RECLAMATION

Managing Water in the West

Potential Failure Modes Related to Seepage and Piping

Potential Failure Mode Analysis Training

November 2007

U.S. Department of the Interior
Bureau of Reclamation

Internal Erosion Failure Modes

- 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

From UNSW

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}

"… the means at our disposal for preventing failures of these types (piping and sliding) are more important than all the other features of the design of the dams, and no "calculated risk" or even remote possibility of such failures can be tolerated."

"The failure of a dam by piping ranks among the most serious accidents in civil engineering."

Terzaghi and Peck
(Soil Mechanics in Engineering Practice)

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Types of Seepage and Piping Problems

- Internal Erosion/Piping (“roofing”)
- Blowout (heave, uplift)
- Seepage Erosion

Piping

- Subsurface erosion conveyed through an open “pipe” in soil or rock 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

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Internal 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
- Blowout = breach of the impervious boundary
- Can lead to stability issue
- Can be the initiating event for a piping mechanism
- Typically judged to occur upon first filling or when reservoir reaches historic high

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Seepage Erosion

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

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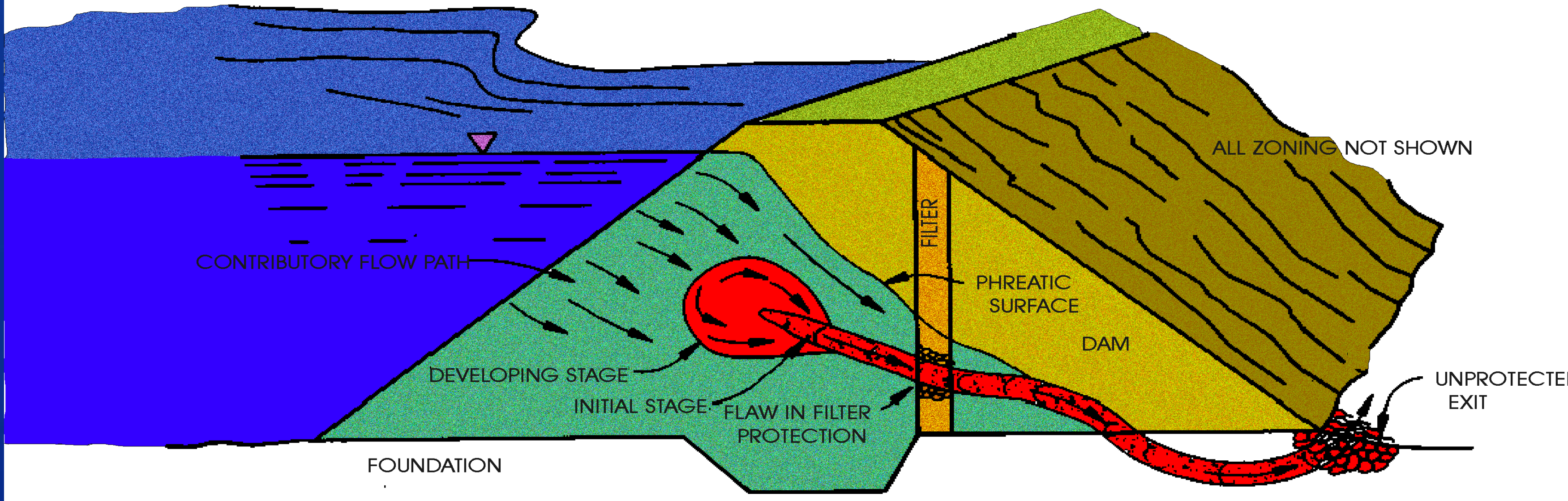
Three General Failure Modes

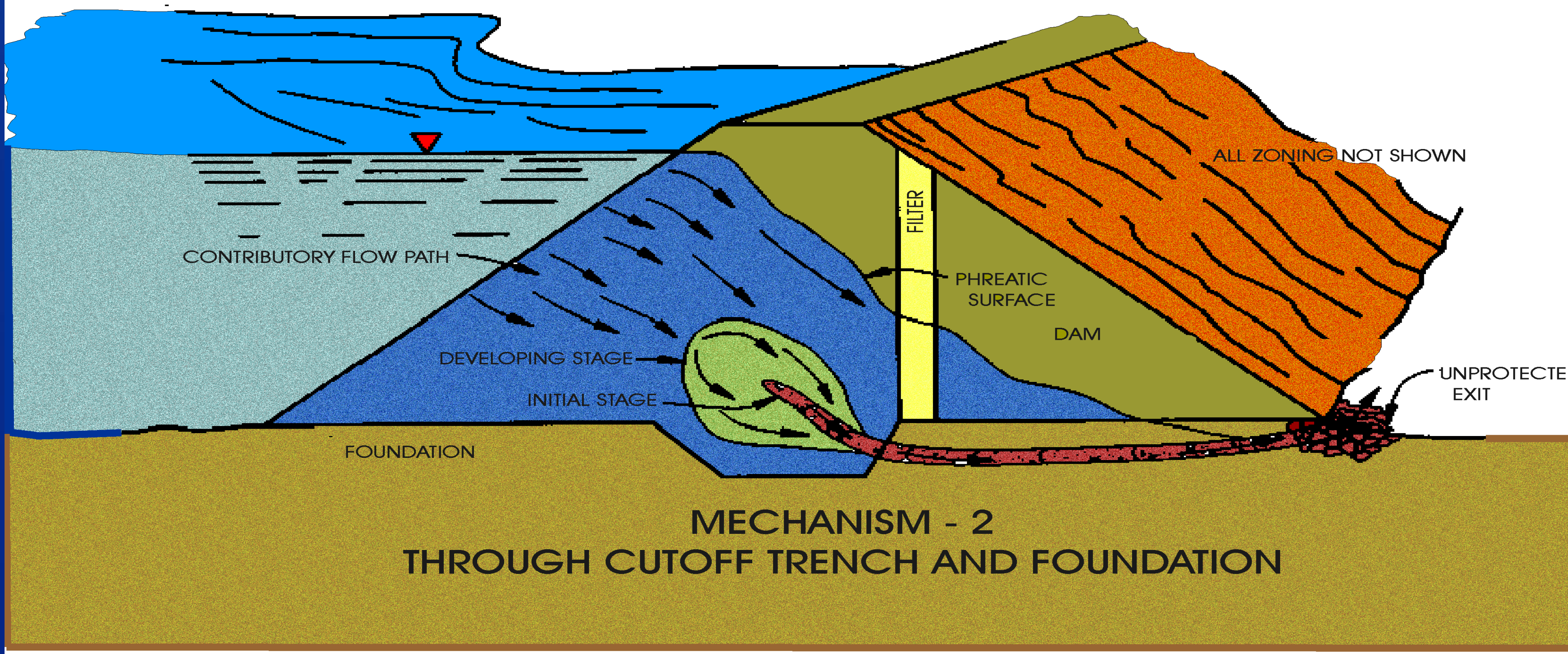
- Internal erosion (piping) through embankment

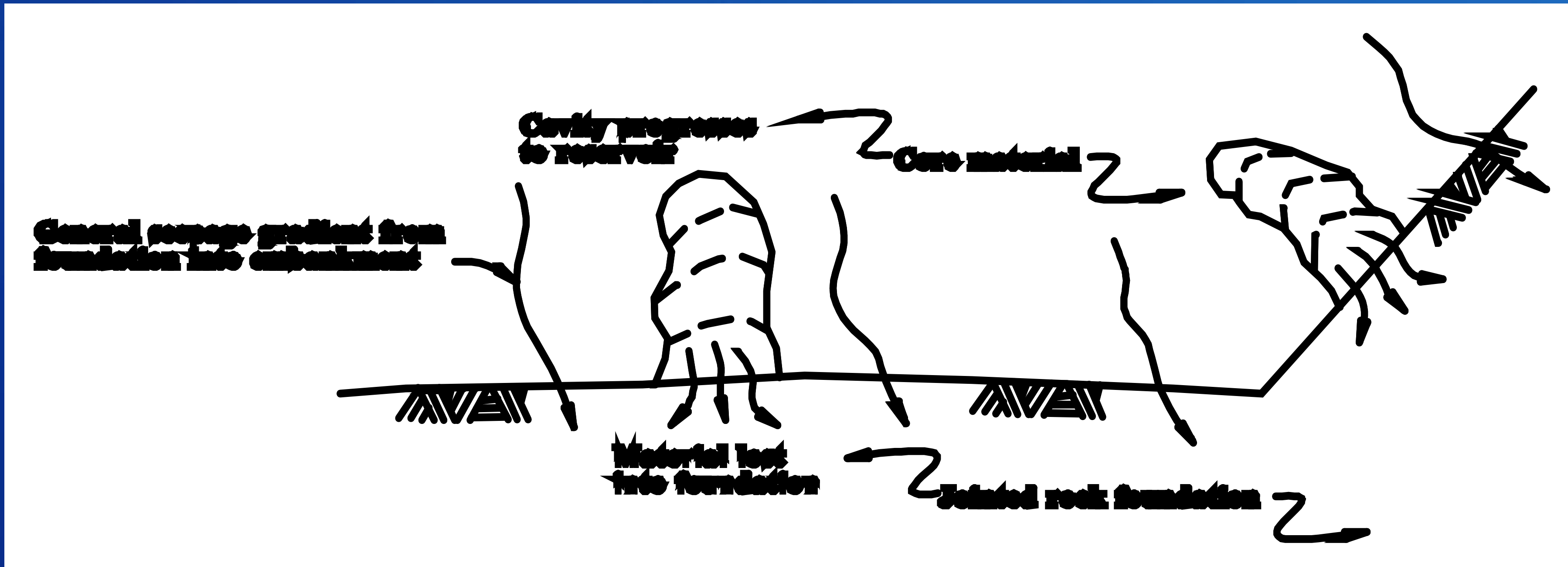


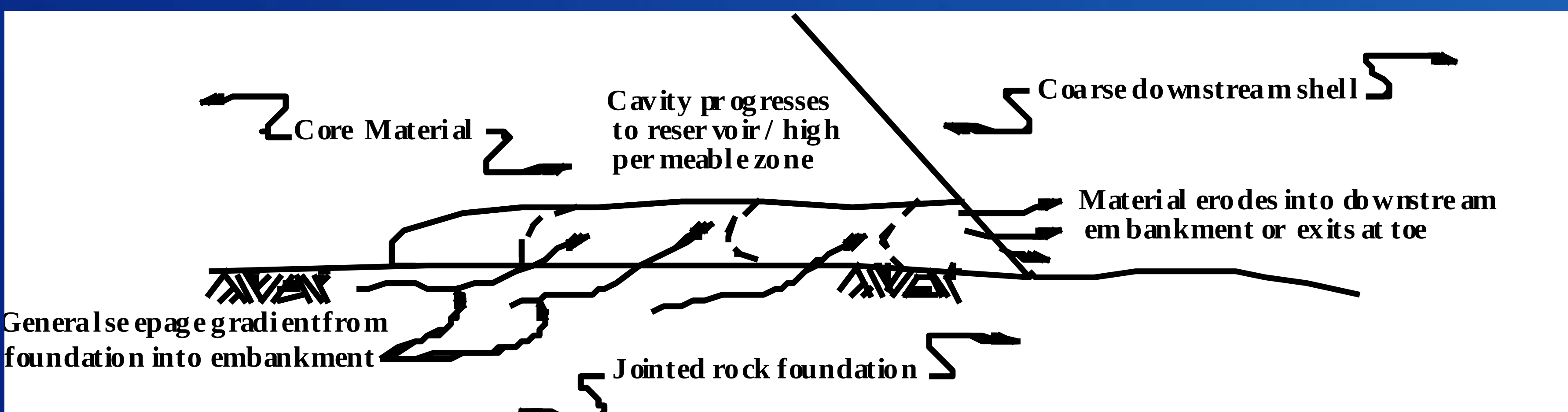
MECHANISM - 1
THROUGH EMBANKMENT

Three Types of Failure Modes

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


ALL ZONING NOT SHOWN
FILTER
CONTRIBUTORY FLOW PATH
PHREATIC SURFACE
DAM
DEVELOPING STAGE
INITIAL STAGE
UNPROTECTED EXIT
FOUNDATION
MECHANISM - 2
THROUGH CUTOFF TRENCH AND FOUNDATION


Cavity progresses
to reservoir
Core material
General seepage gradient from
foundation into embankment
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 Types of Failure Modes

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

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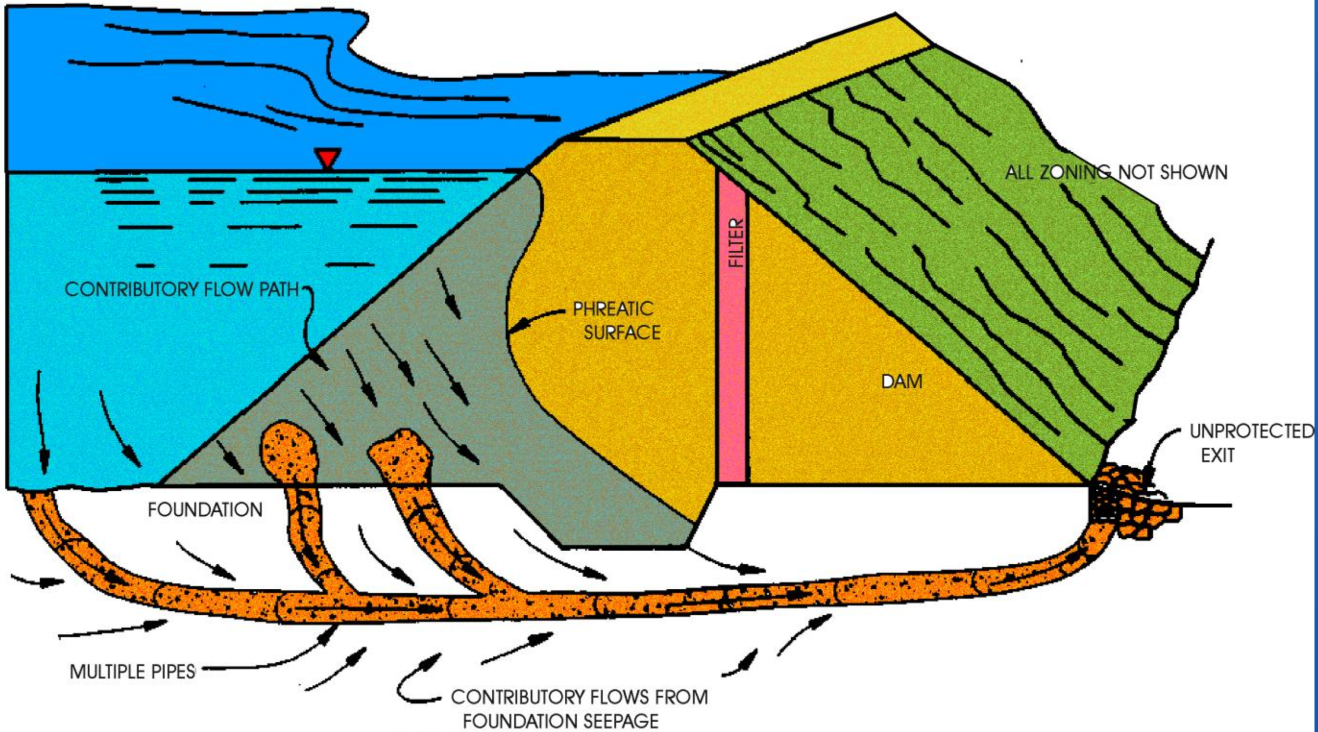

MECHANISM - 4
THROUGH FOUNDATION AND UPSTREAM PORTION
OF EMBANKMENT

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Factors Leading to Initiation of Internal Erosion

- Defects in embankments
  - Cracks
  - Pervious layers
  - Internally unstable materials
- Presence of unfiltered exits
  - Open jointed rock foundations
  - Coarse foundation soils
  - Cracks/openings in conduits or drainage systems
- Reservoir levels reaching historic highs
- Earthquakes
  - Settlement/liquefaction
  - Cracking
  - Slope failures

Potential Embankment Defects

- Cracks, resulting from:
  - Differential settlements due to rock foundation irregularities
  - Differential settlements due to variable overburden soils
  - Differential settlements due to variable embankment materials

- High permeability zones, resulting from:
  - Poor treatment at foundation contact
  - Poor embankment compaction
  - Staged embankment construction
  - Variable borrow areas
  - Construction winter shutdown surfaces
  - Adjacent to conduits or walls

Potential Internal Erosion Avenues

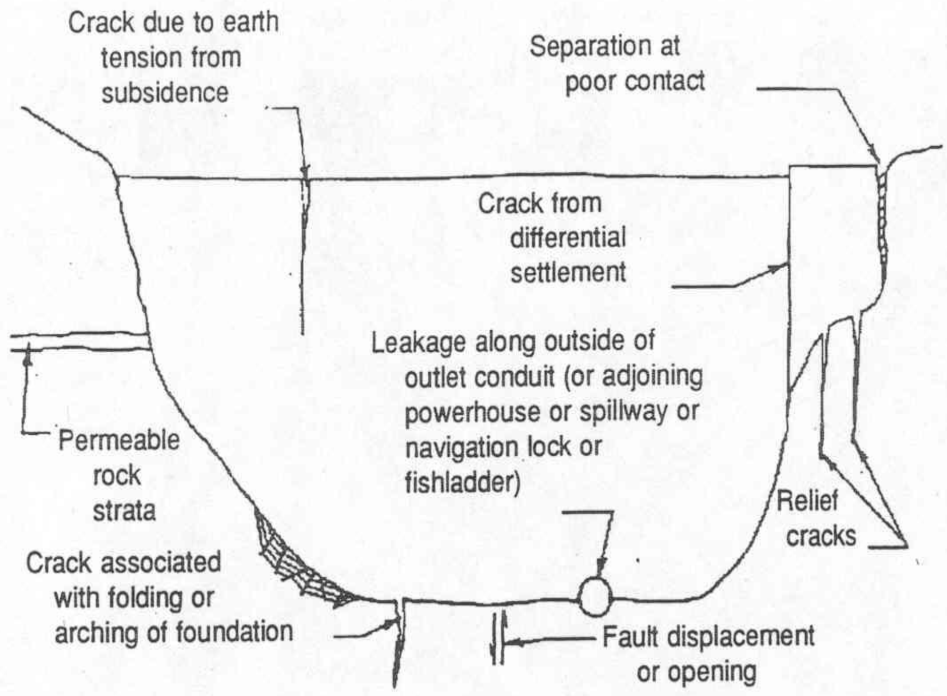

Figure 1. - Schematic illustrations of avenues for internal erosion.

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Special Considerations

Penetrating Structures

- Outlet works conduits
- Spillways
- Stilling basins
- Drain pipes
- Culverts
- Other penetrating features (such as instrumentation)

Erosion Around Conduits Is a Growing Problem

- Tens of thousands of conduits through small dams
- Conduits are aging and corroding
- Often poorly constructed
- Often not inspected frequently, sometimes not at all

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What’s the Problem?

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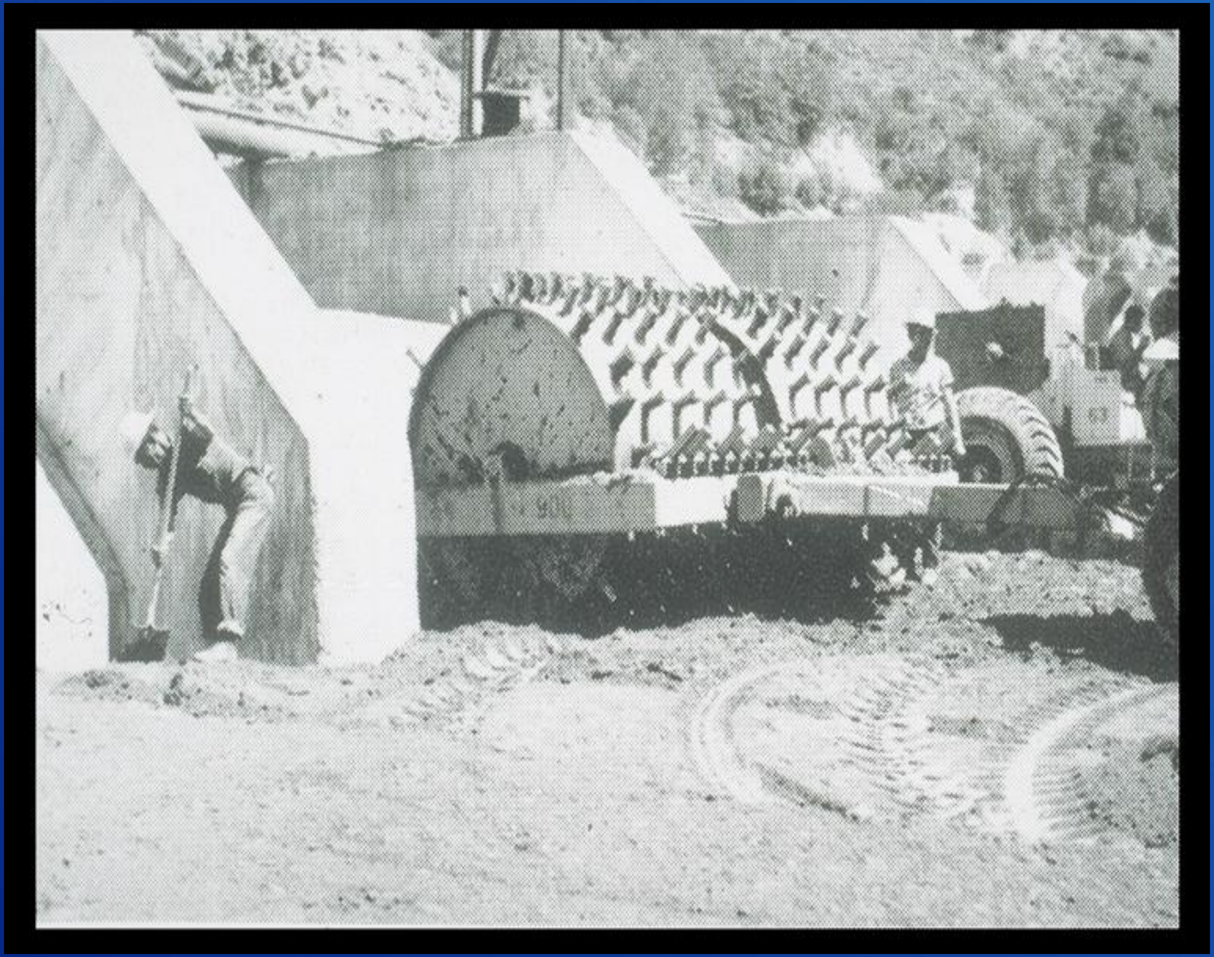
Cutoff Collars Get in the Way



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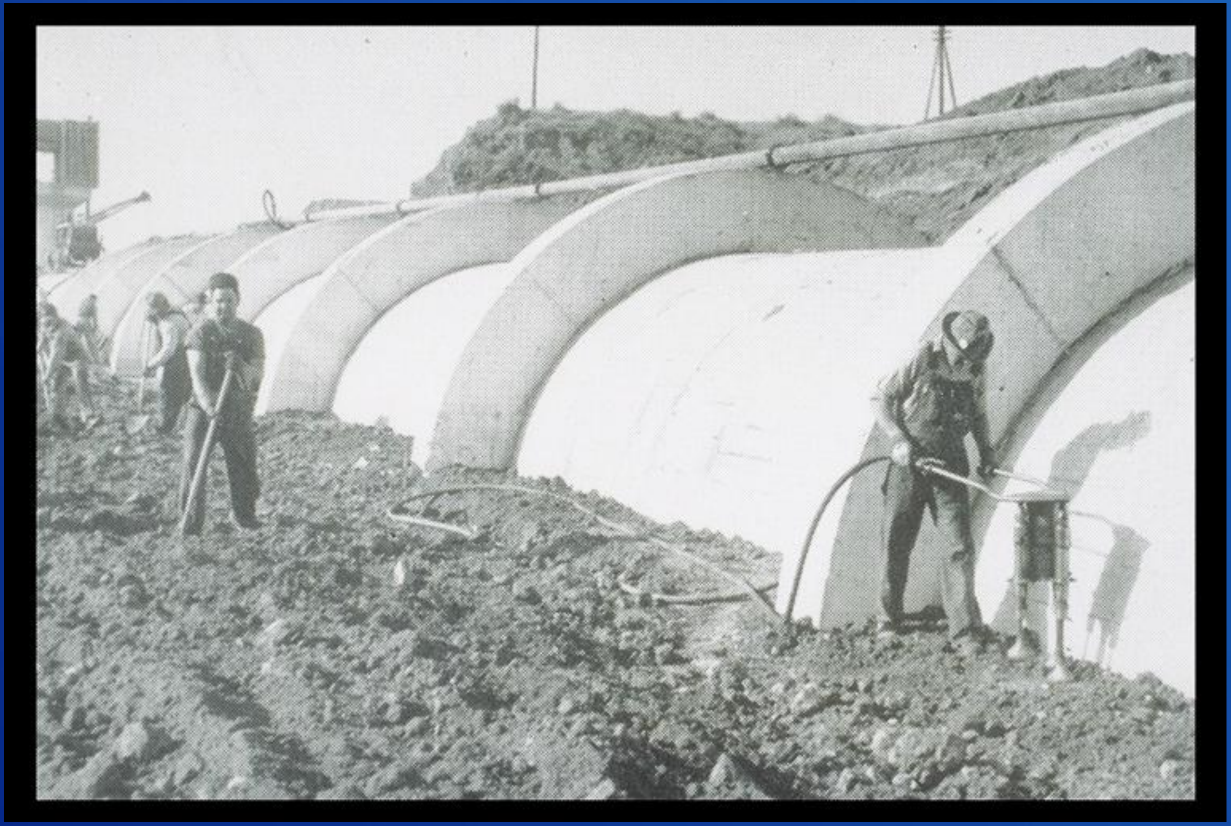
Collars Make Special Compaction Necessary



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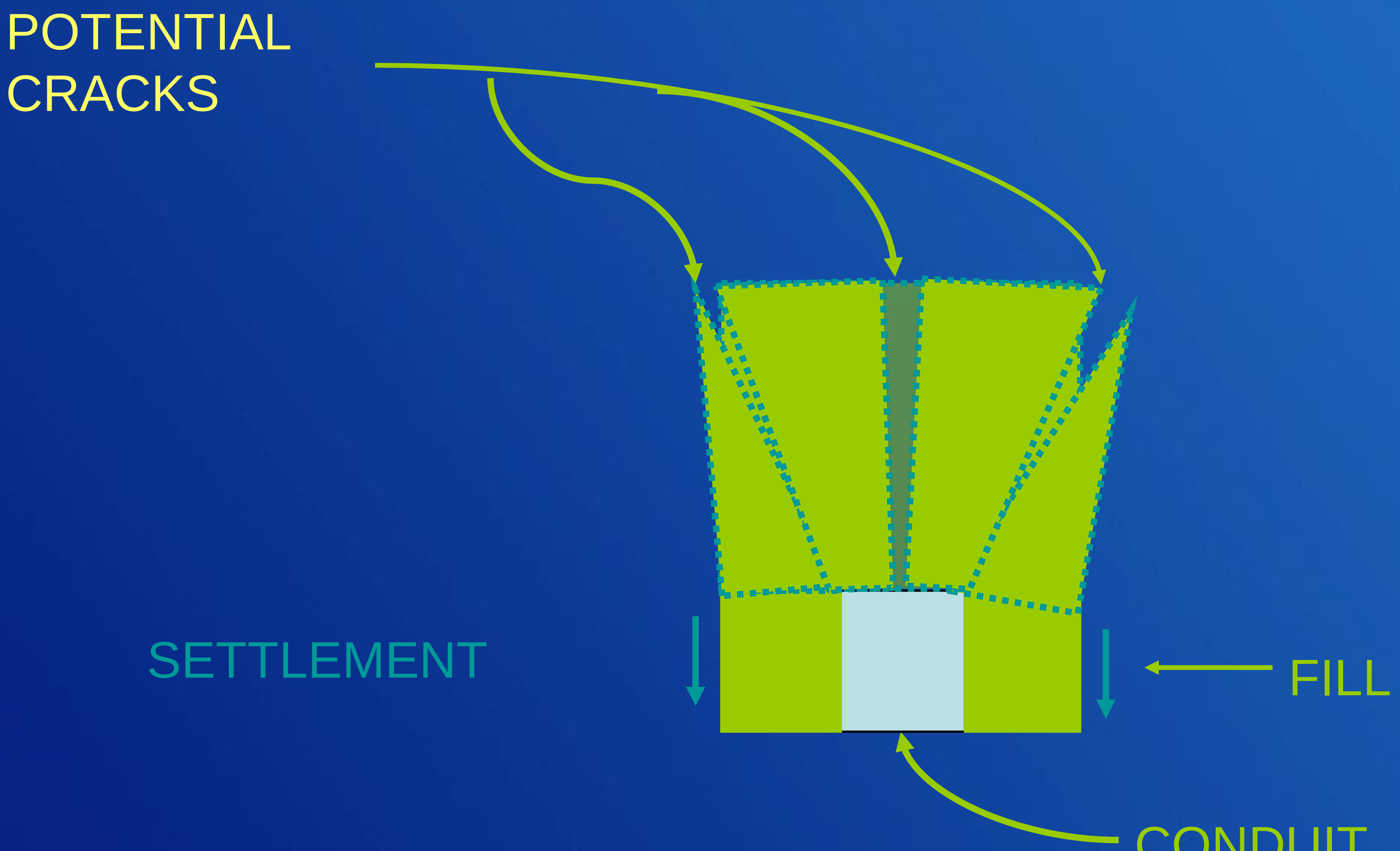
Potential for Cracking



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Excavation Geometry Problems

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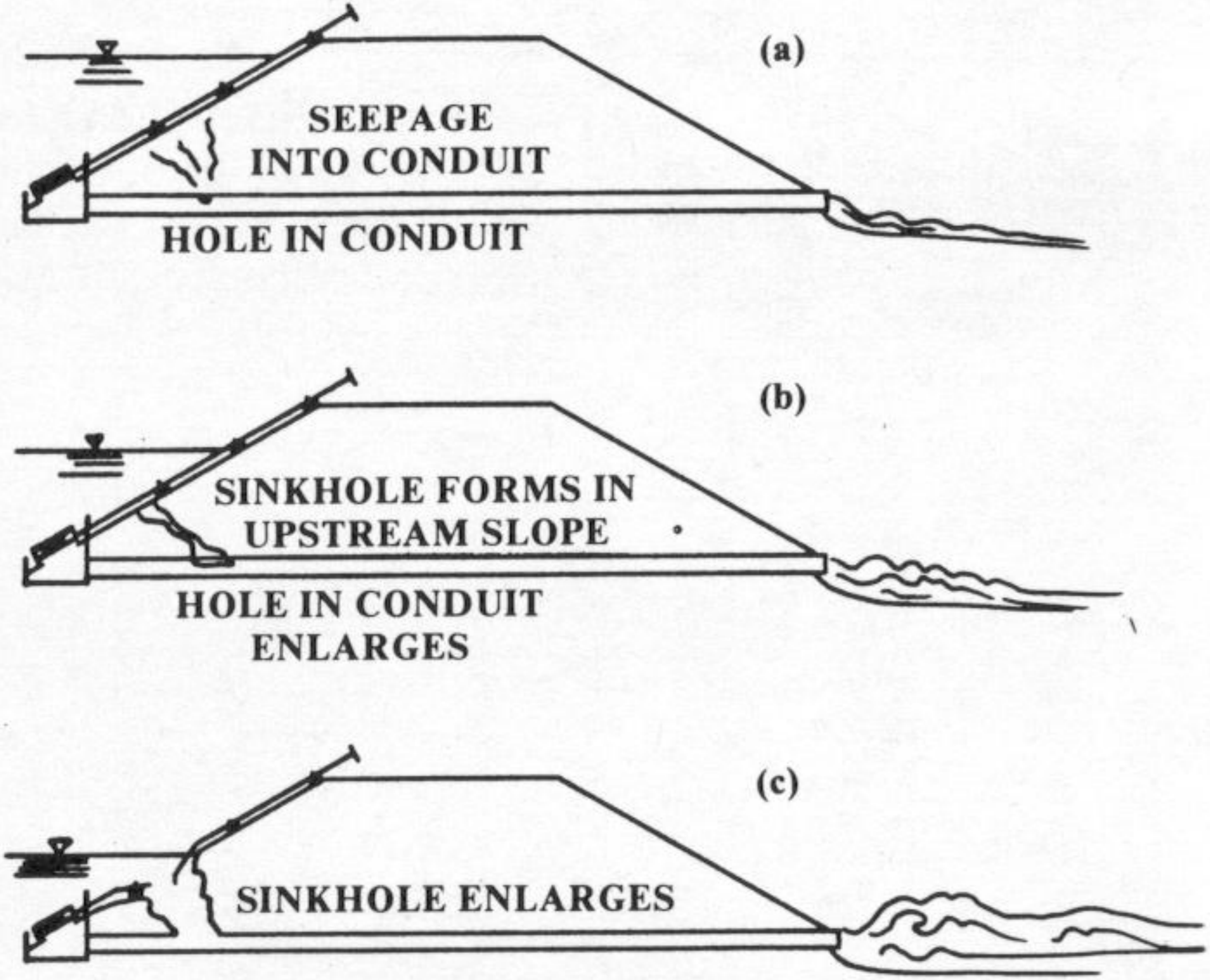

FIGURE 9.4-2 — RESERVOIR EMPTIED THROUGH THE OUTLET BECAUSE OF A HOLE IN THE UPSTREAM END OF THE PIPE.

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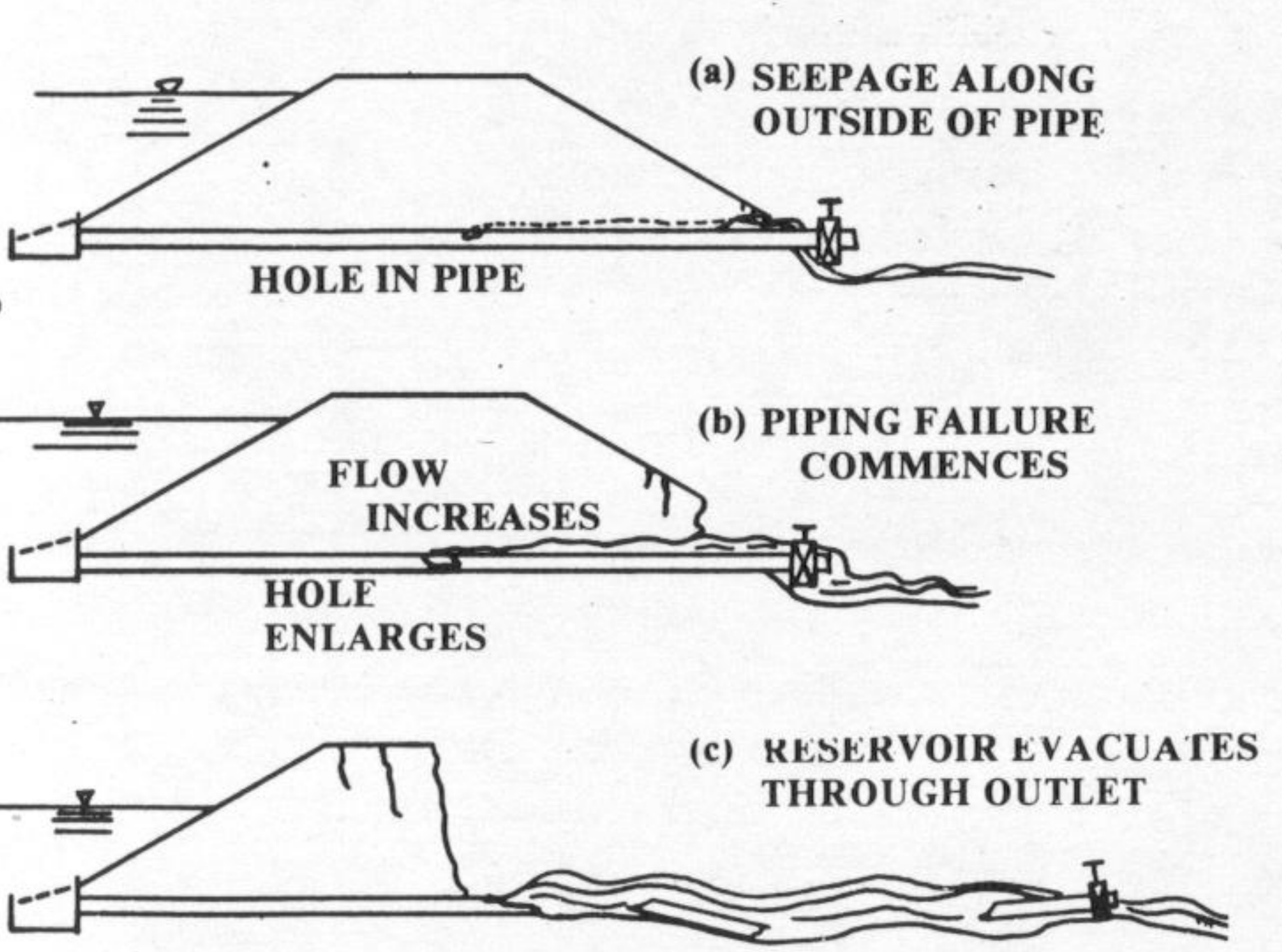

FIGURE 9.4-1 — FAILURE CAUSED BY LEAKAGE ALONG THE OUTSIDE OF THE OUTLET PIPE.

Stilling Basin Under Drains

- Under drains can be damaged during construction, can crack due to settlement, and can potentially be damaged by freezing
- 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 support for basin, formation of an unfiltered exit, and potential for piping along conduit leading to dam breach

Photo 1

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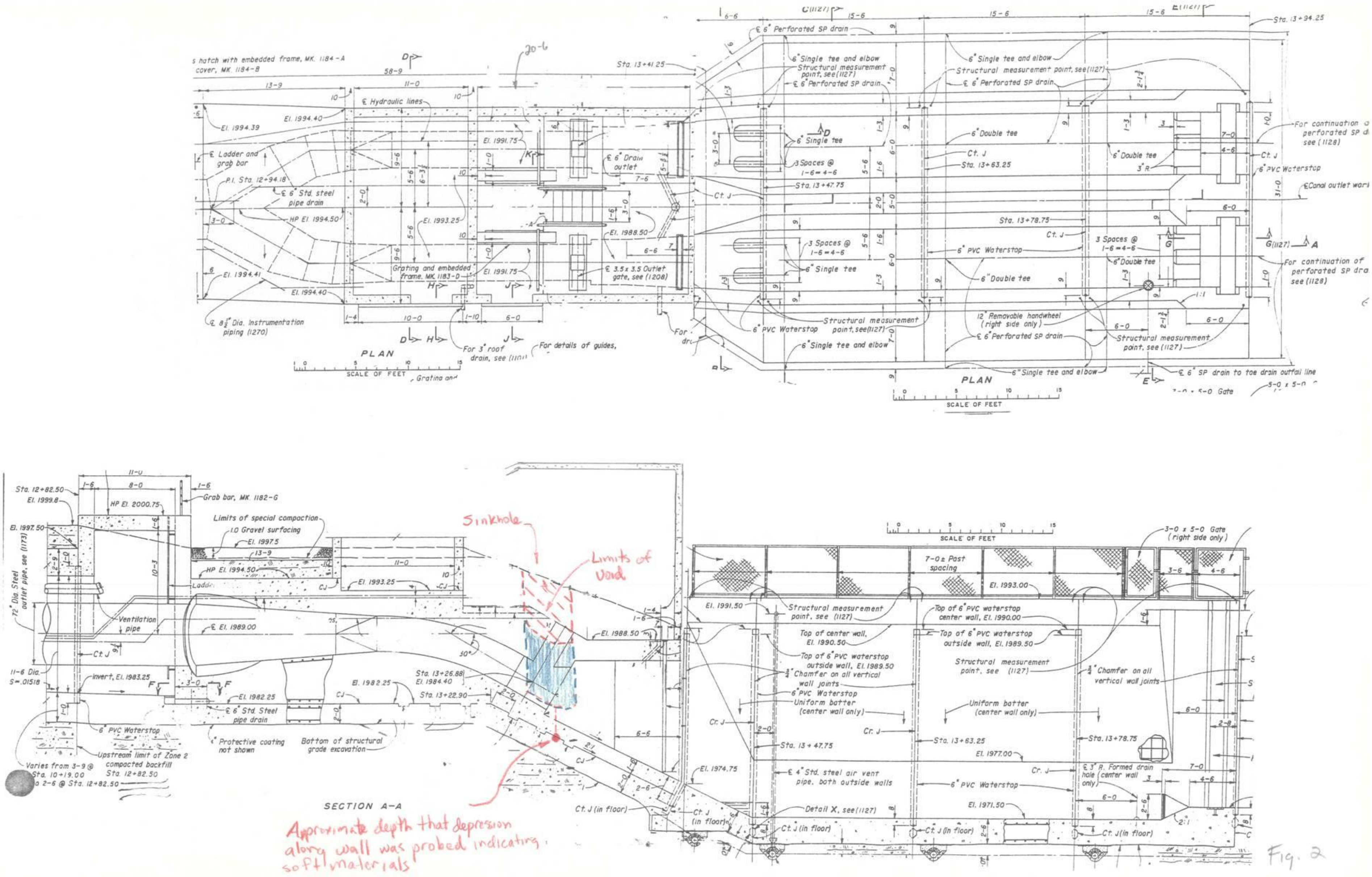
PLAN
SCALE OF FEET
SECTION A-A
Sinkhole
Limits of Void
Approximate depth that depression along wall was probed indicating soft materials
Limits of special compaction
1.0 Gravel surfacing
Structural measurement point, see (1127)
6" PVC Waterstop
Uniform batter (center wall only)
Fig. 2

Sand Boils and Sinkholes

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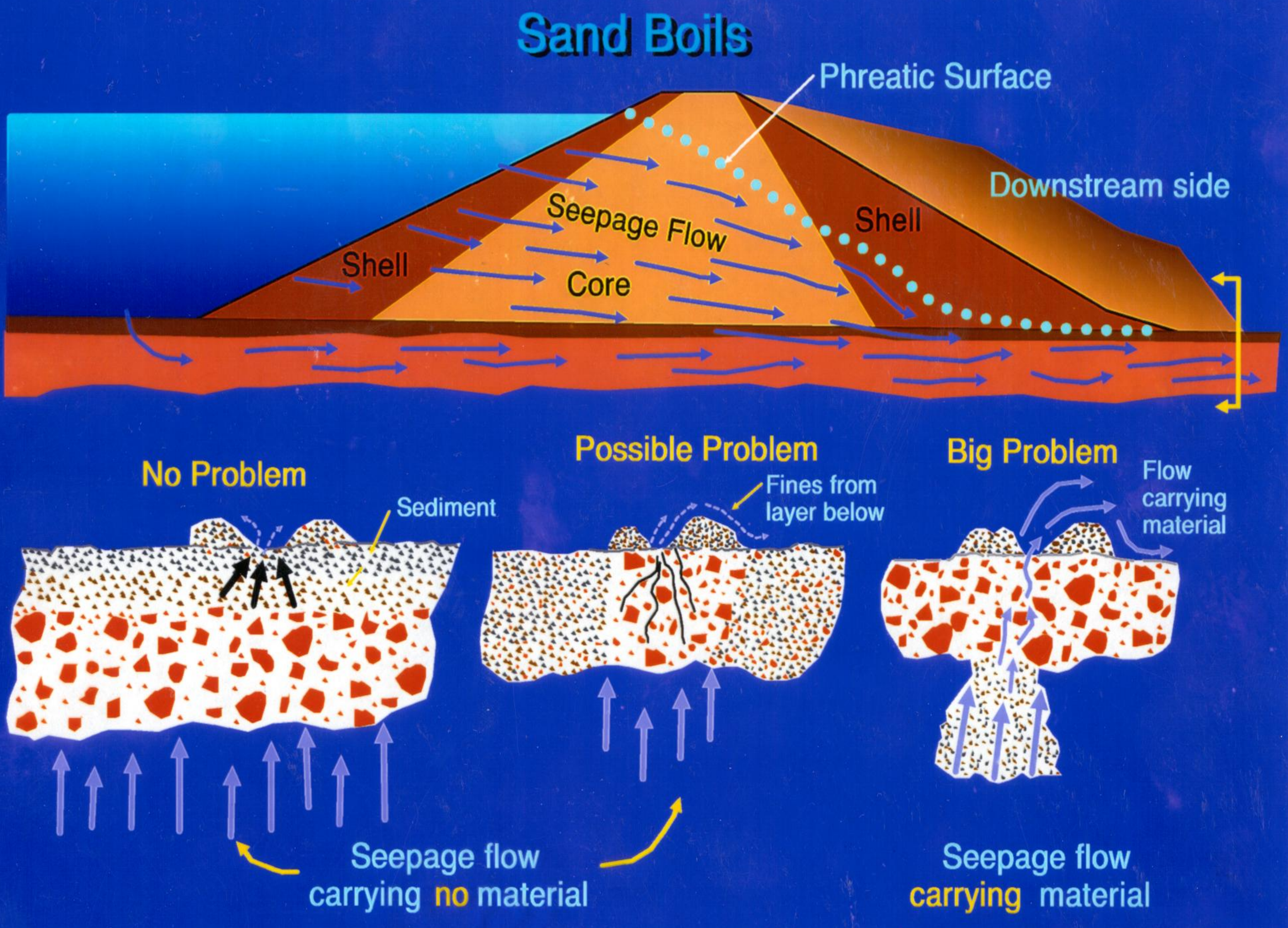
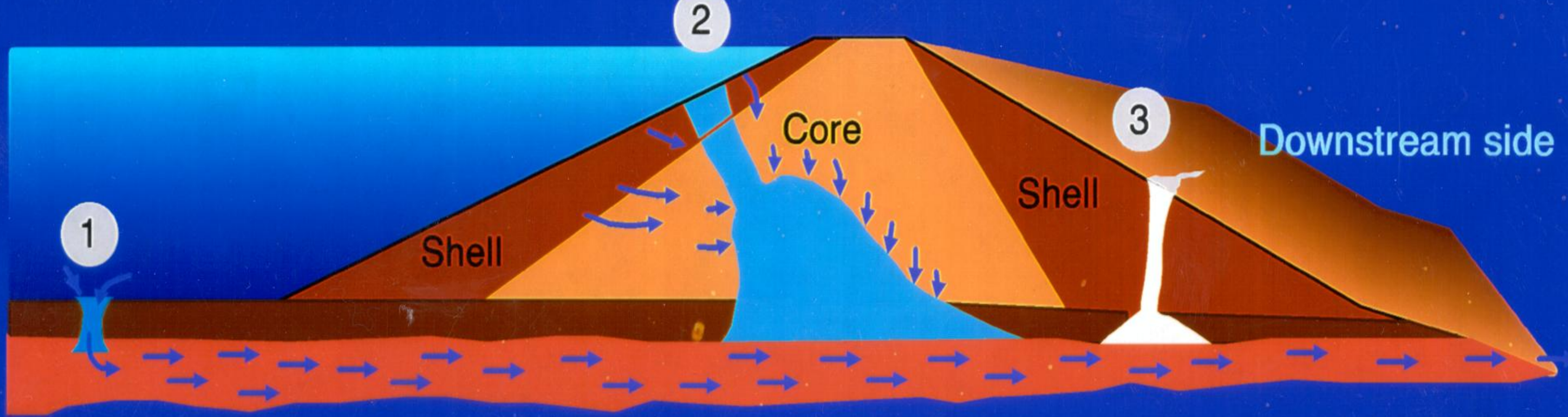

Sand Boils
Phreatic Surface
Downstream side
Seepage Flow
Shell
Shell
Core
No Problem
Sediment
Possible Problem
Fines from
layer below
Big Problem
Flow
carrying
material
Seepage flow
carrying no material
Seepage flow
carrying material

Sinkholes



TYPE 1

- Flow induced
- Limited erosion of materials
- Reservoir floor
- During drawdown bathtub analogy capacity out > supply in

TYPE 2

- Flow + Collapse
- True piping symptom

TYPE 3

- Collapse
- Erosion is from surface of materials

Defining/Describing a Failure Mode

- Use sufficient detail to clearly explain sequence of the entire failure mechanism
- Indicate potential location of the failure mode, if a preferential location (or locations) is apparent

Example Failure Mode Description

- If the backfill surrounding the outlet works conduit was poorly compacted or has cracked, a seepage pathway may exist along the conduit. Seepage flowing along this pathway could erode embankment material into cracks or open joints in the 50-year-old stilling basin underdrain system. Piping, or backward erosion, could initiate from this point. If undetected, the piping could continue to progress, forming a lengthening “pipe” through the dam, or a large void within the dam core. Either the erosion would continue to progress upstream and lead to dam breach or the pipe or void could grow and collapse (sinkhole), leading to crest loss and potential overtopping.

Example Failure Mode Description

- A concentrated seepage path from the reservoir through upstream surficial clay and silt layers, into the underlying fine-sand, and up through the downstream clay and silt layers could begin to exit unfiltered from a natural slope or would start to boil up from a submerged portion along one of the downstream alluvial channels. Backward erosion of the foundation material could begin, and a pipe could work its way to the reservoir. Rapidly increasing seepage flow could enlarge the pipe (or form a large sinkhole) sufficient to breach the overlying embankment.

Example Failure Mode Description

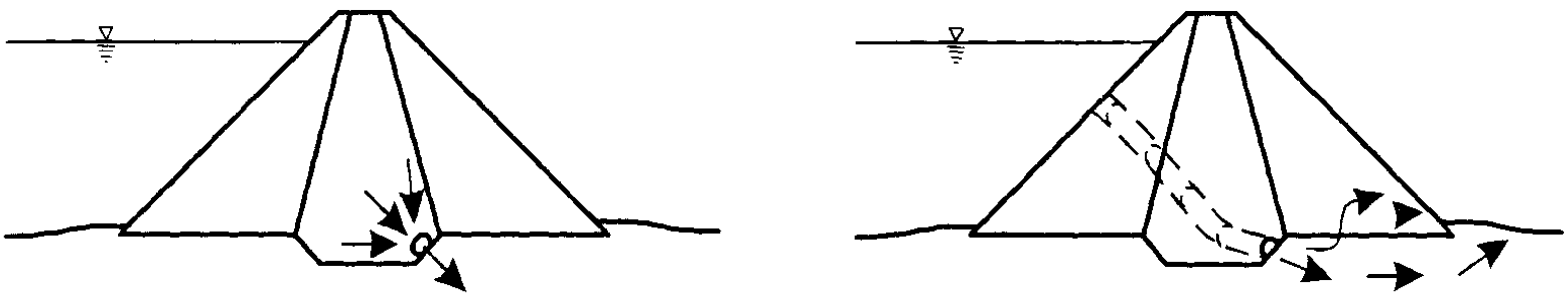
- A concentrated seepage flow through the embankment could move core soil particles into or through the coarser shell or drainage blanket materials. A possible location for this seepage flow would be at the location of the “wet seam” noted on the embankment slope. If undetected, the migration of fines could lead to formation of a “pipe” or void within the core. Once such erosion initiated, seepage velocities could increase and begin eroding more and more impervious materials, carrying these materials through the coarser downstream zones. Ultimately, the developing erosion within the core would either create a large void that could collapse and cause a crest loss to below the available freeboard; or the pipe would erode backward and connect to the reservoir, allowing major flows that could lead to further erosion and breach of the embankment.

Risk Analysis

- Once a failure mode has been considered and thoroughly described in a failure mode evaluation process, an obvious next step can be to perform a quantitative risk analysis.

- Failure mode is broken into a series of steps, with the probability of each step estimated.

General Event Tree Model



INITIATION	→	CONTINUATION	→	PROGRESSION	→	BREACH/FAILURE
Leakage exits the core into the foundation and backward erosion initiates as core erodes into the foundation		Continuation of erosion		Backward erosion progresses to form a pipe. Eroded soil is transported in the foundation		Breach mechanism forms

(d) Internal erosion from the embankment to foundation initiated by backward erosion

Typical Event Tree for Risk Analysis

- Reservoir Rises
  - Initiation – Flaw exists [1]
    - Initiation – Erosion starts
      - Continuation – Unfiltered exit exists (consider: no erosion/some erosion/excessive erosion/continuing erosion)
        - Progression – Roof forms
          - Progression – Upstream zone fails to crack stop
            - Progression – Upstream zone fails to limit flows
              - Intervention fails
                - Dam breaches (consider all likely breach mechanisms)
                  - Consequences occur

Questions

and

Discussion