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Managing Water in the West

Internal Erosion

Dam Safety Risk Analysis Best Practices

Last Modified by Reclamation 4/7/2010

U.S. Department of the Interior
Bureau of Reclamation

Presentation Taken From One Developed for Reclamation Best Practices

- This is a slightly modified version and is not meant to fully represent how Reclamation would teach Best Practices for Internal Erosion

- The presentation is to provide an introduction to important concepts that Reclamation has developed over many years

Internal Erosion in Embankments and Foundations

- One of the leading causes of failure of embankment dams has been internal erosion, or “piping”

- Because internal erosion can occur due to normal operations, it may pose higher risks to a dam than remote loading conditions like floods and earthquakes

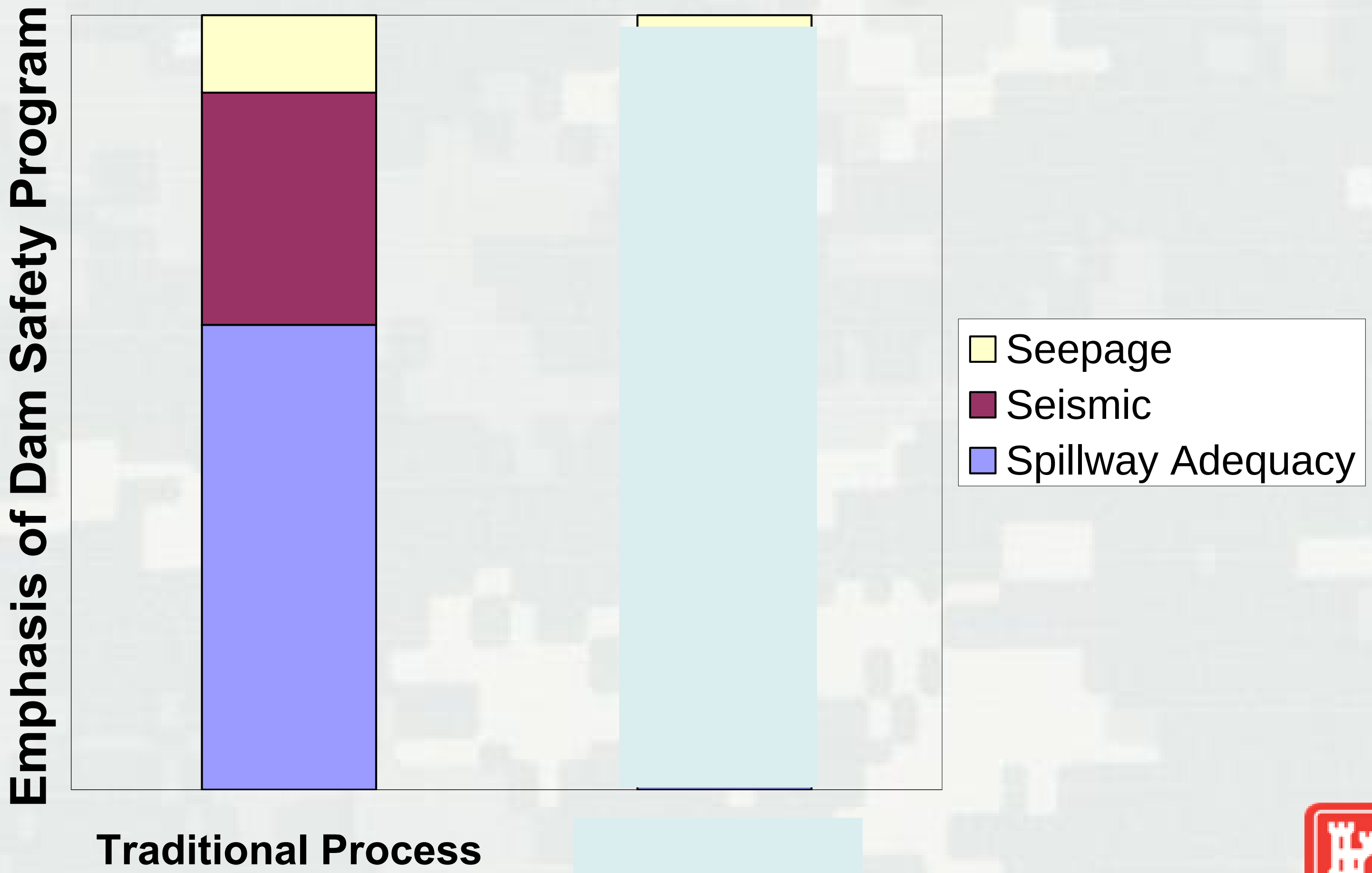
Mode of Failure	% Total Failures (where mode of failure known)	% Failures pre 1950	% Failures post 1950
Overtopping	34.2 %	36.2 %	32.2 %
Spillway/gate (appurtenant works)	12.8 %	17.2 %	8.5 %
Piping through embankment	32.5 %	29.3 %	35.5 %
Piping from embankment into foundation	1.7 %	0 %	3.4 %
Piping through foundation	15.4 %	15.5 %	15.3 %
Downstream slide	3.4 %	6.9 %	0 %
Upstream slide	0.9 %	0 %	1.7 %
Earthquake	1.7 %	0 %	3.4 %
Totals (3)	102.6 %	105.1 %	100 %
Total overtopping and appurtenant works	48.4 %	53.4 %	40.7 %
Total piping	46.9 %	43.1 %	54.2 %
Total slides	5.5 %	6.9 %	1.6 %
Total no. of embankment dam failures (exc. During construction)	124	61	63
Total embankment dam years operation (up to 1986)	300,400	71,000	229,400
Annual probability of failure	4.1×10^{-4}	8.6×10^{-4}	2.7×10^{-4}

From UNSW

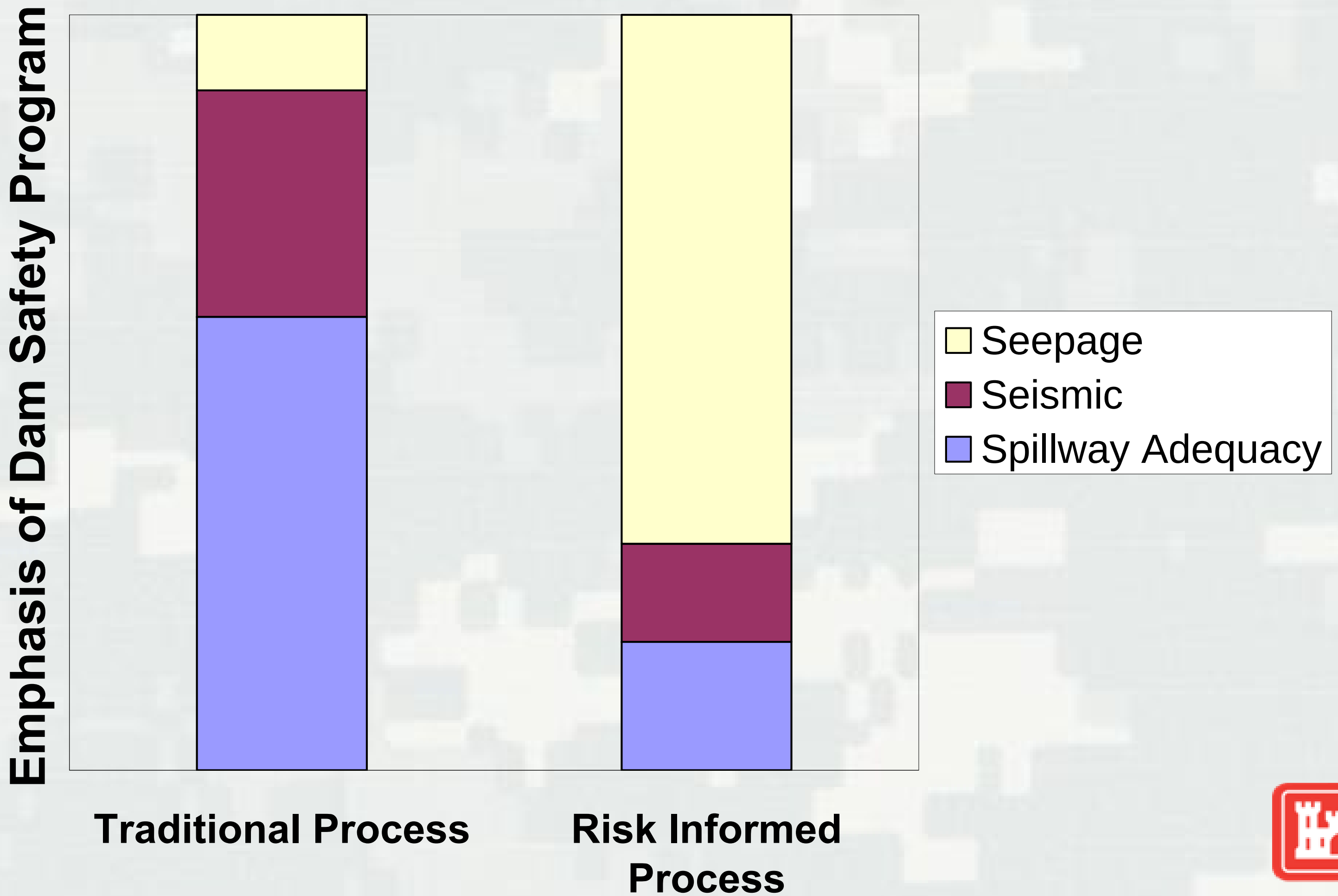
Percent Failures by Type of Failure United States Earth Dams

Height	Category	Overtop	Found.	Piping	Sliding	Structural	Spillway	E.Q.
All Dams	Eastern	42	12	23	4	8	11	0
	Western	45	5	34	3	9	1	3
Dams > 15 m	Eastern	20	16	20	12	16	16	0
	Western	20	0	60	8	4	0	0
Dams < 15 m	Eastern	46	11.5	23.5	2.5	6.5	10	0
	Western	57	4	21	0	12	2	4

Change in Dam Safety Focus



Change in Dam Safety Focus



Types of Internal Erosion Problems

- Classical Piping (“roofing”)
- Progressive Erosion
- Blowout (heave, uplift)
- Scour
- Suffusion (internal instability)

Piping

- Subsurface erosion conveyed through an open “pipe” in soil under a roof of natural or manmade materials.
- Required Conditions
  - Flow path/source of water
  - Unprotected exit
  - Erodible material in flow path
  - Material to support a roof is present

Progressive Erosion

- Particles removed to form a temporary void, the void grows until a roof is no longer stable and material collapses into the void, temporarily stopping pipe development. Failure results when mechanism repeats itself until the core is breached or downstream slope is over-steepened to the point of instability.

Uplift, Blowout, Heave

- Result of excessive uplift pressures
- Usually occurs near an overlying impervious boundary at d/s toe
- Blowout = breach of the impervious boundary
- Can lead to instability
- Can be the initiating event for a piping mechanism
- Typically occurs upon first filling or when reservoir reaches historic high

Scour

- Failure as the result of loss of material from an erosional surface (crack through a dam, dam/foundation contact, downstream toe).
- Could be rapid, or prolonged and gradual.
- Erosion results in loss of reservoir through the eroded area.

Suffusion

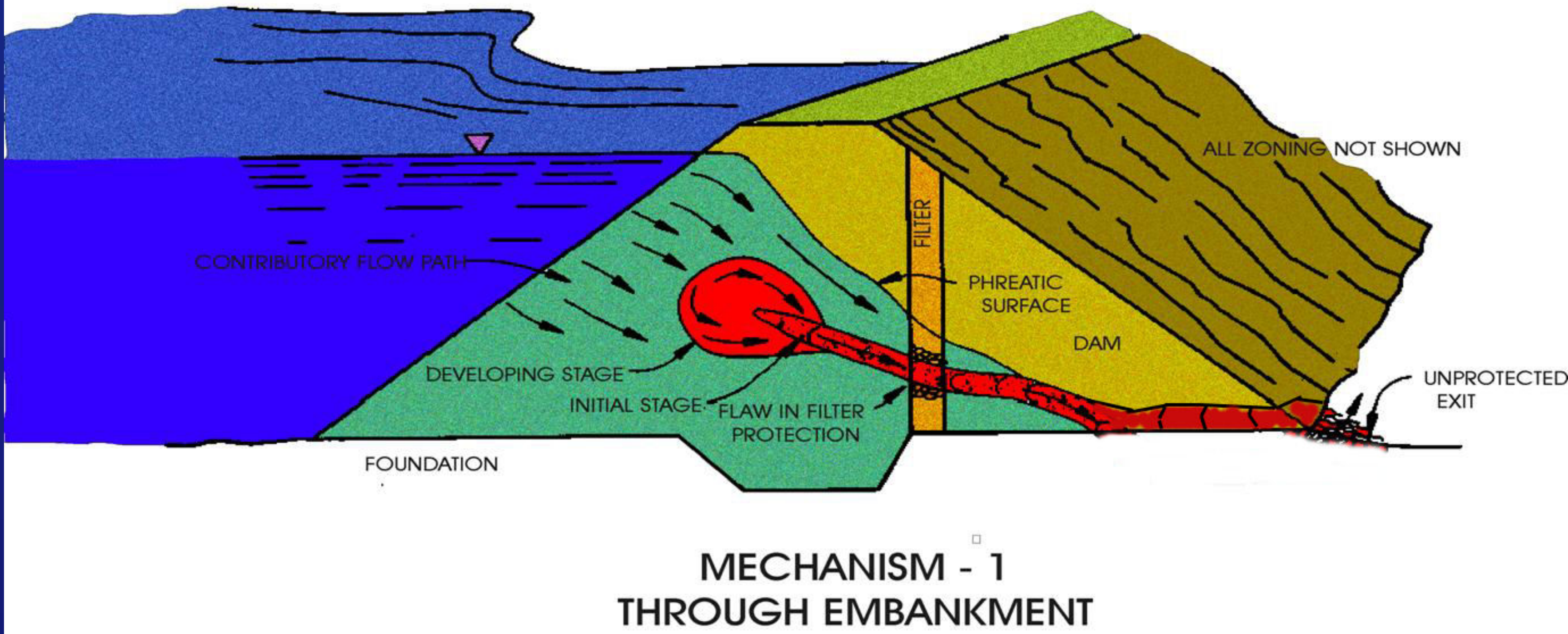
- Failure as the result of the “finer fraction” of a soil eroding through the “coarser fraction”.
- Leaves behind a coarser soil skeleton.
- If suffusion occurs in a filter or transition material, the material left behind will be less compatible with core.

Three General Groups of Failure Modes

- **Note that these are "types" of failure modes, and definitely not sufficient to consider as "descriptions" of failure modes**

- **Internal erosion (piping) through embankment**

Piping through Embankment



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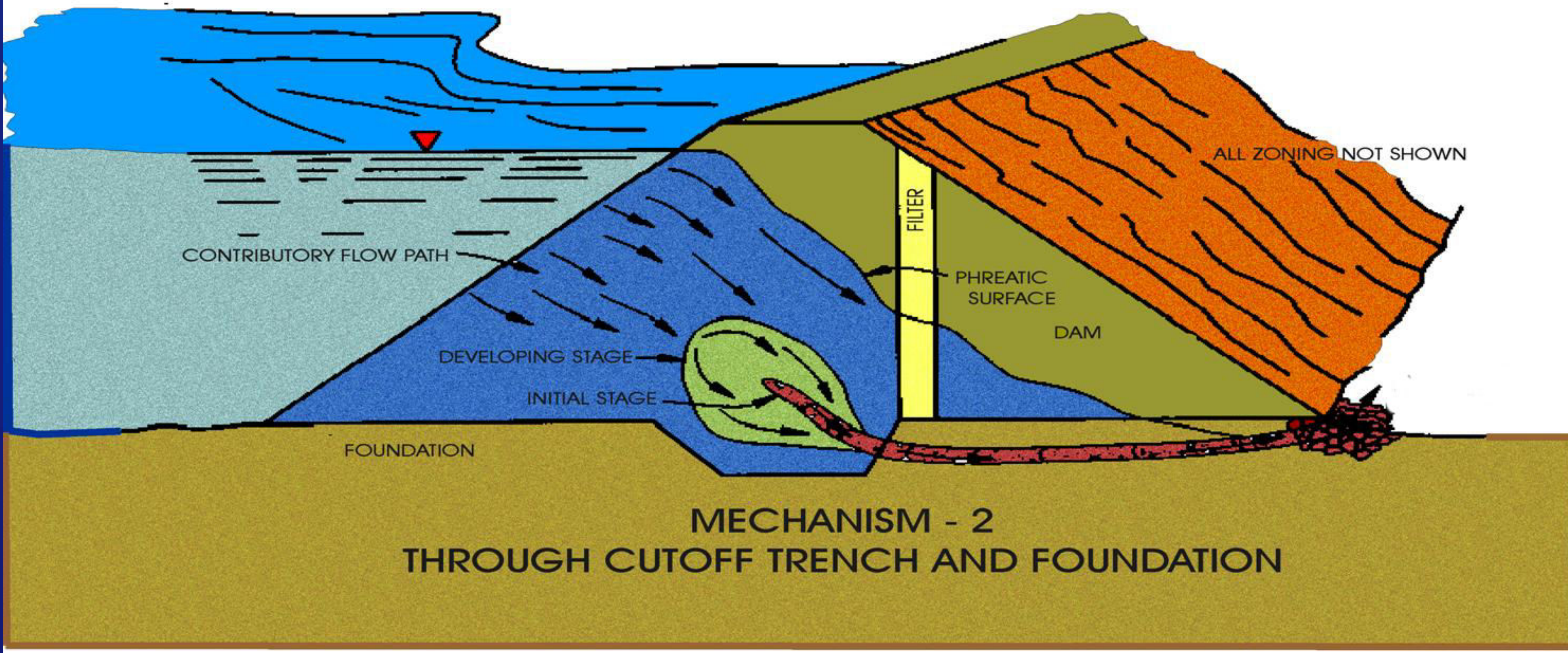
Three Groups of Failure Modes

- Internal erosion (piping) through embankment
- Internal erosion (piping) from embankment into foundation

Internal Erosion from Embankment into Foundation



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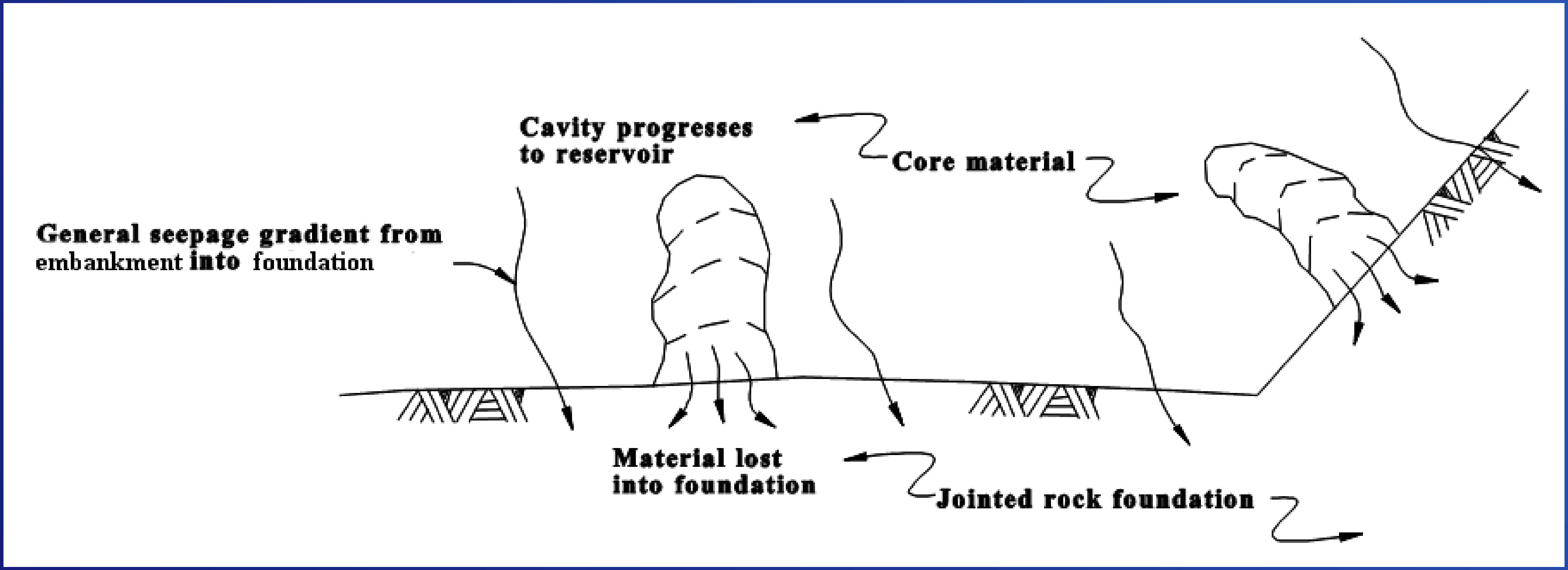
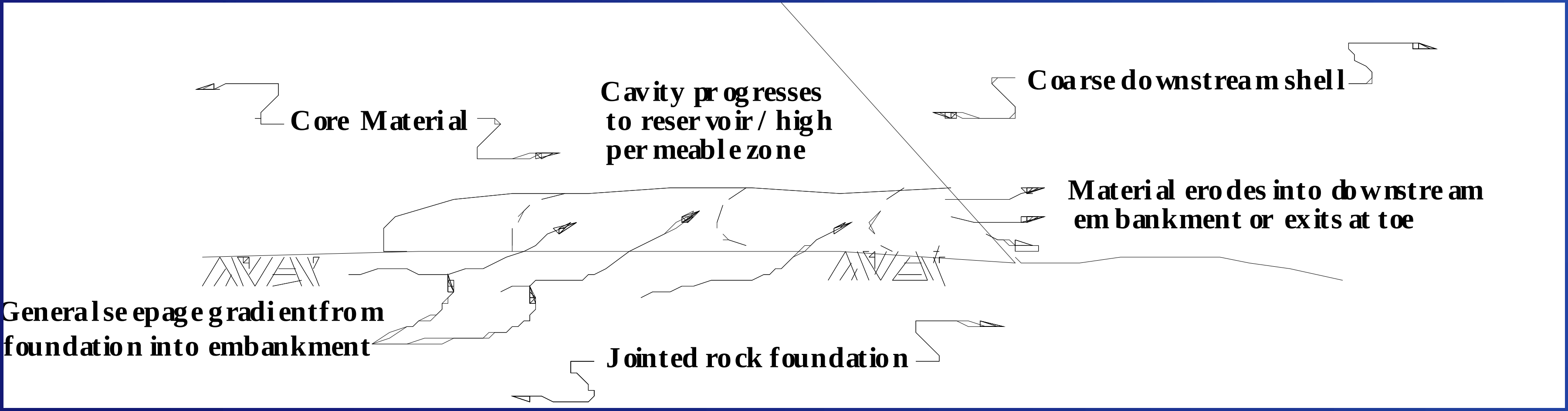
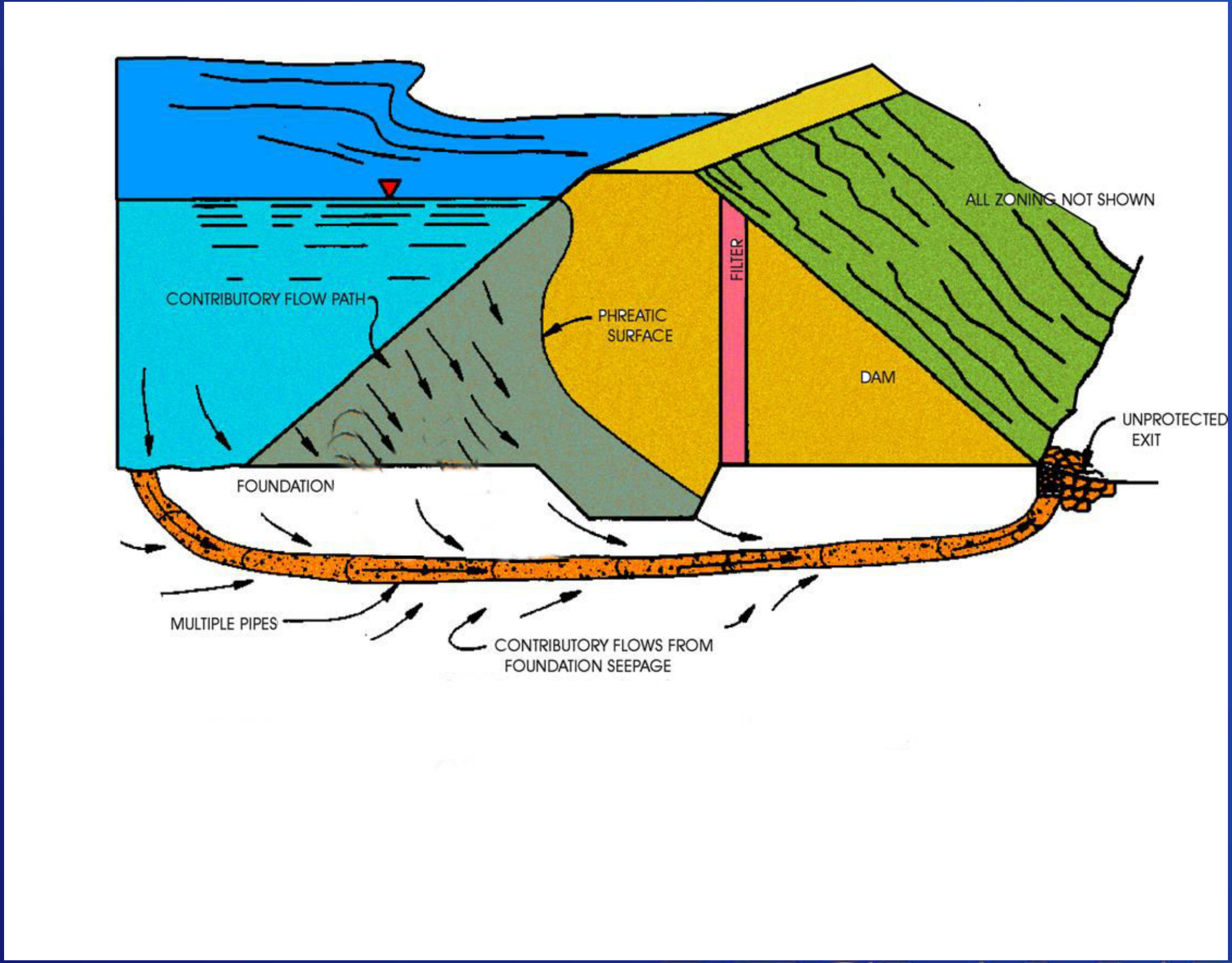

Cavity progresses to reservoir
Core material
General seepage gradient from embankment into foundation
Material lost into foundation
Jointed rock foundation


Core Material
Cavity progresses to reservoir / high permeable zone
Coarse downstream shell
Material erodes into downstream embankment or exits at toe
General seepage gradient from foundation into embankment
Jointed rock foundation

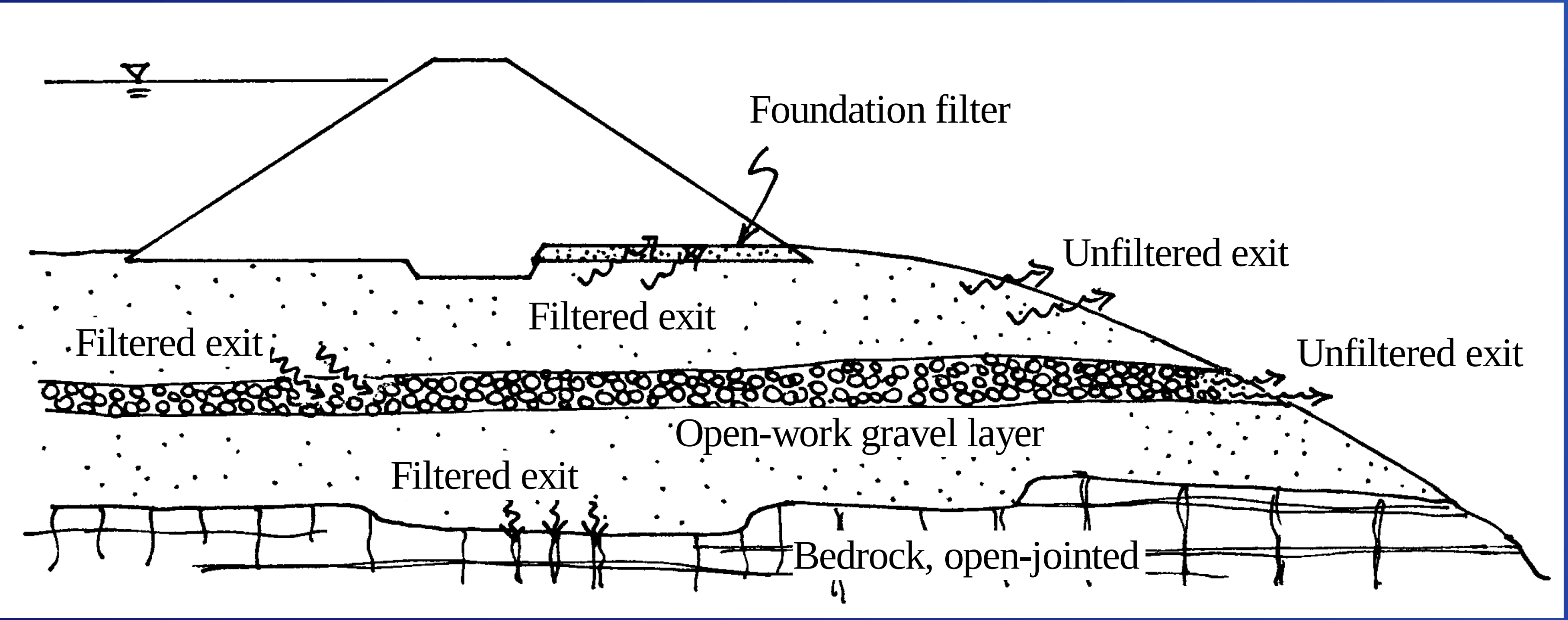
Three Groups of Failure Modes

- Internal erosion (piping) through embankment
- Internal erosion (piping) from embankment into foundation
- Internal erosion (piping) through foundation

Internal Erosion Through Foundation



Possible Pathways/ Exit Points



Typical Event Tree Structure

- Reservoir rises to threshold level
  - Initiation – Erosion starts (Flaw and erosion)
    - Continuation – Unfiltered or inadequately filtered exit exists
      - Progression – Roof forms to support a pipe*
        - Progression – Upstream zone fails to fill crack
          - Progression – Constriction or upstream zone fails to limit flows
            - Intervention fails to prevent breach
              - Dam breaches

*Node eliminated for Progressive Erosion

Reservoir Rises to Critical Level

- Risk team defines "critical level"
- For reservoirs that do not typically fill every year, an annual reservoir exceedance plot can be used to estimate the probability that the reservoir will fill in a given year
- Loads should be divided where structural response is expected to change from the baseline (where significant performance history is available) – for example, if sand boils manifest at some reservoir level below maximum, it may be necessary to include more than one reservoir range with a break at where the boils occur.

Erosion Initiates

- This is typically considered the key node in the entire event tree
- It essentially represents the probability that erosion will initiate (the first grains will start to move) in a given year
- Important factors are the potential for concentrated seepage paths, the possibilities of defects, the hydraulic gradients along the path, and soil erodibility

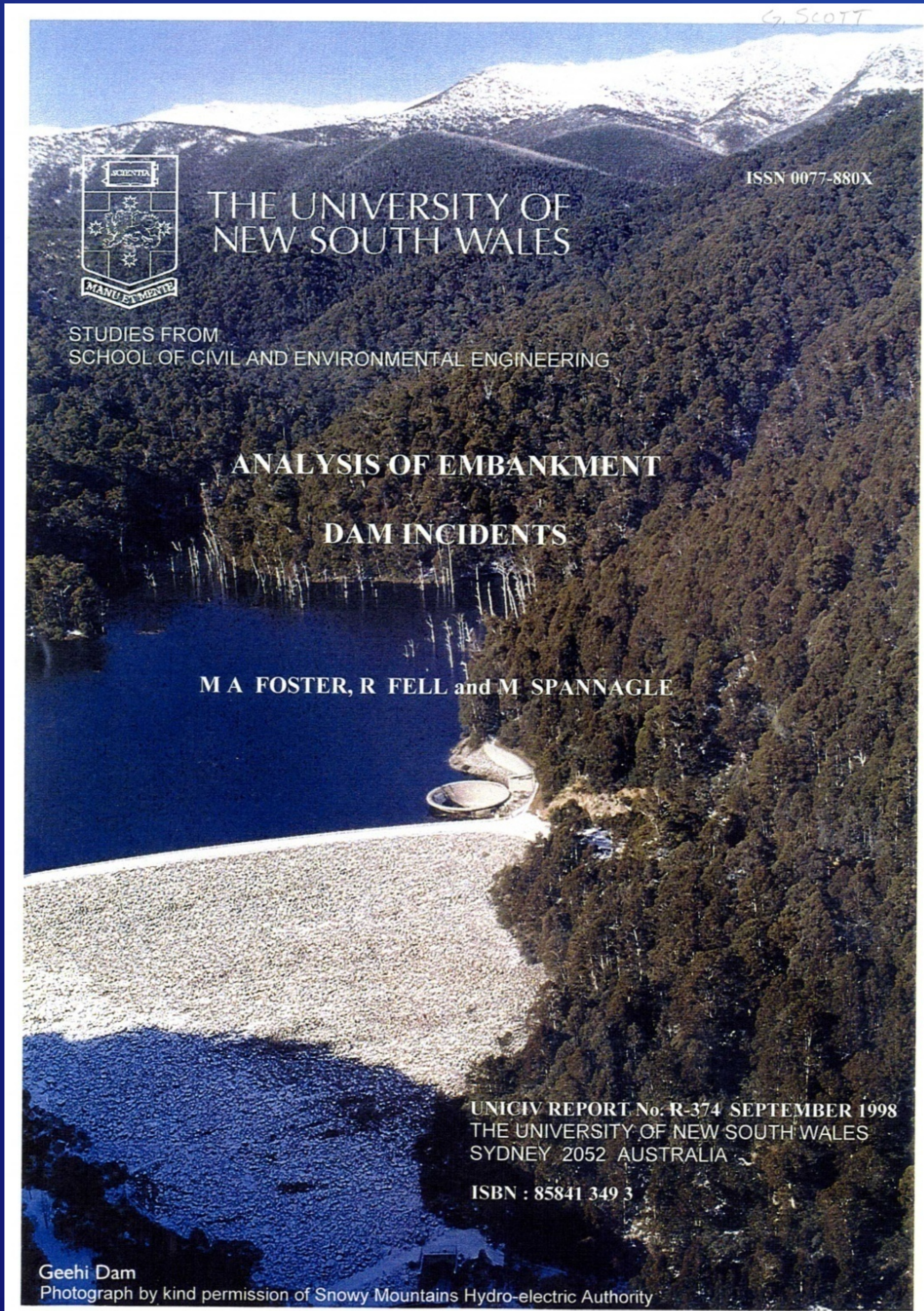
Erosion Initiates

- When possible and if applicable, consider historical behavior (base frequencies) when looking at this node
- Tentative proposed *best estimate* ranges of the probability of initiation of internal erosion in a typical BOR dam are (assuming about 12,600 dam years of operations):

  (Note: foundation only applies to cases without fully penetrating cutoff)

Type of Internal Erosion	Range of Initiation Probability
Embankment only	3×10^{-4} to 1×10^{-3}
Foundation only	2×10^{-3} to 1×10^{-2}
Embankment into foundation	3×10^{-4} to 7×10^{-4}
Into/along conduit	4×10^{-4} to 1×10^{-3}
Into drain	1×10^{-4} to 1×10^{-3}

UNSW Study



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Piping Potential of Soils

Greatest Piping Resistance Category (1)	Plastic clay, (PI>15), Well compacted.
	Plastic clay, PI>15), Poorly Compacted.
Intermediate Piping Resistance Category (2)	Well-graded material with clay binder, (6<PI<15), Well compacted.
	Well-graded material with clay binder, (6<PI<15), Poorly compacted.
	Well-graded, cohesionless material, (PI<6), Well compacted.
Least Piping Resistance Category (3)	Well-graded, cohesionless material, (PI<6), Poorly compacted.
	Very uniform, fine cohesionless sand, (PI<6), Well compacted.
	Very uniform, fine, cohesionless sand, (PI<6), Poorly compacted.

Note: Dispersive soils may be less resistant than Category 3

Factors Increasing Likelihood of Initiation of Internal Erosion

- Defects in embankments
  - Cracks
  - Pervious layers
  - Internally unstable materials
- Earthquakes
  - Settlement/liquefaction
  - Cracking
  - Slope failures

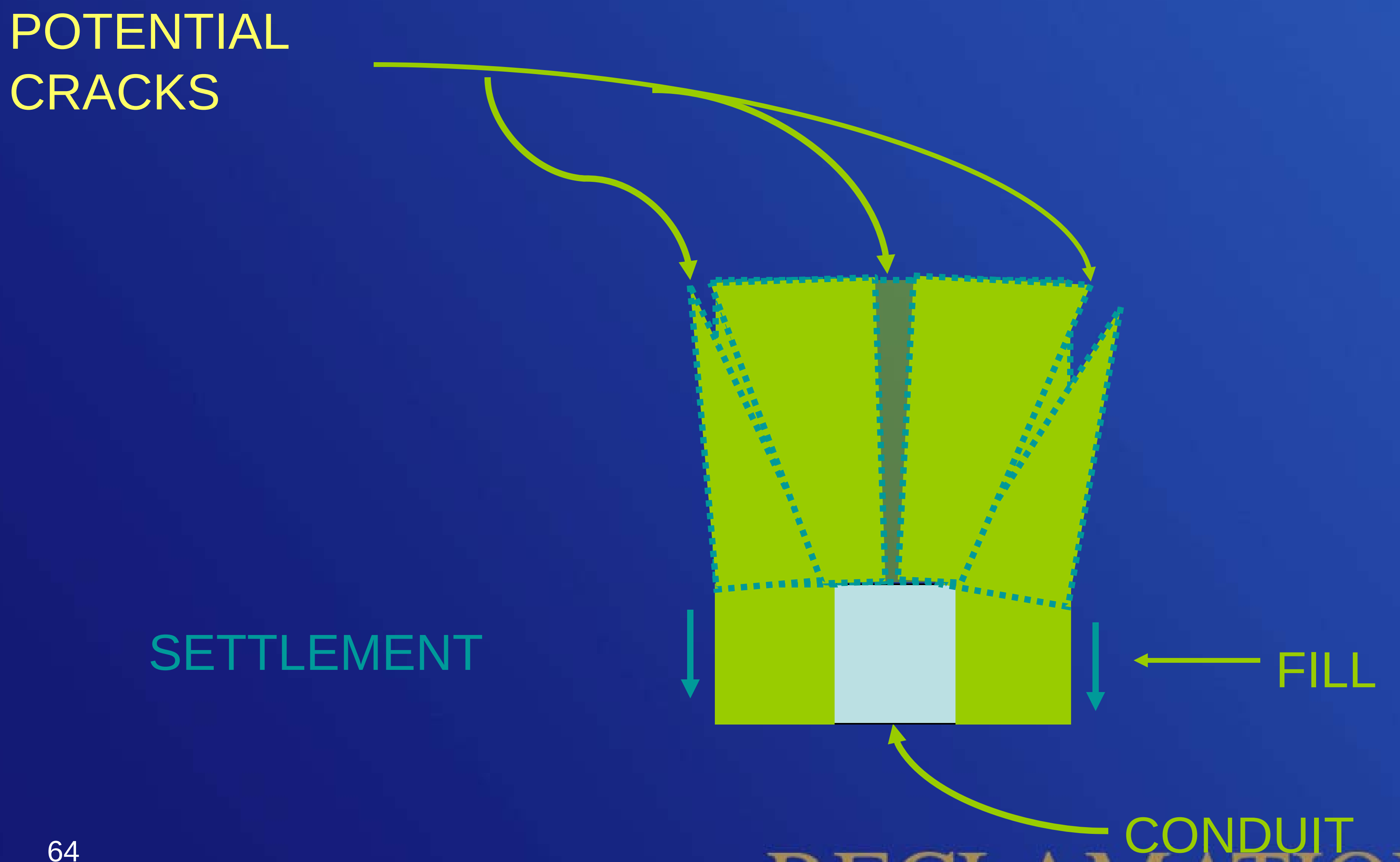
Potential Embankment Defects

- Cracks, resulting from differential settlements due to:
  - Rock foundation irregularities or steep rock abutments
  - Stiffer conduits projecting into brittle embankment soils
  - Variable foundation and/or embankment materials
  - Hydrocompaction of loess
- Arching across narrow valleys/ trenches creating low density zones with the potential for hydrofracturing
- Rodent Holes and root balls:
  - Burrowing at low reservoir exposed at high reservoir
  - Decaying roots lead to seepage pathways
- High permeability zones, resulting from:
  - Poor treatment at foundation contact
  - Poor embankment compaction at bottom of lifts
  - Staged embankment construction
  - Variable borrow areas
  - Construction winter shutdown surfaces
  - Limited compaction adjacent to conduits or walls

Penetrating Structures

- These types of features can introduce a transverse defect through an embankment, which may promote seepage and potentially internal erosion
  - Outlet works conduits
  - Spillways
  - Stilling basins
  - Drain pipes
  - Culverts
  - Other penetrating features (such as instrumentation)

Potential for Cracking



Excavation Geometry Problems

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Potential Internal Erosion Avenues

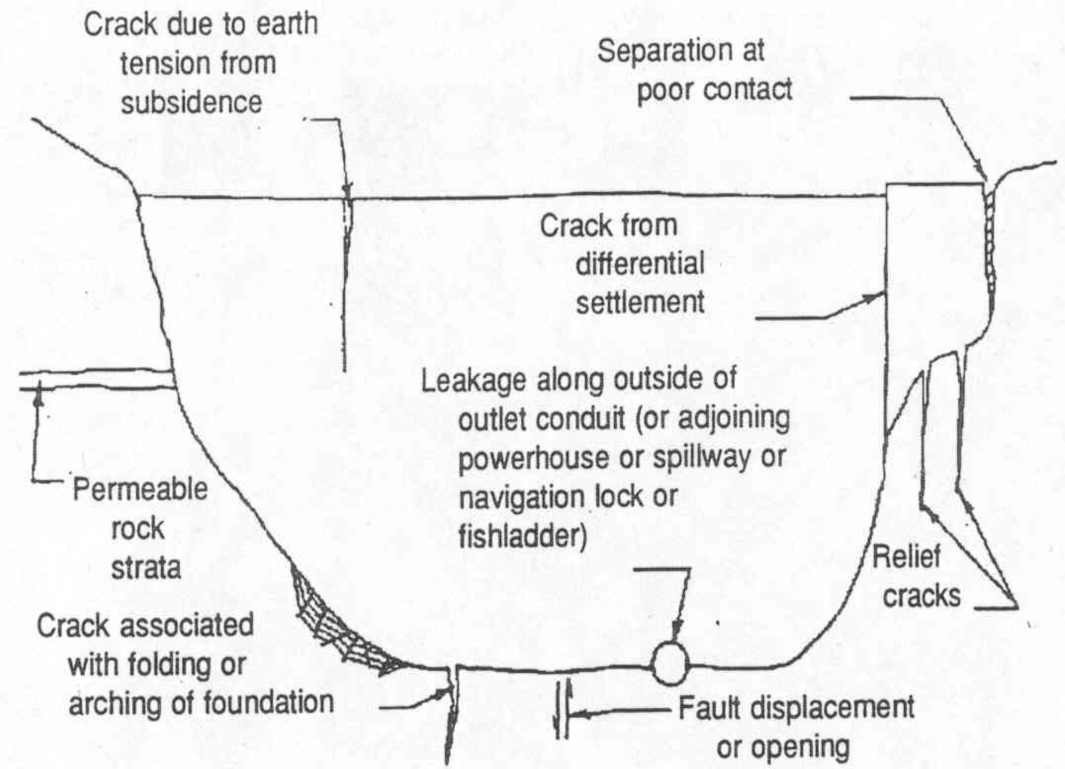

Figure 1. - Schematic illustrations of avenues for internal erosion.

Schmertmann's Method

- Based on flume tests with clean sands (no silty fines or gravels)
- Controlled laboratory tests
- Several adjustments needed to approximate field conditions
- Nevertheless, appears to be about the best available for cohesionless materials
- Indicates that piping can initiate at average gradients of ~ 0.05 under the right conditions

Heave

- F.S. = σ(V)/u
- σ(V) = total vertical stress at base of confining layer
- u = pore pressure at base of confining layer

F.S.	Prob of Heave
1.3	0.01
1.23	0.05
1.12	0.2
1.0	0.95
0.92	0.99
0.82	0.999

Unfiltered Exit

- This branch represents the probability of an open, unfiltered, or inadequately filtered exit point for the seepage
- This may not only include adjacent embankment or foundation soils, but apertures in bedrock or conduits/ drainage systems
- If “no erosion” filter criteria is satisfied, this probability is likely low
- Also look at whether “continuing” or “excessive” erosion filter criteria are met (Foster and Fell, 2003)
- Consider whether segregation or internal stability may impact the ability to filter
- Consider whether the incompatible material is truly continuous and has an open exit
- Consider whether you actually have sufficient representative soils information to perform (and trust) a gradation analysis

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Stilling Basin Under Drains

- Under drains can be damaged during construction, can crack due to settlement, and can potentially be damaged by freezing
- In addition, they may include open-jointed pipe, and coarse envelope
- These drainage systems are often difficult to monitor
- Embankment or foundation materials can be eroded into these systems over long periods of time before being detected
- Results can include loss of material and support for basin and potential for piping along conduit leading to dam breach

Roof Forms

- Since most internal erosion failure modes involve the core of the dam, this node is typically addressing the probability of roof support in the zone 1 core
- Most cores can support a roof – becomes more likely as plasticity and fines content increases
- However, sands and gravels with less than 15 percent non-plastic (or quite low plasticity) fines may collapse
- Conduits and structures can serve to enhance roof support
- Foundation deposits that feature clay layers or hardpan/caliche layers are classic examples of natural roofs

Roof Forms

Note: Fragility tables, such as this one, are presented throughout this section. It is recommended that the numbers not be used directly, but rather used to help develop a list of adverse and favorable factors.

Soil	% Fines	Plasticity	Moisture	Probability of Supporting Roof
CL, CH	>50	Plastic	Any	0.9+
ML, MH	>50	Either	Any	0.9+
SC, GC	15-50	Plastic	Any	0.9+
SM, GM	>15	Nonplastic	Moist Saturated	0.7-0.9+ 0.5-0.9+
Granular w/ cohesive fines	5-15	Plastic	Moist Saturated	0.5-1.0 0.2-0.5
Granular w/ cohesionless fines	5-15	Nonplastic	Moist Saturated	0.05-0.1 0.02-0.05
SP, SW, GP, GW	<5	Either	Any	0.001-0.01

Upstream Zone Fails to Fill Crack

- This node addresses the probability that an upstream zone can supply “crackstopping” materials that will help seal a crack or defect (typically in the dam core) and/or plug a developing erosion pathway
- Difficult to estimate – no specific numerical guidance
- Factors influencing this node include:
  - Thickness of upstream zones
  - Whether upstream zone is truly cohesionless
  - The gradation of the upstream zone
  - Nature of downstream zones (can they trap these materials)
- Need to also consider if this progression node will play a role early in the failure mechanism (particularly if erosion is along a crack) or later on (if backwards erosion)

Constriction or upstream Zone Fails to Limit Flows

- This node describes the possibility that seepage flows may be limited by some feature
- Typical upstream features that may serve to limit flows include:
  - Wide, upstream impervious (or semi-pervious) zones with limited potential to crack (and thus serve to limit flows)
  - Thick, semi-pervious shells that have a low potential to sustain a crack
  - Cutoff walls (concrete, sheetpile, etc) in embankment
  - Well-constructed cutoffs around conduits
  - Soil-cement (or similar) slope protection
- In addition, the limited aperture sizes in bedrock or in conduits serve a similar role in limiting the flows and thus throttling the amount of seepage erosion that can take place (note that these are not “upstream zones”)

Constriction or upstream Zone Fails to Limit Flows

- Modern concrete walls anchored to rock least chance of failure (0.001-0.01)
- Steel sheet pile walls in good condition (0.1-0.5)
- Upstream facing in good condition (0.1-0.5)
- Steel sheet pile walls or upstream facing in poor condition (~1.0)

Intervention Fails

- This step in the event tree evaluates the potential that (1) a developing failure mechanism will be recognized, and (2) mitigating efforts can stop or slow the process
- Encompasses 2 components – detection, and ability to intercede
- Case histories suggest that we have effectively intervened in a large number of incidents
- Factors to consider include:
  - "Eyes on the dam"
  - Erosion potential of embankment/foundation soils (which affects the rate at which the failure mode will progress)
  - Amount of freeboard, size of reservoir
  - Release capacity of appurtenant structures (can reservoir be drawn down?)
  - Ability to stop erosion (access, availability of materials, etc)

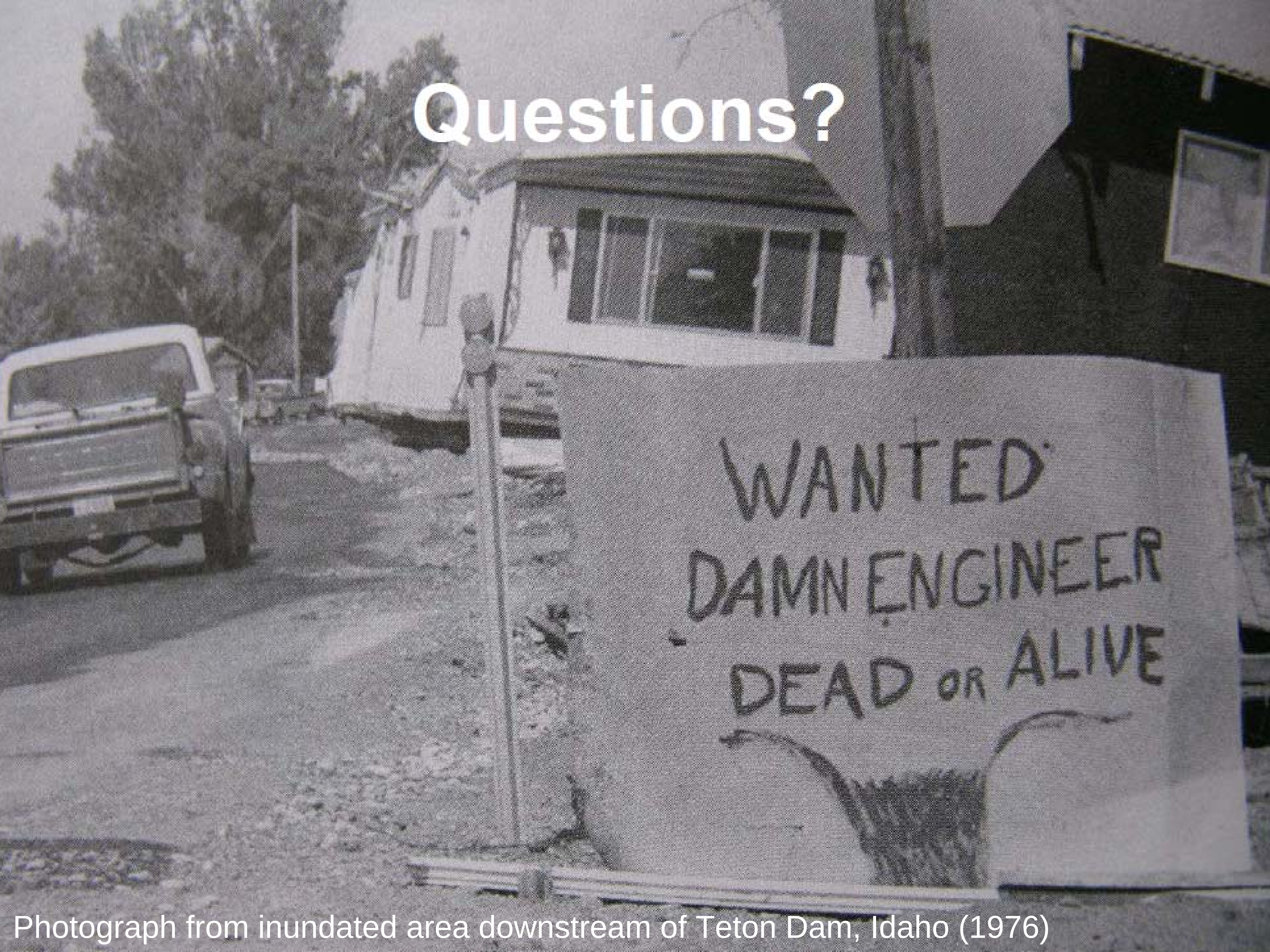
Breach Forms

- Type of breach typically defined in failure mode description
  - Connection of the “pipe” to the reservoir resulting in rapid erosion enlargement of the pipe until the crest collapses below the reservoir level (gross enlargement).
  - Over-steepening of the downstream slope due to progressive erosion and slumping leading to slope instability and complete loss of freeboard (sloughing/unraveling).
  - Stoping of material upward creating a sinkhole or depression in the crest that drops the crest below the reservoir level (sinkhole development).
  - (Increasing pore pressures/ global instability)
- Can consider more than one and assign likelihood to each or carry each through event tree

Breach Forms

- At this point of the event tree, the internal erosion failure mechanism has progressed and intervention has been unsuccessful
- Generally, an embankment dam will probably fail
- However, there are factors that reduce the probability that the event will continue to a full breach:
  - A great deal of freeboard exists
  - A large downstream rockfill zone is present
  - A corewall (or similar feature) remains in place
  - The reservoir may be so small that it drains away before a dam breach can form (there has been a case history of this involving internal erosion along a conduit)

Questions?



Photograph from inundated area downstream of Teton Dam, Idaho (1976)