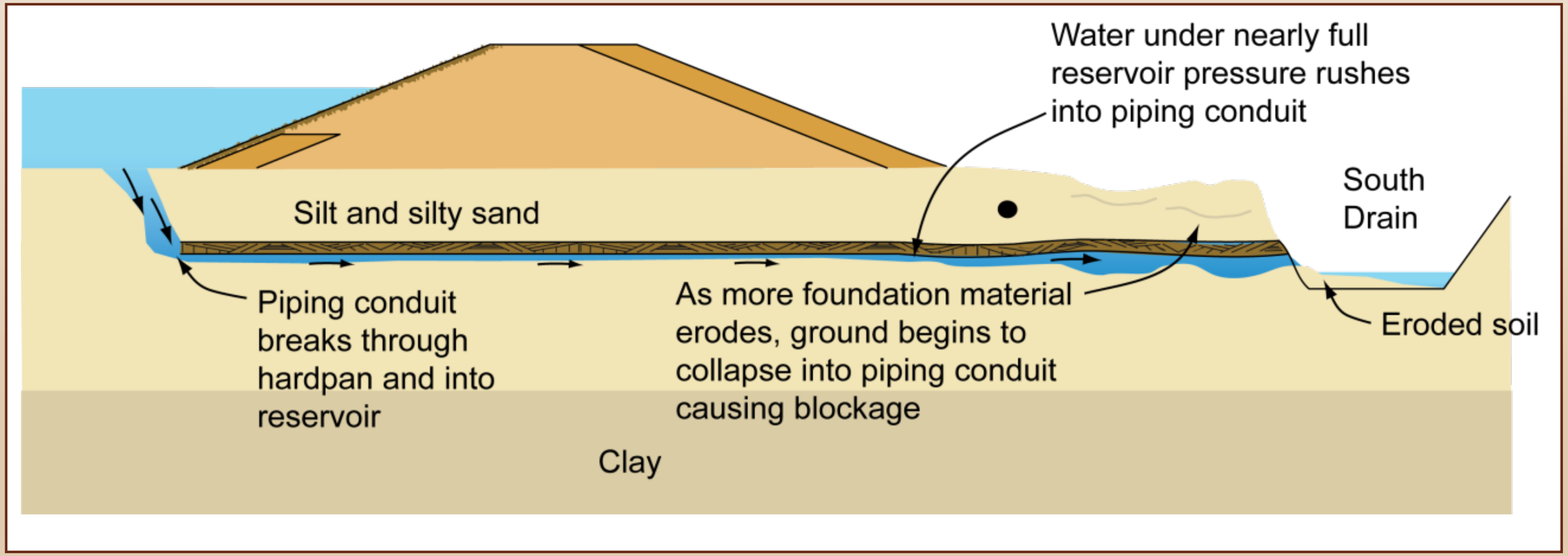
- Internal erosion potential failure modes can be categorized into general categories related to the physical location of the internal erosion pathway:
  - Internal erosion through the embankment
  - Internal erosion through the foundation
  - Internal erosion of the embankment into or at the foundation (including along the embankment/foundation contact)
  - Internal erosion into/along embedded structures such as conduits or spillway walls
  - Internal erosion into drains
- These are *not* potential failure mode descriptions

Backward Erosion Piping



Backward Erosion Piping (BEP) Through the Foundation (w/o Blanket over exit) A.V. Watkins Dam

- Example of backward erosion piping in foundation sands beneath a caliche roof to an unfiltered exit.
- Horizontal global gradient is important in this case typical of levees as well
- Embankment would have likely failed without intervention efforts both at the downstream toe and the upstream face.

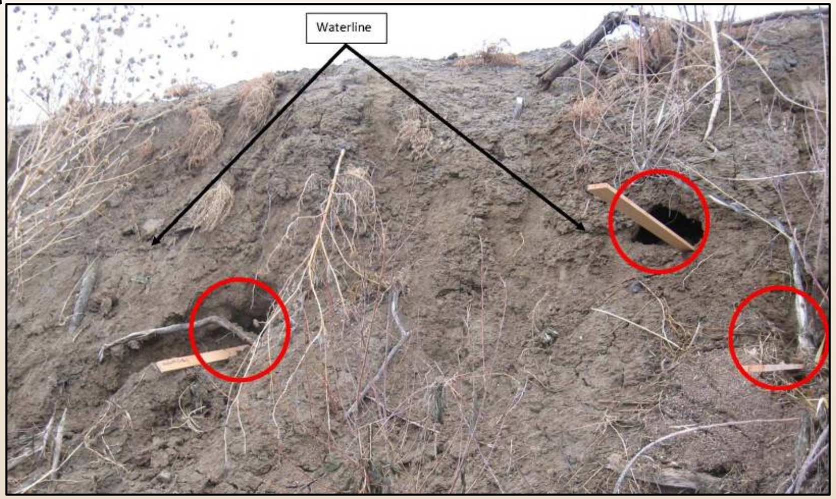


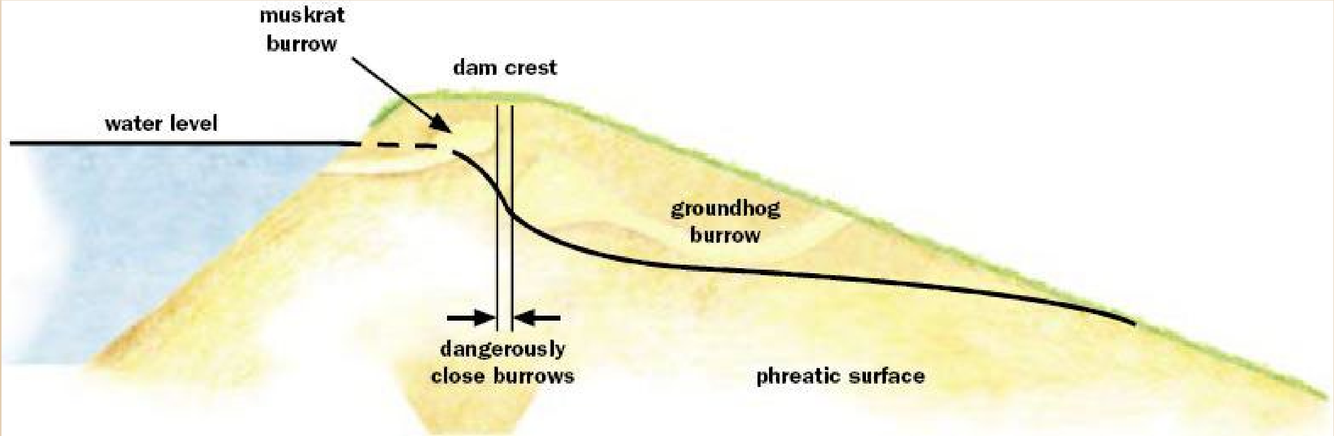
BEP Through the Foundation (w/ Blanket over exit) Ensley Levee

- USACE levee near Memphis, Tennessee
- 300-ft long seepage berm added in 1990 consisting of bottom/fly ash
- During spring 2011 “epic” Mississippi River flooding, ±30 sand cones observed (2.5 feet tall and 10 feet in diameter)
- Flood fighting was successful
- Several pipe collapses identified in early 2012

BEP Through the Embankment

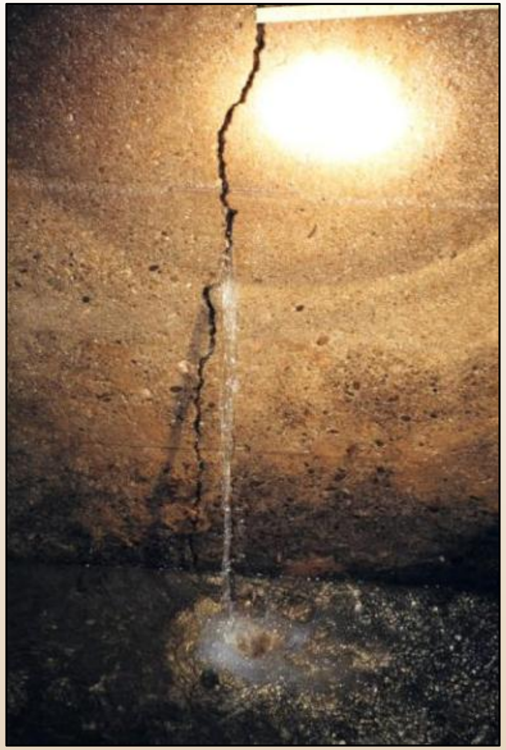
- Potential for Rodent Hole (canal for example)
- Reclamation Canal in Nevada, failed in 2008
- Forensic investigations – muskrat burrows

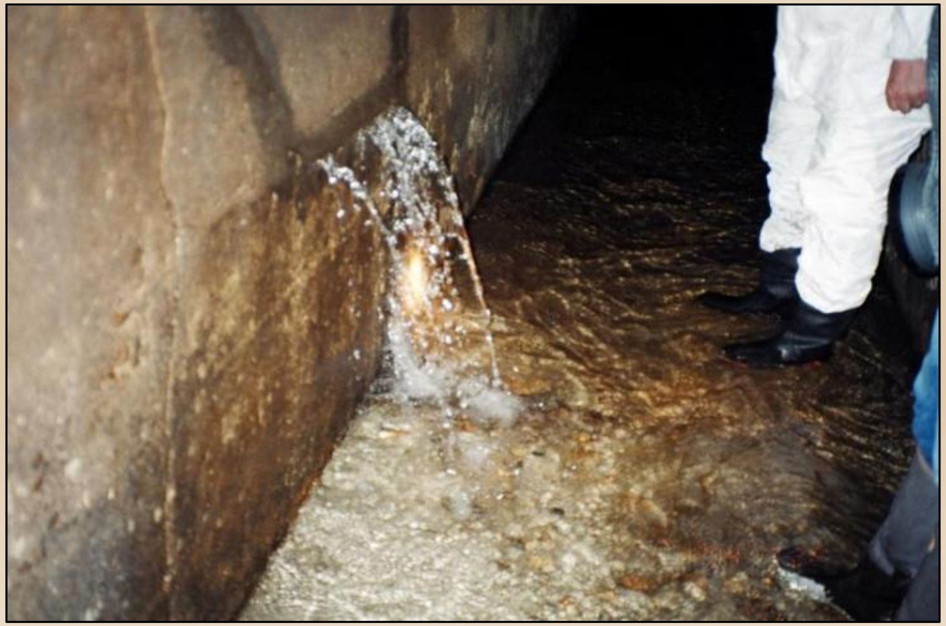




BEP Into and Along Conduits
Deer Flat Dam (Caldwell Canal O/W)

- Reclamation dam in Idaho
- Required emergency actions in 2006 after 94 years of operation
- Seepage transported embankment materials into conduit through cracks
- Significant voids found under much of conduit length
- Case of internal erosion into/along conduit





Into Drains

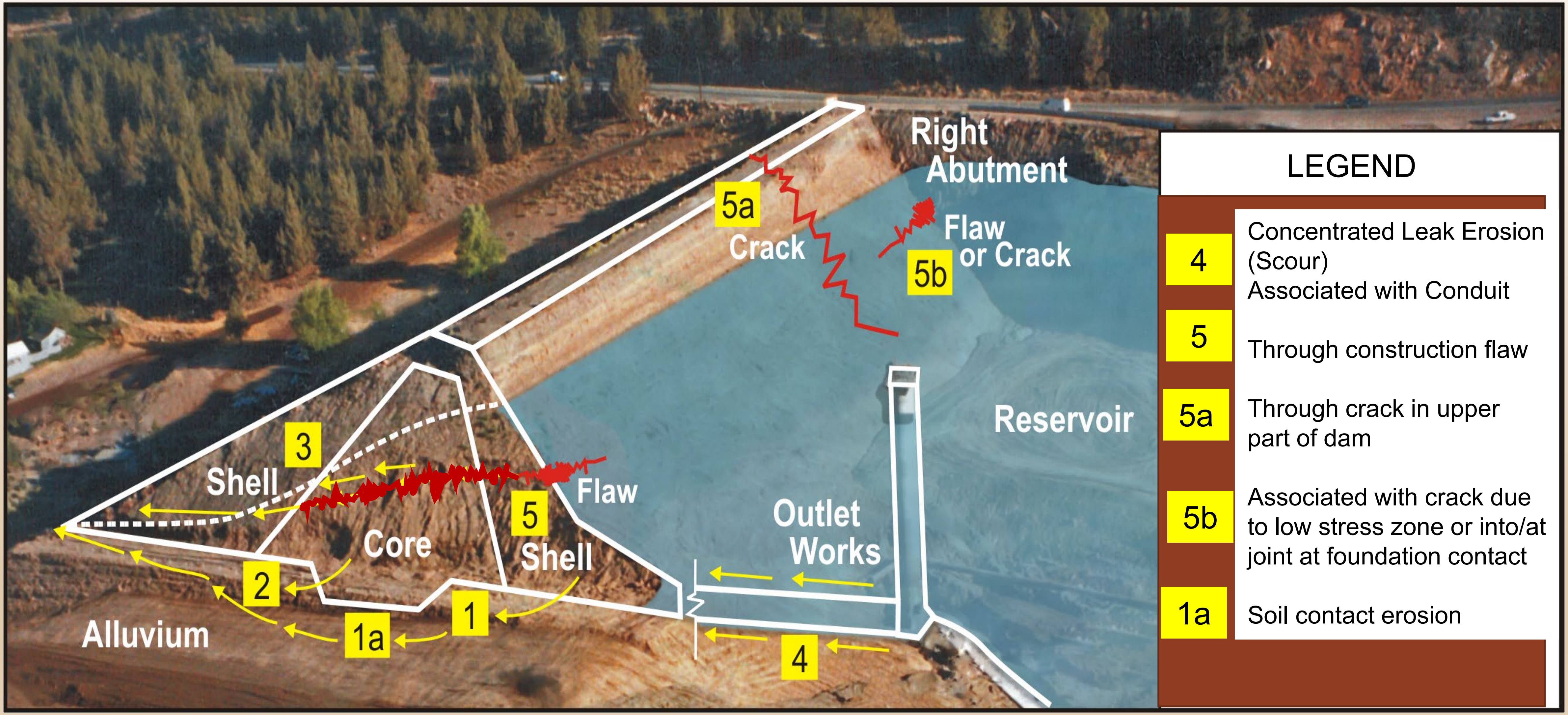
- Toe drains
- Structure underdrains

Can lead to BEP but internal migration and sinkholes are most common

Typically associated with incident as opposed to failure

Photo 1 – Sinkhole on 9/27/2007 showing settlement of sand which was placed in hole in May 2007.

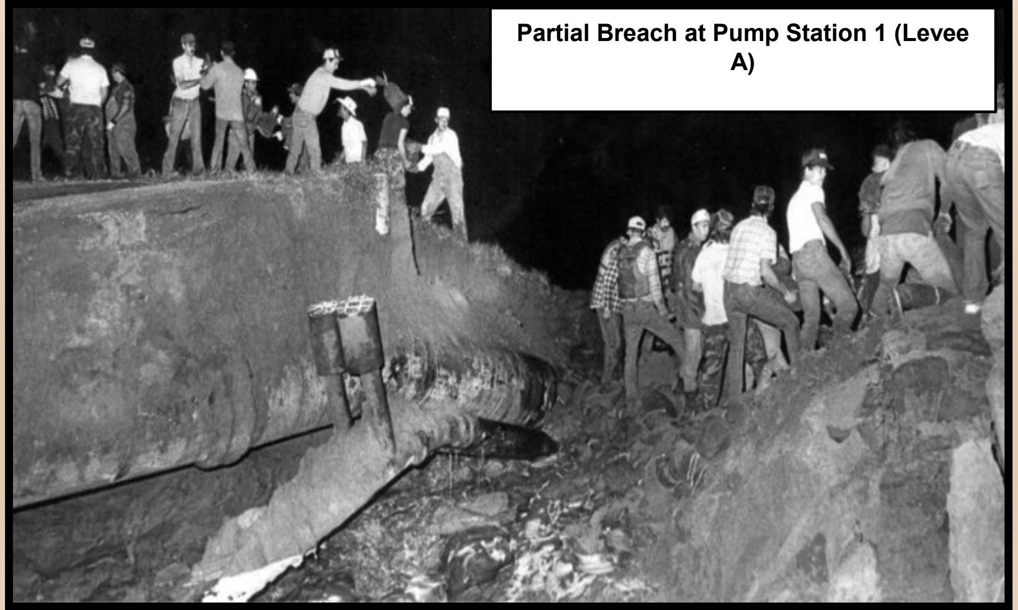
Scour/Concentrated Leak Erosion



Scour/CLE along Conduit

- Tulsa-West Tulsa Levee loaded approx. 80% in Oct 1986.
- CLE along steel pump station outlet pipes.
- Levee partially breached in vicinity of pump station.
- Flood fighting included temporary dike to seal breach and prevent catastrophic flooding
- Flaw likely due to poor compaction along and under pipes. Multiple pipes!

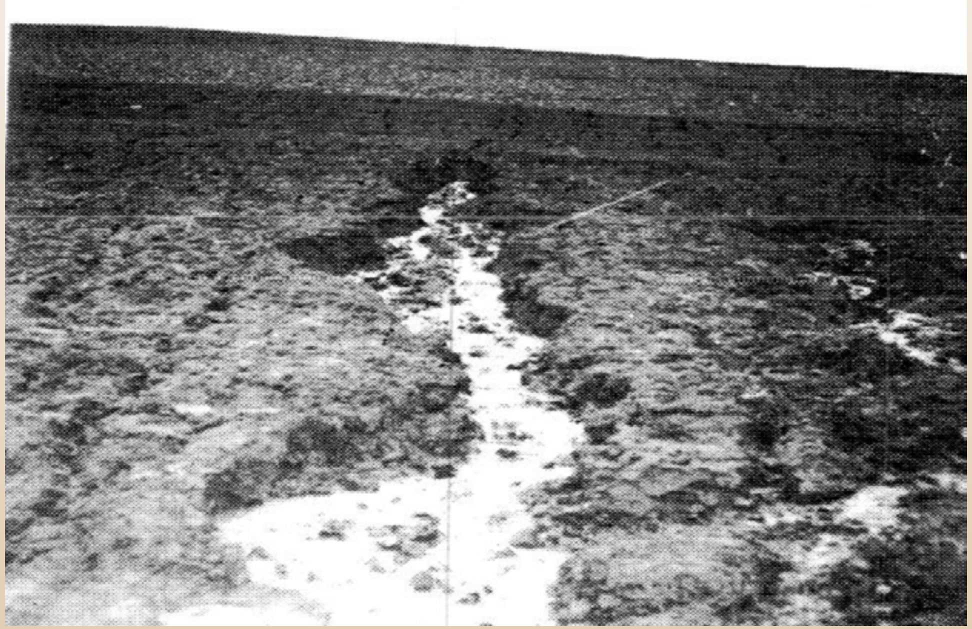
Backflow out of manhole just before breach (Levee A)

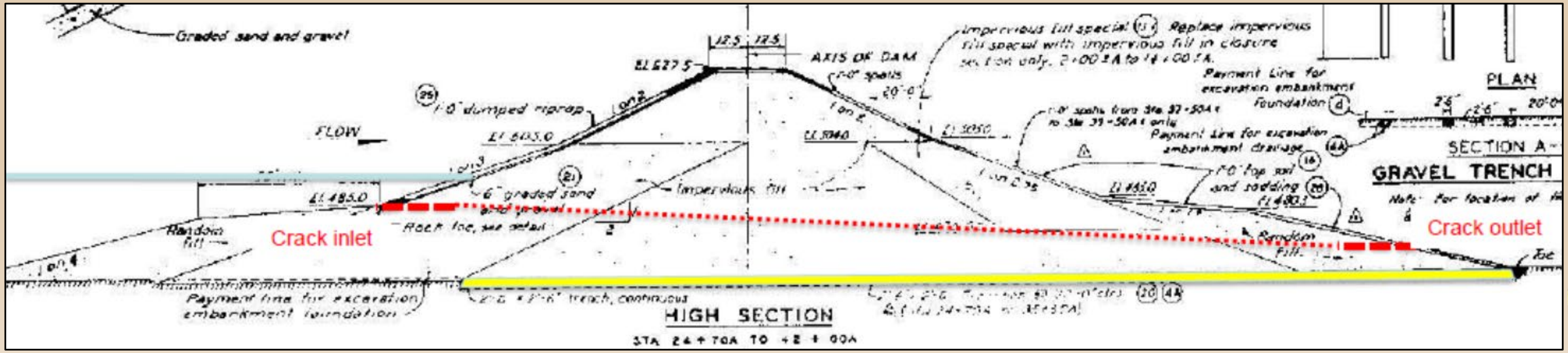


Partial Breach at Pump Station 1 (Levee A)

Scour/CLE Through the Embankment (Differential Foundation Settlement) Wister Dam

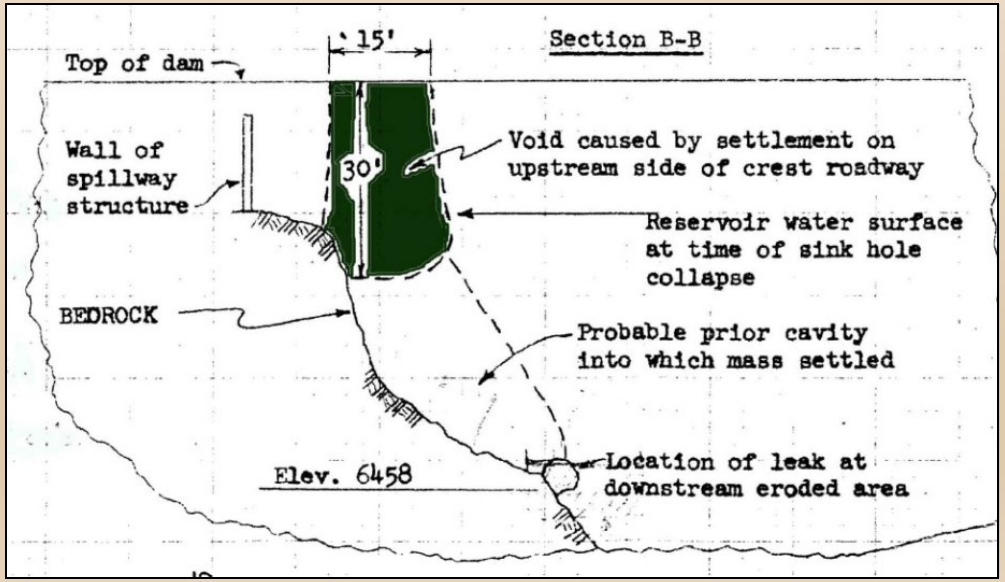
- USACE dam in Oklahoma
- Experienced serious concentrated leak erosion in 1949 during initial filling
- Muddy leakage emanated from downstream face (under a gradient of only 0.02)
- Believe to be a result of cracking due to differential settlement of foundation
- Case of internal erosion through the embankment





Fontenelle Dam – Scour/CLE of Embankment into or at the Foundation

- Incident attributed to internal erosion of embankment into/along foundation
- Zoned earthfill dam with low plasticity core, founded on jointed (stress relief) bedrock
- Dam may well have failed if not for ability to lower pool level.

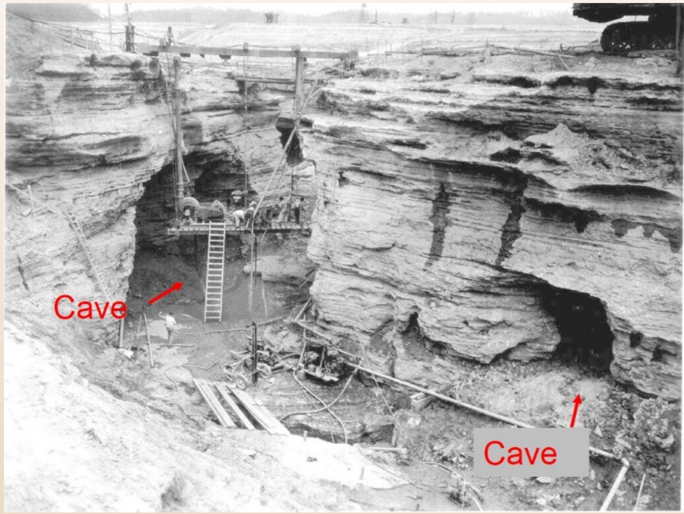


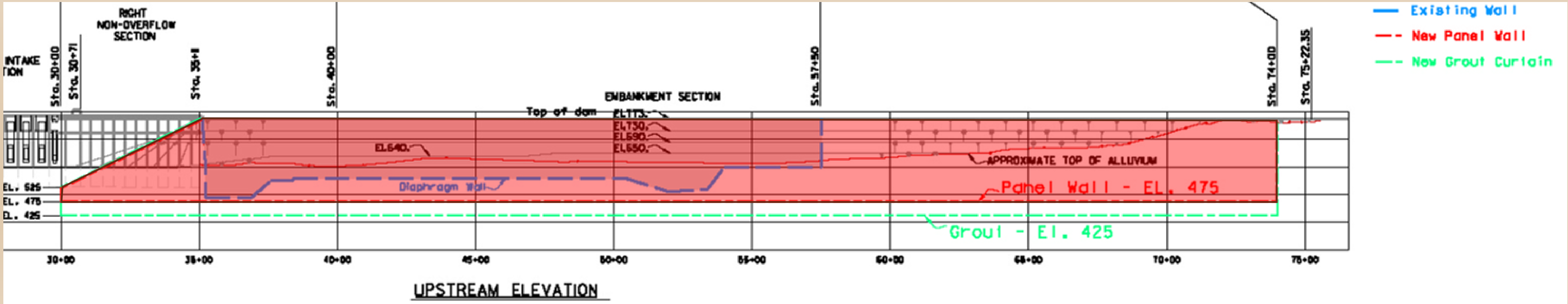
Quail Creek Dike - Scour/CLE of Embankment into or at the Foundation

- Washington County (Utah) Water Conservancy District
- Failed in 1989 after 4 to 5 years of operation and multiple
- 80-foot high dike; reservoir release of 25,000 ac-ft
- No fatalities but $12 million in damages
- Due to Scour/CLE of embankment into or at the foundation

Wolf Creek Dam - Scour/CLE of Embankment into or at the Karst Foundation

- USACE dam in KY. Nashville Dist. Constructed in 1941 to 51 on karst. 140-foot high homogeneous embankment approx. 1 mile long. Poor foundation treatment. Reservoir approx. 4,000,000 ac-ft
- 1rst incidents - sinkholes, muddy flow and wet areas observed in1960's. Treated with emergency grouting and a limited albeit cutting edge cutoff wall finalized in the 70's.
- Signs of distress since the 70's lead to more a comprehensive cutoff wall and grouting effort that was completed in 2013.





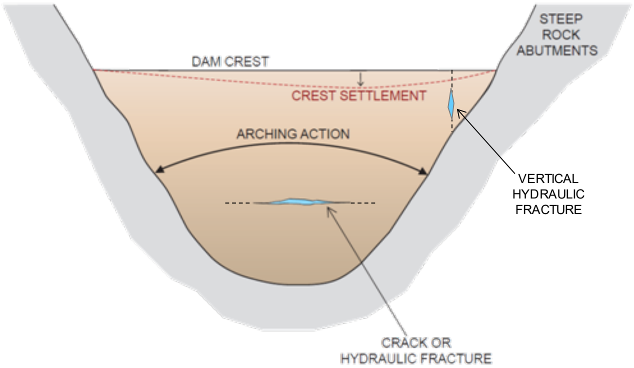
Overview of Event Trees to Represent Internal Erosion Potential Failure Modes

Typical Event Tree for Risk Analysis (Reclamation)

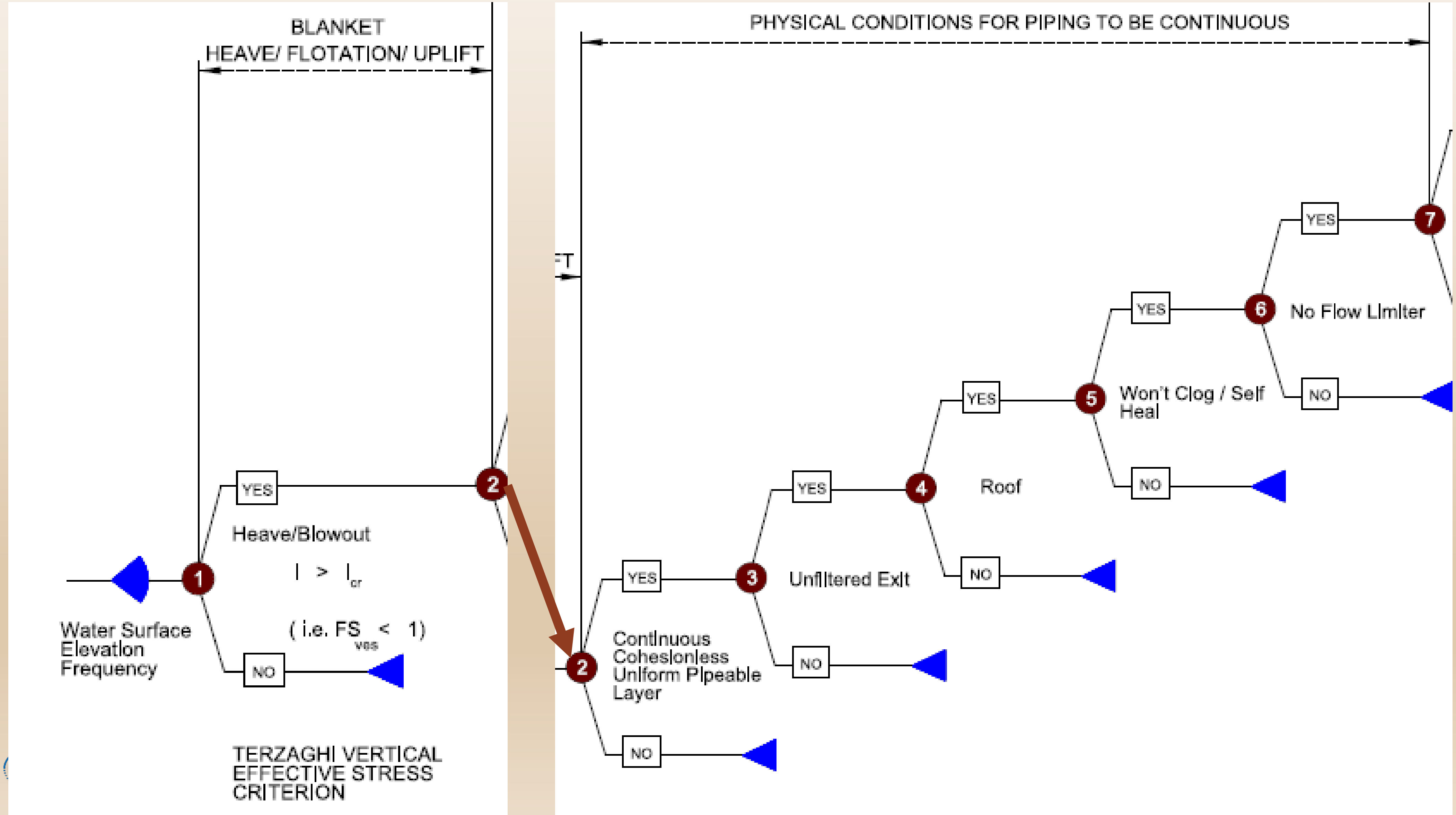
- Reservoir at or above threshold level
  - Initiation – Erosion starts
    - Continuation – Unfiltered or inadequately filtered exit exists
      - Progression – Continuous stable roof and/or sidewalls
        - Progression – Constriction or upstream zone fails to limit flows
          - Progression – No self-healing by upstream zone
            - Unsuccessful detection and intervention
              - Dam breaches (uncontrolled release of reservoir)

USACE

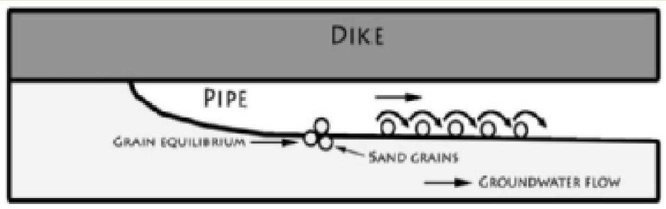
- Flaw exists – Continuous crack, high permeability zone, zones subject to hydraulic fracture, etc.

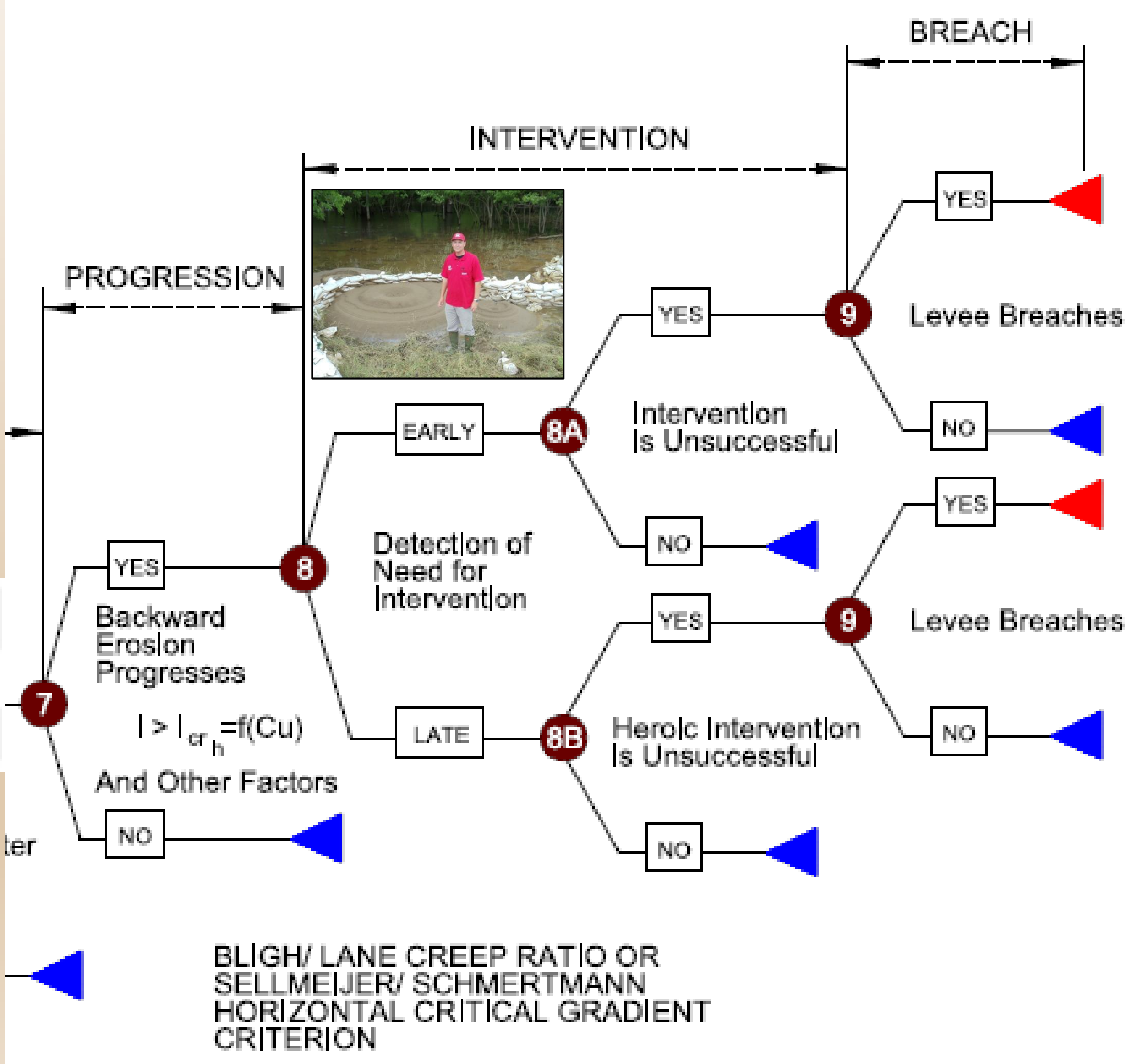


Backward Erosion Piping Due to Levee Underseepage



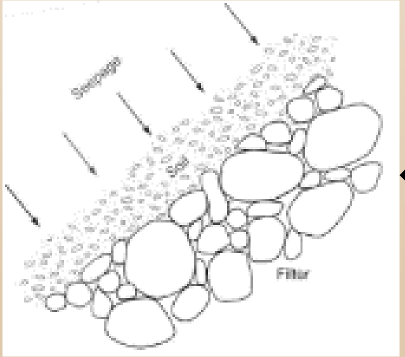
Backward Erosion Piping Due to Levee Underseepage

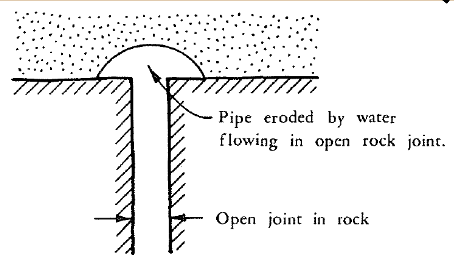




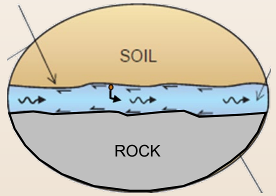
Scour/CLE of the Embankment into or at the Foundation

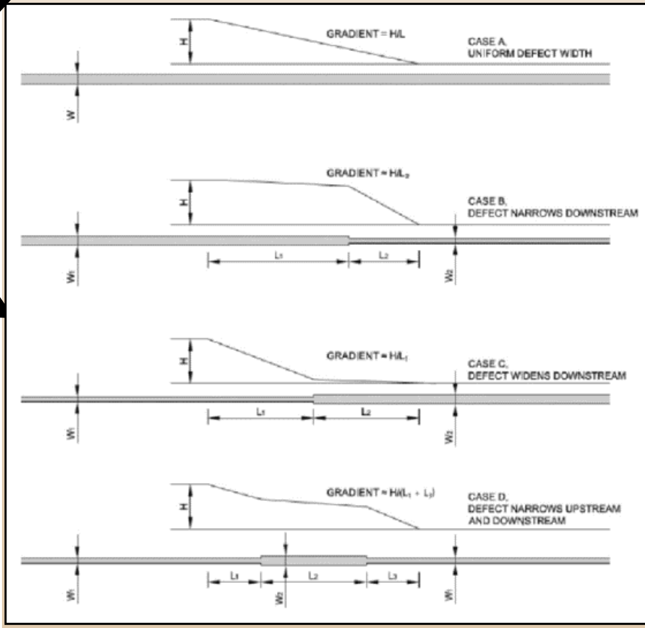
Dental concrete, slush-grout, concrete bulkheads, etc.

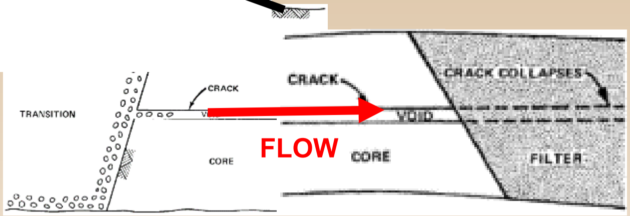




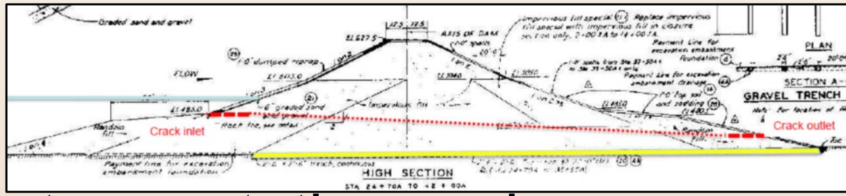
- Loading (at or above threshold level)
  - Flaw exists –, continuous crack, high permeability zone, zones subject to hydraulic fracture, etc.
  - Flaw exists – Foundation treatment is ineffective
    - Initiation – Sufficient Gradient exists to initiate Scour/CLE into or at the foundation
    - Continuation – Unfiltered or inadequately filtered exit exists
      - Progression – Leakage pathway fails to clog
        - Progression – Continuous stable roof and/or sidewalls Constriction or upstream zone fails to limit flows
          - Progression – No self-healing by upstream zone
            - Unsuccessful detection and intervention
              - Embankment breaches (uncontrolled release of impounded water)







Assemble Available Background Information and Perform Supporting Evaluations



- Develop/gather large format drawings
  - Prefer drawings that show geology, dam zoning, instrumentation and historical location of seepage as well as response of instruments.
- Partition loadings
- Data on construction and material properties
- Data on performance (including both visual and instrumentation and construction photo’s)
- Identify and perform (when needed) supporting evaluations and info needed to develop “more likely” and “less likely” factors for key events

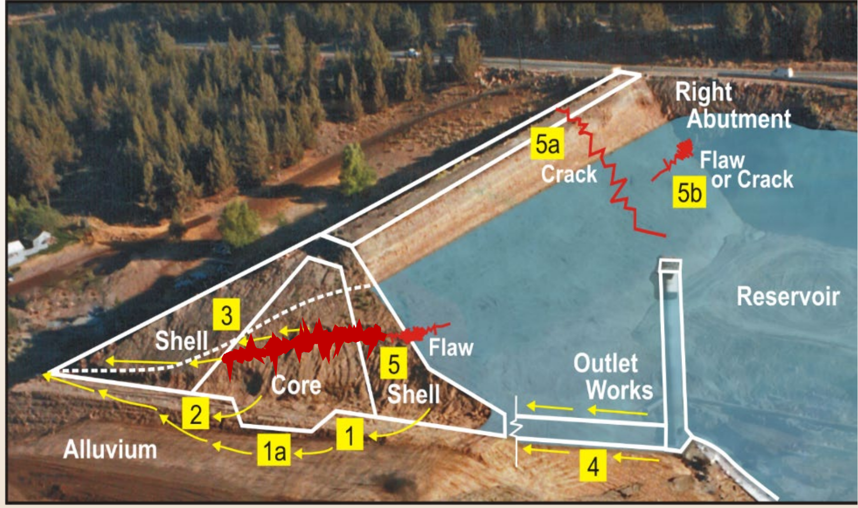
Potential Supporting Evaluations

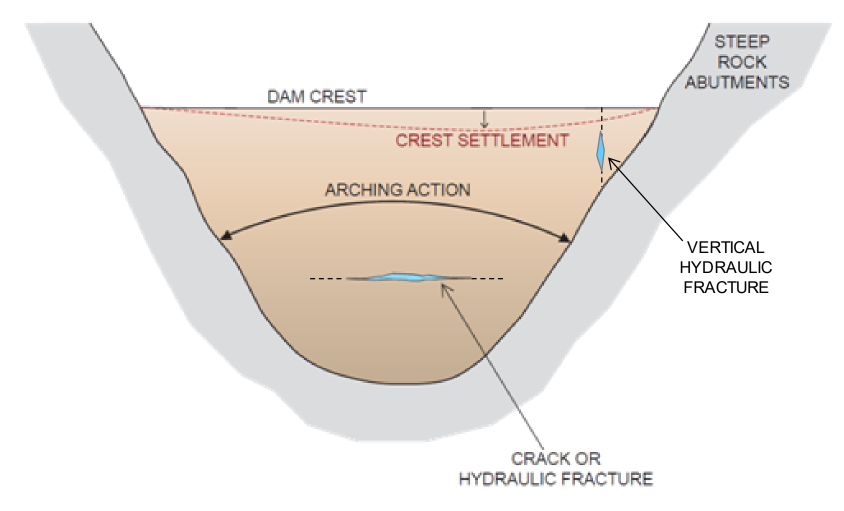
- Instrumentation and monitoring trends
- Review pertinent case histories
- Typical analyses include:
  - Filter compatibility
- Analyses utilized in some situations:
  - Seepage analysis
  - Uplift stability
  - Critical gradient for initiation and progression

Reservoir/River Rises to Critical Level

- The potential for internal erosion is related to the water level behind an embankment or levee.
- This initial event is important as it can play a role in several phases of an internal erosion process, including initiation, progression, intervention, and breach.
- Typically, the probability of a given reservoir elevation is determined through the use of reservoir exceedance curves, which are discussed in another portion of this Best Practices class.

Flaw

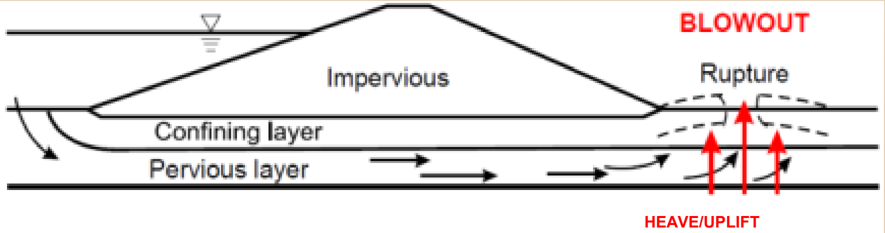


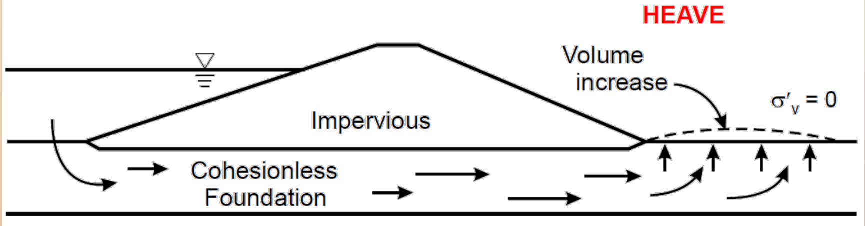


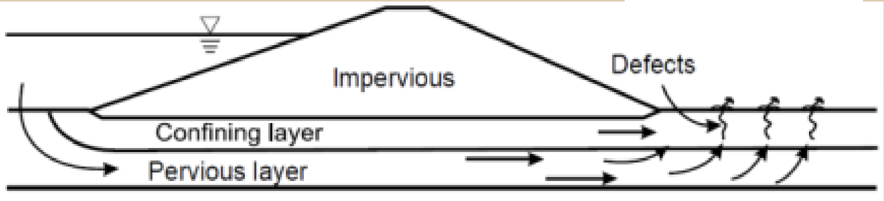
- In soil foundation
  - W/blanket
  - W/O blanket
- Penetrating structures
- In embankment
  - Built in
  - Caused by deformation
- At foundation contact
  - With bedrock – open, continuous joints and bedding planes across contact
    - Large capacity features in rock (e.g., caves) may have started as joints/planes
  - With soil – openwork materials

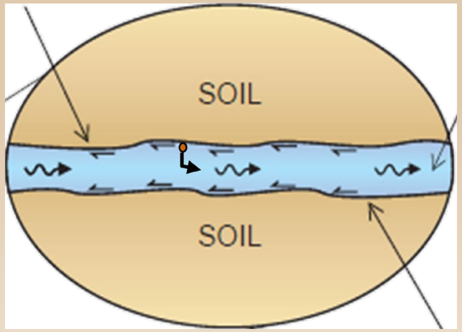
Erosion Initiates

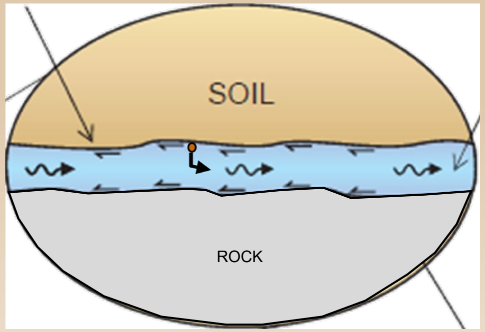
- This is typically considered the key event in the failure mode sequence and also probably the most difficult one to estimate.
- It essentially represents the probability that erosion will initiate (i.e., the first grains will start to move)
  - In a given year (Reclamation)
  - Given the loading and a flaw exists (USACE)











Erosion Initiates – Key Factors

- Soil erodibility/material properties
- Hydraulic conditions
- Stress conditions and associated defects
  - Arching
  - Differential settlement
  - Hydraulic fracturing
- Foundation defects
- Embankment defects
- Penetrating structures

Estimating the Probability of Initiation

- Reclamation relies primarily on the use of historical "base rate frequencies" developed from the number of incidents observed from the nearly 15,000 dam-years of operation.
- USACE looks at a variety of studies, research, and analyses to gain an understanding of the potential for a flaw and the potential for internal erosion to initiate for the given conditions at the dam being evaluated, as well as considers base rates where they apply.

Initiation – Use of historical Rates

USBR - Proposed Best Estimate Values of Annual Probabilities of Initiation by Category/Location

Category of internal erosion	Range of initiation probability
Embankment only	$4x10^{-4}$ to $1x10^{-3}$
Foundation only	$2x10^{-3}$ to $6x10^{-3}$
Embankment into foundation	$2x10^{-4}$ to $7x10^{-4}$
Into/Along conduit	$1x10^{-3}$ to $2x10^{-3}$
Into drain	$1x10^{-3}$ to $2x10^{-3}$

Initiation – Use of historical Rates

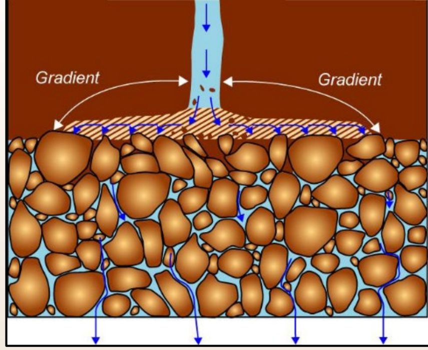
USBR - Proposed Best Estimate Values of Annual Probabilities of Initiation by Mechanism

Type of internal erosion	Range of initiation probability
Backward erosion piping	$1x10^{-3}$ to $3x10^{-3}$
Internal Migration	$2x10^{-3}$ to $4x10^{-3}$
Scour	$2x10^{-3}$ to $4x10^{-3}$
Suffusion/suffosion	$8x10^{-4}$ to $2x10^{-3}$

Initiation

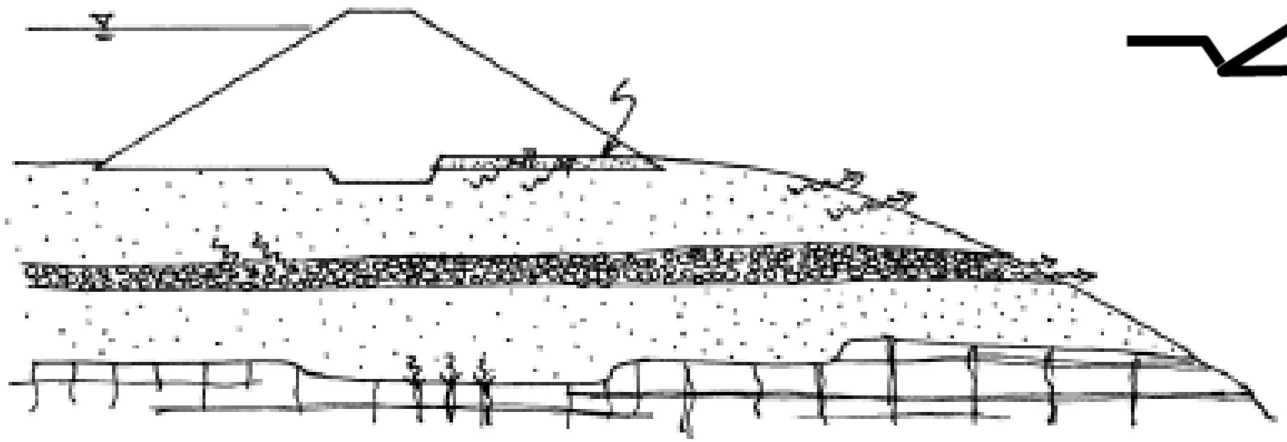
- See Chapter and appendix - Consider applicable studies, research, and analyses to gain an understanding of the potential that internal erosion may initiate for the given conditions at the dam being evaluated, as well as historical rates where applicable.
- Eroding Forces $\geq$ Resisting Forces = Initiation
- Concentrated leak erosion
  - Evaluate estimated shear stresses applied versus critical
- Backward Erosion Piping (w/blanket, w/out blanket)
  - With blanket – first evaluate uplift resulting in free exit
  - Without blanket - Evaluate estimated exit gradient versus critical
  - Estimate critical gradient for progression of the pipe
- Soil Contact Erosion and Suffusion (Can lead to other mechanisms)

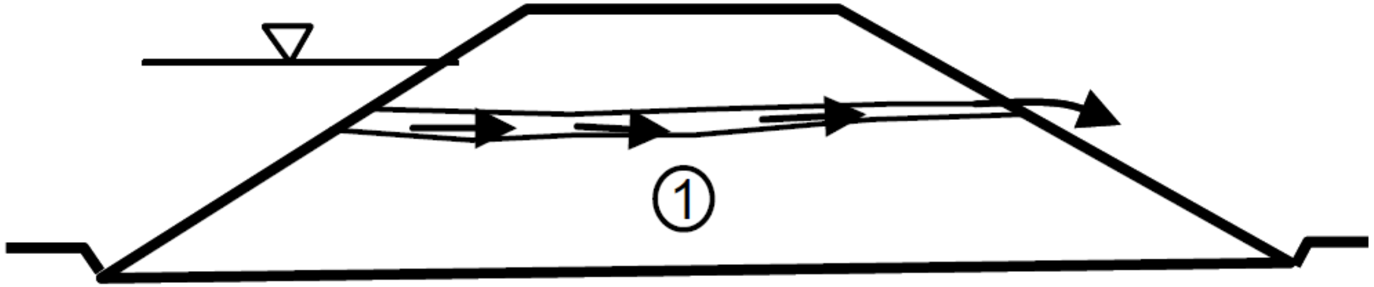
Continuation

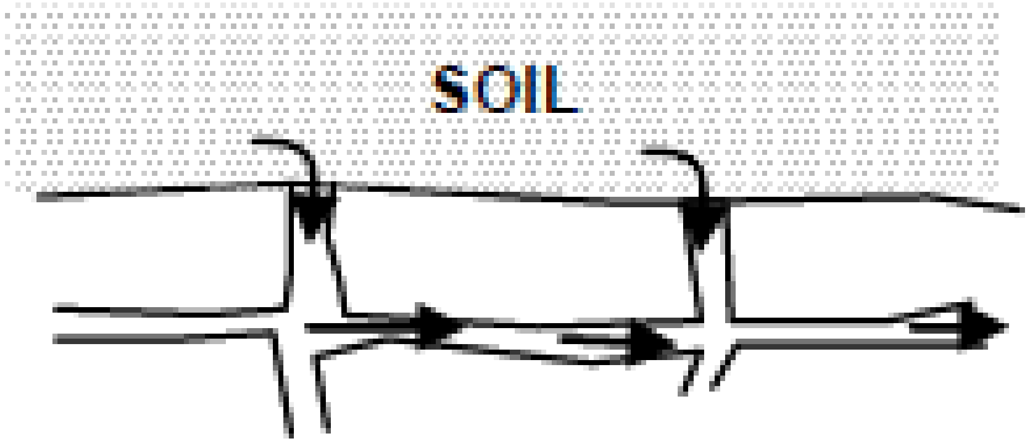


- An open, unfiltered, or inadequately filtered exit (or repository) allows erosion of the embankment or foundation materials to continue.
- Foster and Fell used to evaluate zones that do not meet modern filter criteria but may still provide a defense.
- When considering the potential for continuation at a particular dam, the downstream embankment zones and foundation materials are evaluated to assess their ability to provide filtering.

Typical Unfiltered Exit Locations



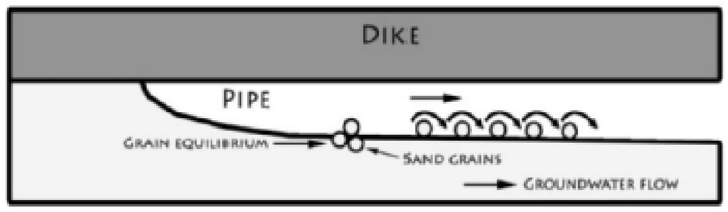




Continuation: Unfiltered Exit Other Considerations

- Filter width
- Internal instability
- Segregation
- Cohesion and cementation
- Compaction

Progression

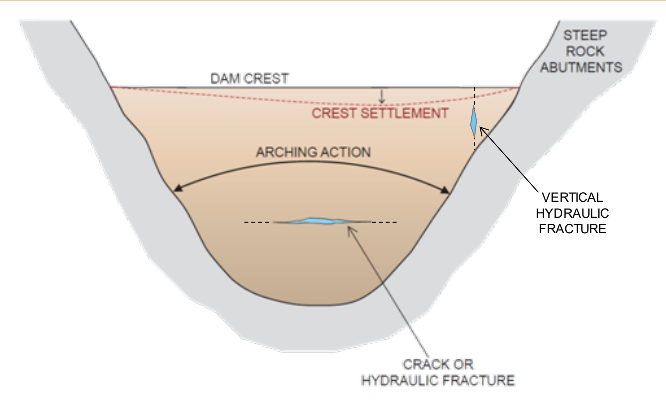


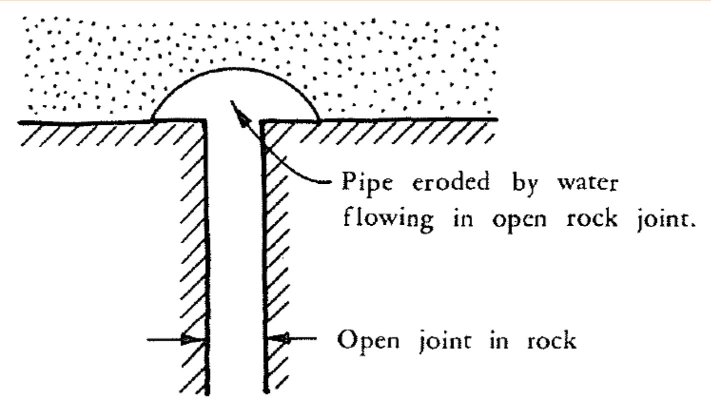
- Continuous stable roof and/or sidewalls
  - Considers if collapse will prevent a pipe or tunnel from forming
- Constriction or upstream zone fails to limit flows
  - Considers upstream zone or flow constriction at any point along the path that could arrest erosion
- No self-healing by upstream zone
  - Considers if an upstream granular zone will enter the pipe and arrest erosion.

-These three progression events do not necessarily occur in a linear progression (e.g., roof could be initially stable, but collapses when the pipe enlarges after flow limiting was unsuccessful).
-Not all may occur

Continuous Stable Roof/Sidewalls

- Primary consideration is whether a continuous hard layer or stiff zone exists in the embankment or foundation above the eroding materials under consideration.
  - Concrete structures such as conduits, spillways or walls can serve as a roof.
  - Hardpan, caliche, basalt, or stiff clay in the foundation can serve as a roof.
  - Absent a continuous structure or hard layer, the ability to sustain a roof depends mainly on soil properties of the eroding soil (core or foundation).





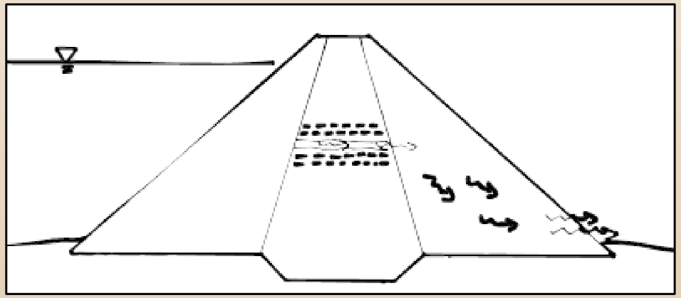
Constriction or Upstream Zone Fails to Limit Flows

- Considers upstream zone or flow constriction at any point along the path that could prevent further progression of erosion
- Flow limitation can potentially result in an equilibrium between flow velocity (forces tending to erode the soil) and the ability of the soil to withstand the erosion, so the erosion process could stabilize. Expressed another way,

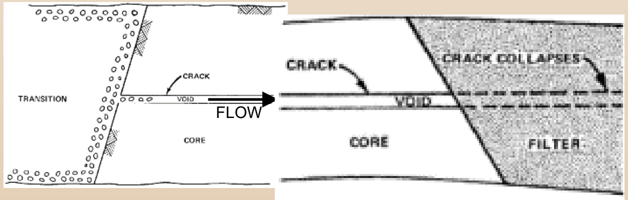
$$\text{Eroding Forces} \leq \text{Resisting Forces} = \text{Progression Stops}$$

No Self-healing by Upstream Zone

- Are upstream zone materials capable of being transported to a downstream zone or constriction (such as a bedrock joint) where a filter could form sufficient to prevent further erosion of the core?



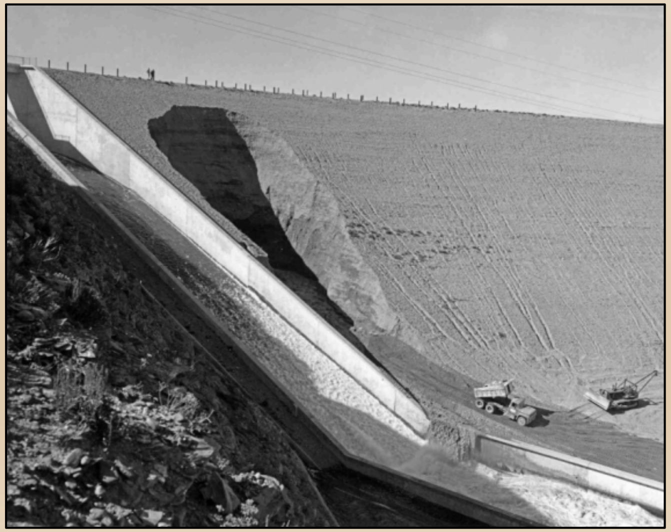
No benefit to this event if no downstream zone or constriction exists



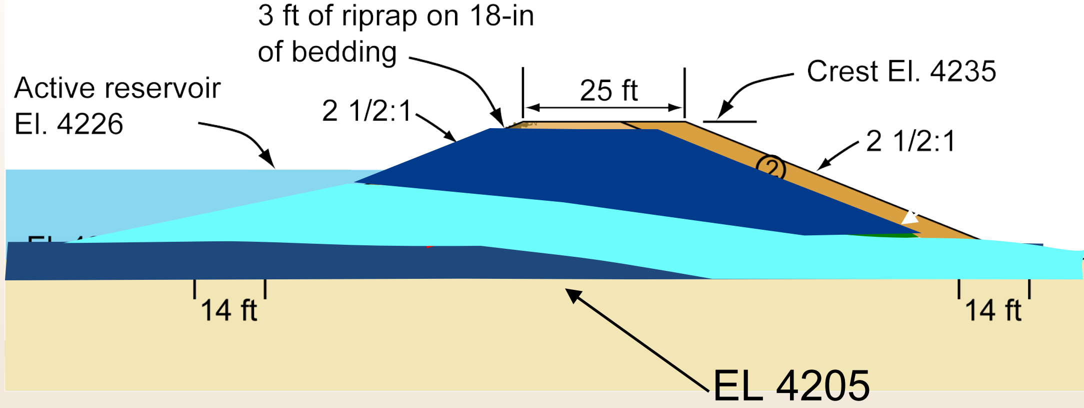
- Favorable characteristics of upstream zone:
  - Coarse, clean, cohesionless upstream materials with wide range of particles sizes
  - Large volume of upstream materials
  - Presence of a downstream zone that can provide a “stop” for the upstream materials that are carried through the core

Unsuccessful Detection and Intervention

- Unsuccessful Detection: Whether, or when, a developing failure mechanism would be observed and recognized as a problem
- Inability to successfully intervene: Can mitigating efforts be implemented in time to stop or slow the failure process to the point where dam breach does not occur?



Breach Initiates



Internal Erosion along the Outlet Works Conduit Example

- Gross enlargement of a pipe or concentrated leak followed by collapse of the embankment, loss of freeboard, and overtopping is most common mechanism for internal erosion failure modes.
- Sloughing or unraveling of the downstream slope due to high seepage flows resulting in an over-steepened slope that progressively works toward the reservoir
- Sinkhole development sufficiently large to drop the crest below reservoir level or disrupt it enough so that it can no longer retain the reservoir
- Slope instability resulting from increased foundation or embankment pore pressures caused by internal erosion

Develop “More Likely” and “Less Likely” Factors for Each Event

- A number of methods, tests, and tools are available to assist in evaluating the likelihood of each event of internal erosion in the Best Practices chapter on Internal Erosion
- Results from analyses typically result in more or less likely factors.
- Risk estimating teams are encouraged to use the 11x17 tables of “more likely” and “less likely” factors included in the Best Practices Chapter.
- These tables provide a number of factors that make each step of the internal erosion process more likely or less likely to occur.
- The tables represent a compilation of the findings and judgment from many researchers, as well as findings from empirical cases related to the development of each phase of internal erosion.

Use of 11x17 Tables

- Risk estimating teams are encouraged to use the table of “more likely” and “less likely” factors included in the Best Practices Chapter.
- These tables provide a number of factors that make each step of the internal erosion process more likely or less likely to occur.
- The tables represent a compilation of the findings and judgment from many researchers, as well as findings from empirical cases related to the development of each phase of internal erosion.

Estimate the Probabilities for Each Event

- Utilize the best available and multiple methods, but all final probabilities are estimated using team elicitation procedures based upon the totality and strength of the evidence.
- The risk team discusses the factors and other factors that were identified and decides which should receive the most weight.
- These in combination with observations and the experience of the risk team provide the evidence against which the probability estimates are made.
- A range of reasonable estimates would then be made, and the "case" or evidence for why the estimates make sense would be described. (See Chapter A-6 Subjective Prob.)

Comments or Questions?

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