Federal Energy Regulatory Commission

Potential Failure Modes for Piping and Internal Erosion

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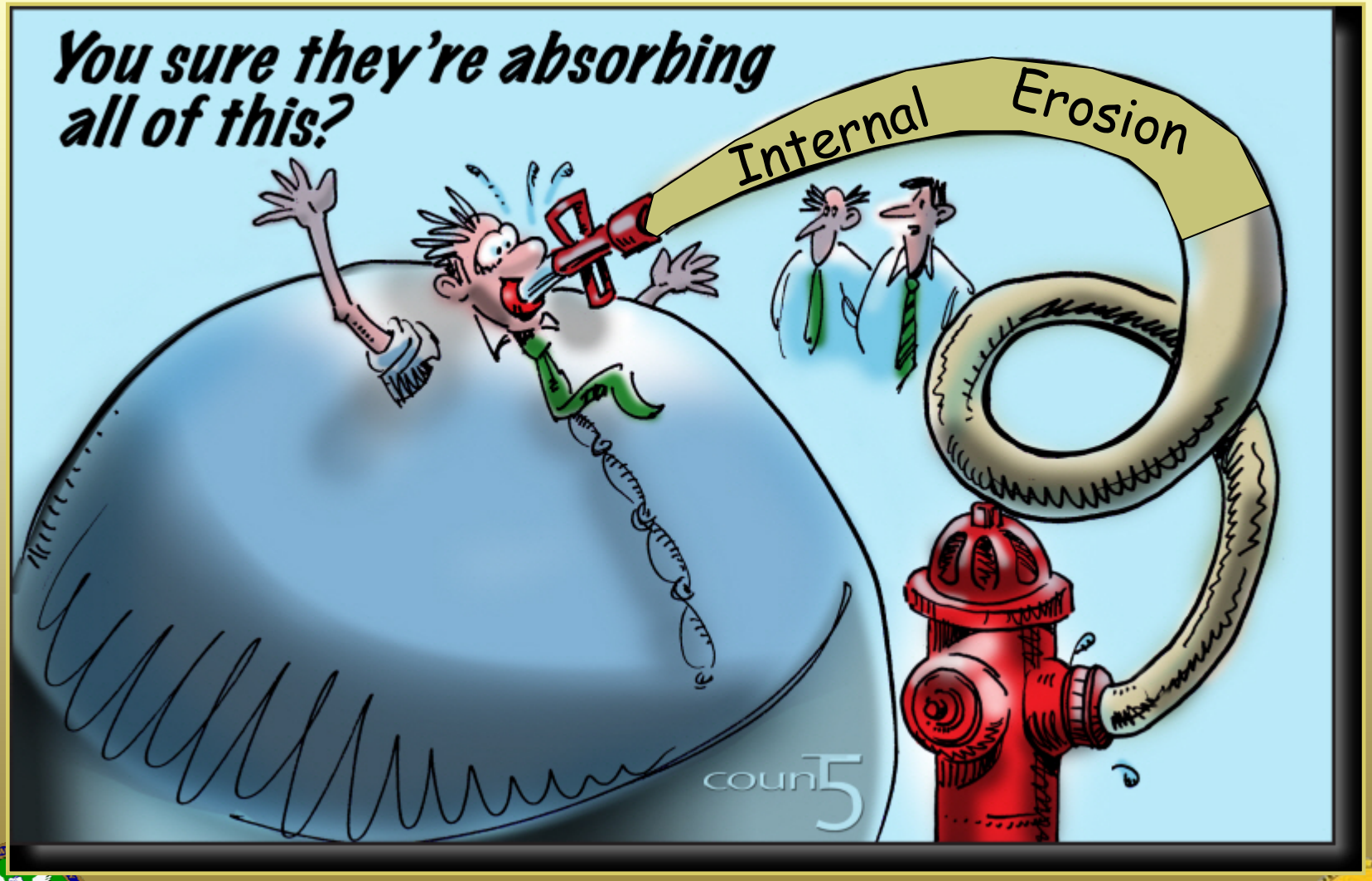
2013 Oregon Dam Safety Conference
February 26, 2013


You sure they're absorbing all of this?
Internal Erosion
count5

Internal Erosion in Embankment Dams

- 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
- One of the most **difficult** mechanisms to understand

Internal Erosion vs Piping*

- **Internal Erosion –** The formation of voids within soil or soft rock caused by the mechanical or chemical removal of material by seepage. See erosion.

- **Simply – Transportation of the finer grained soil portion of a well-graded soil by water**

- **Piping –** The erosion of embankment or foundation material (soil) due to seepage/leakage. The action of water passing through or under an embankment dam and carrying with it to the surface at the downstream face some of the finer material. The progressive removal of soil particles from a mass by percolating water leading to the development of channels. The progressive development of internal erosion by seepage, appearing downstream as a hole discharging water. The process of conveying erodible embankment or foundation materials through a continuous, open "pipe" which is able to maintain a self-supported roof. The pipe normally begins at an unprotected exit and works it's way upstream (up gradient) along an erodible flow path until the reservoir is reached

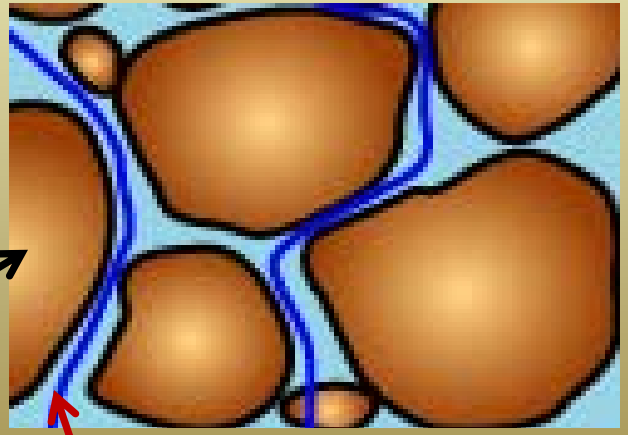
- **Simply - Soils being washed out of an earthen structure through an unfiltered exit.**

*** http://www.usbr.gov/library/glossary/**

Internal Erosion in Embankment Dams

Three components of soil

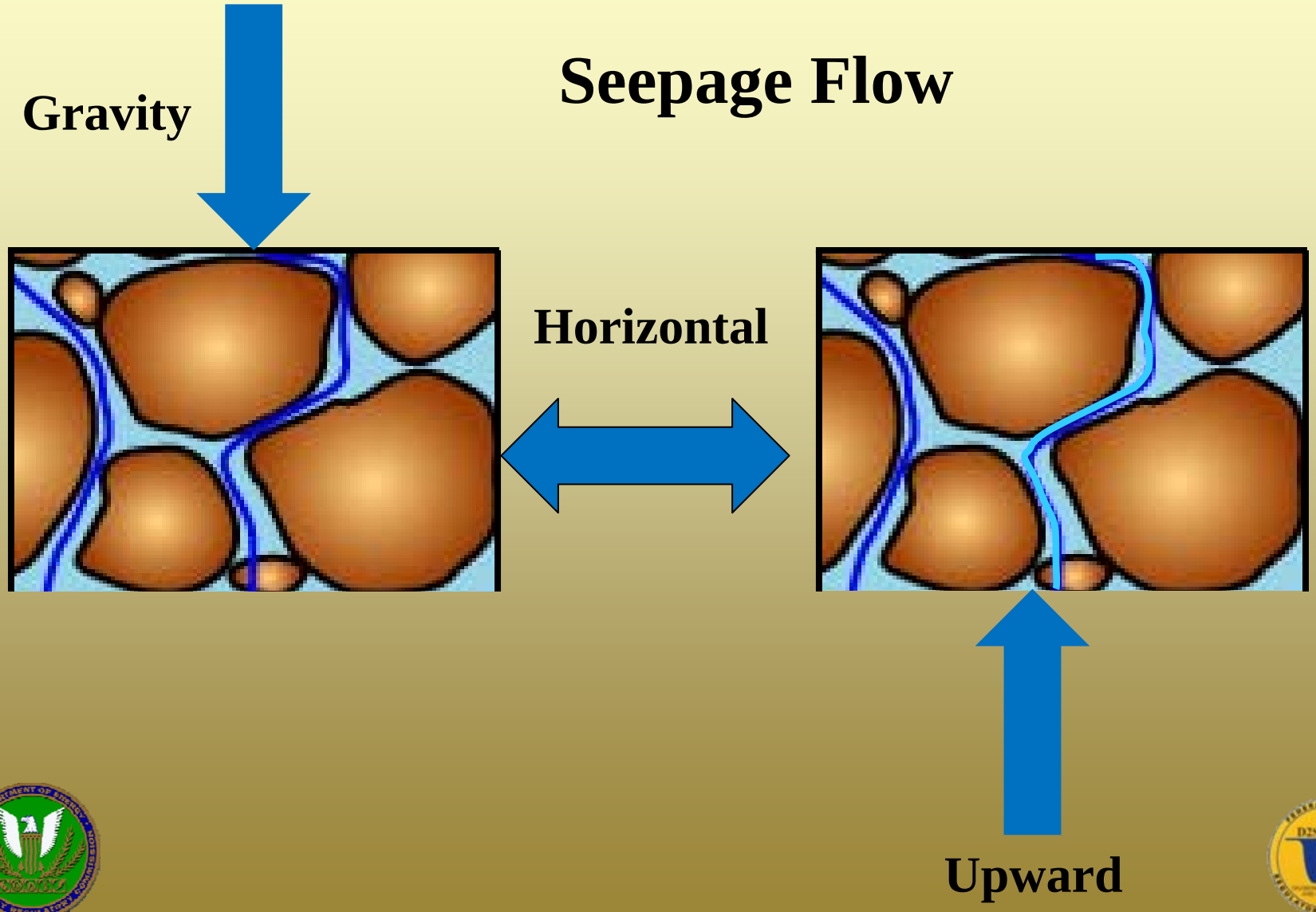
1. Soil Grains
2. Air
3. Water



Soil Grain

Void Spaces filled
with water and/or air

Internal Erosion in Embankment Dams



Internal Erosion in Embankment Dams

Particle Size

clay silt sand cobbles

Plasticity in this range limits the potential for grains to detach

Forces typically not large enough to move particles in this size range

Potential for soil grain movement is bounded by size

Piping Potential of Soils

Greatest Piping Resistance	Plastic clay, (PI>15), Well compacted.
	Plastic clay, PI>15), Poorly Compacted.
Intermediate Piping Resistance	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	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

Types of Internal Erosion Problems

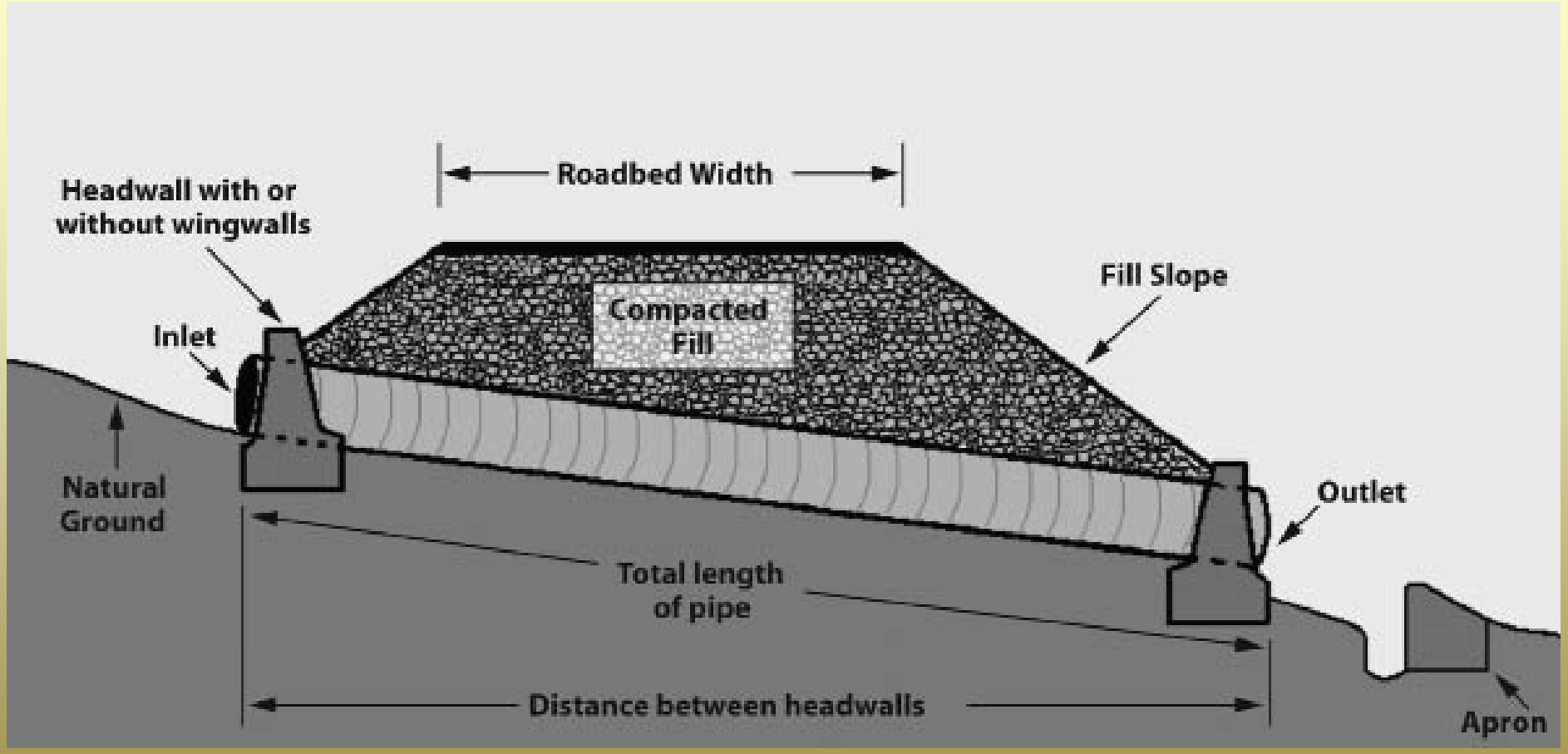
- Classical Piping ("roof forms")
- Progressive Erosion (Sinkhole development)
- Blowout - Heave, Uplift (can be multiple mechanisms)
- Scour
- Suffusion (internal instability)

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**

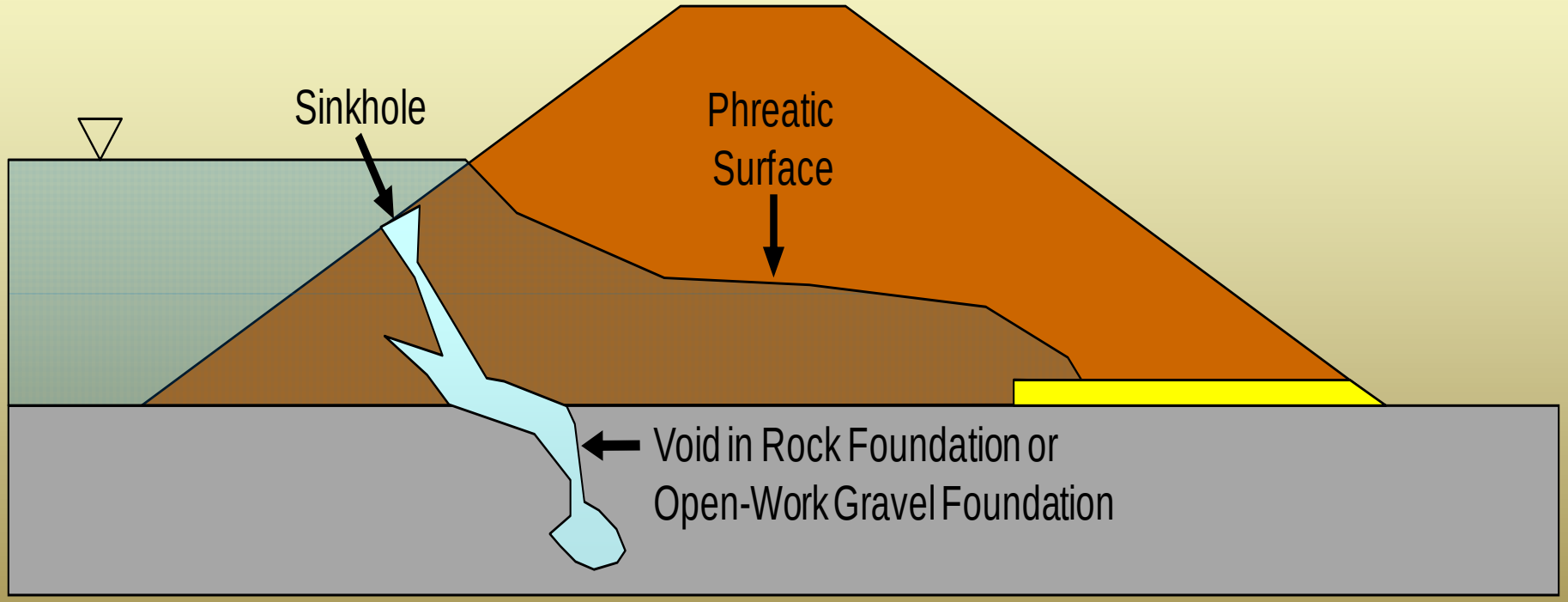
Piping


Roadbed Width
Headwall with or without wingwalls
Fill Slope
Compacted Fill
Inlet
Natural Ground
Outlet
Total length of pipe
Distance between headwalls
Apron

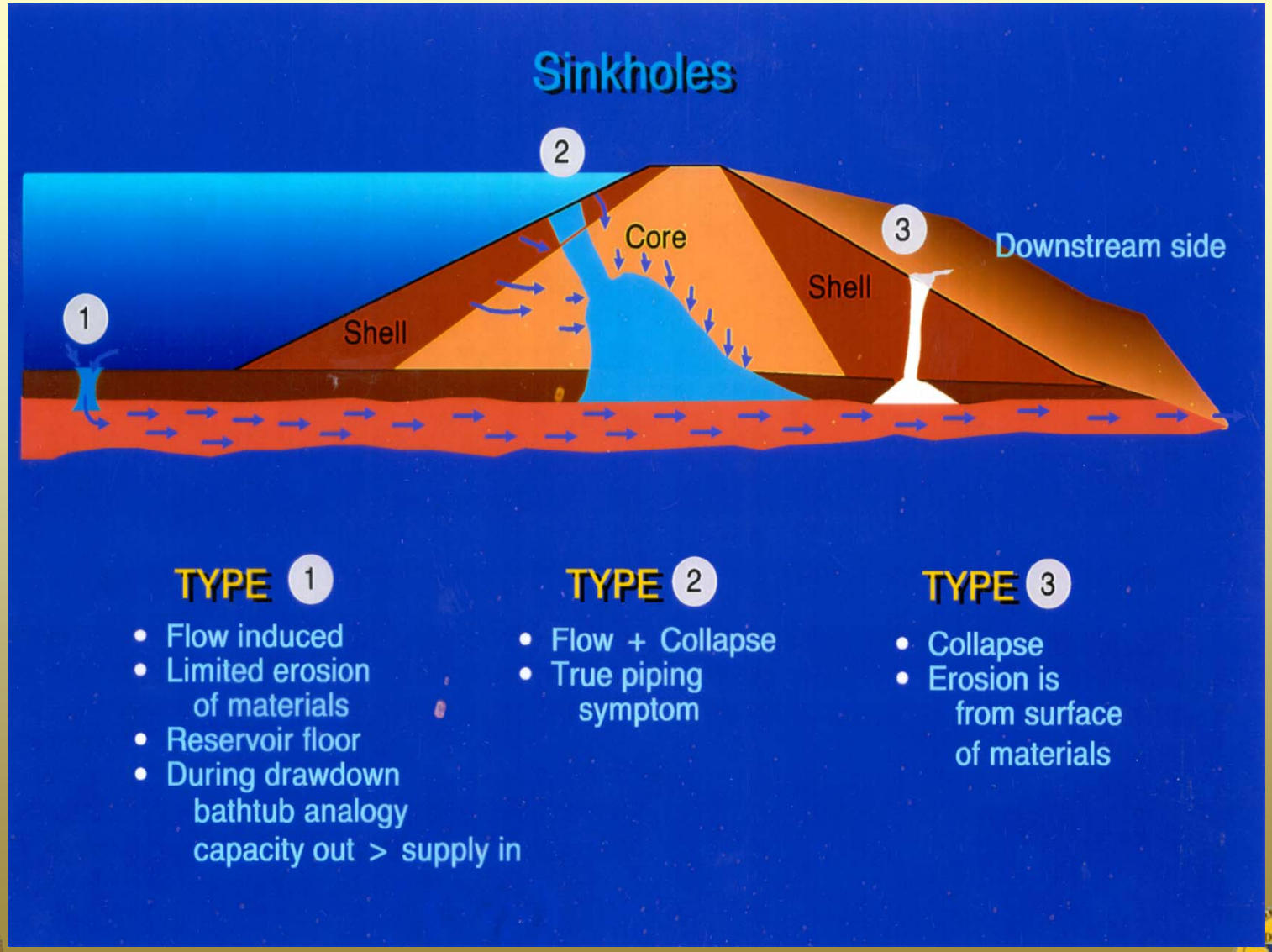
Progressive Erosion

- 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 a **sinkhole develops** at the surface of the dam. May result in a breach of the core **or instability** of the upstream or downstream slope.

Progressive Erosion



Sinkholes

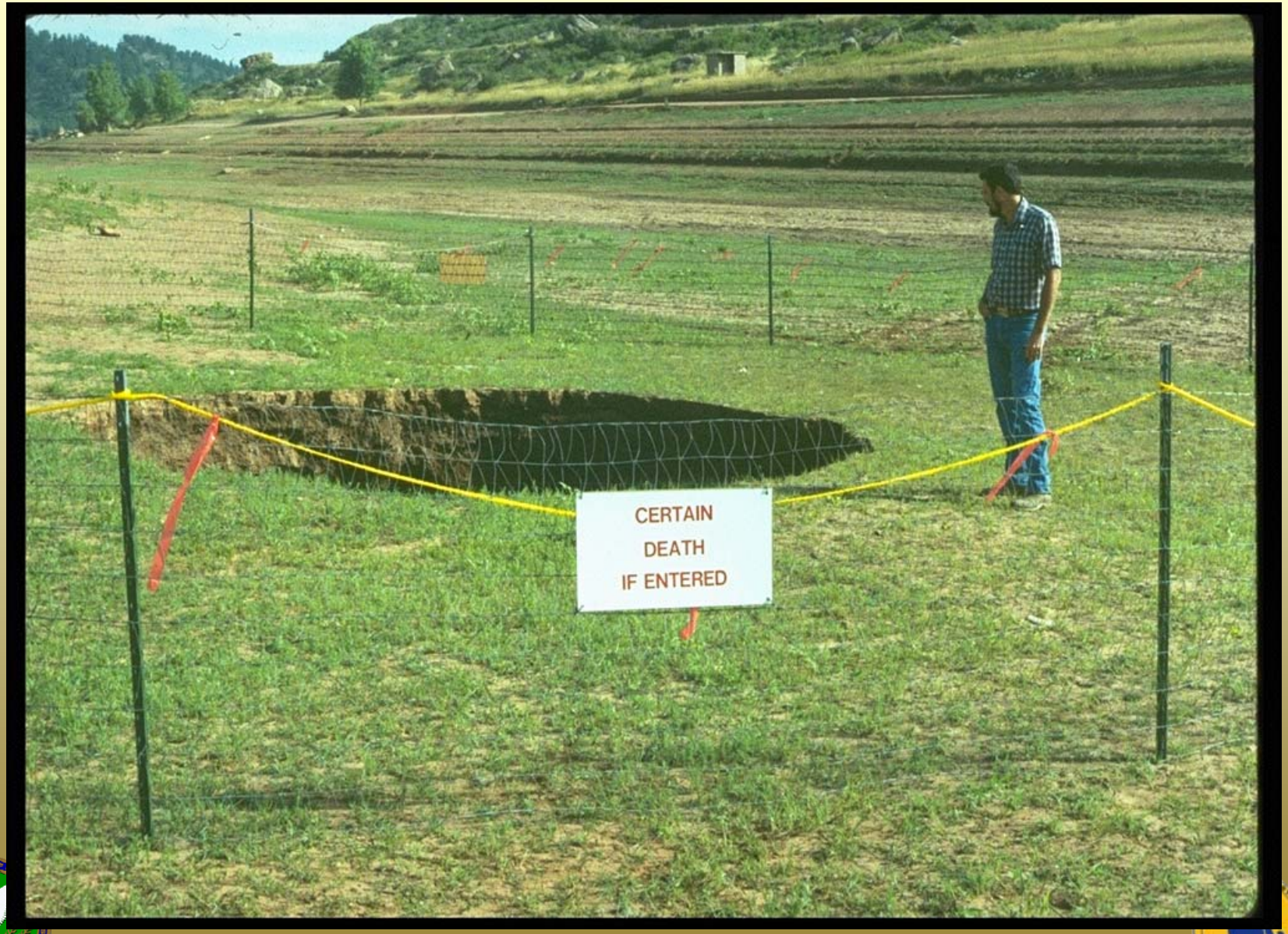

Sinkholes
2
Core
3
Downstream side
Shell
1
Shell
TYPE 1
• Flow induced
• Limited erosion of materials
• Reservoir floor
• During drawdown bathtub analogy capacity out > supply in
TYPE 2
• Flow + Collapse
• True piping symptom
TYPE 3
• Collapse
• Erosion is from surface of materials

Sinkholes

Sinkholes

Sinkholes

Sinkholes

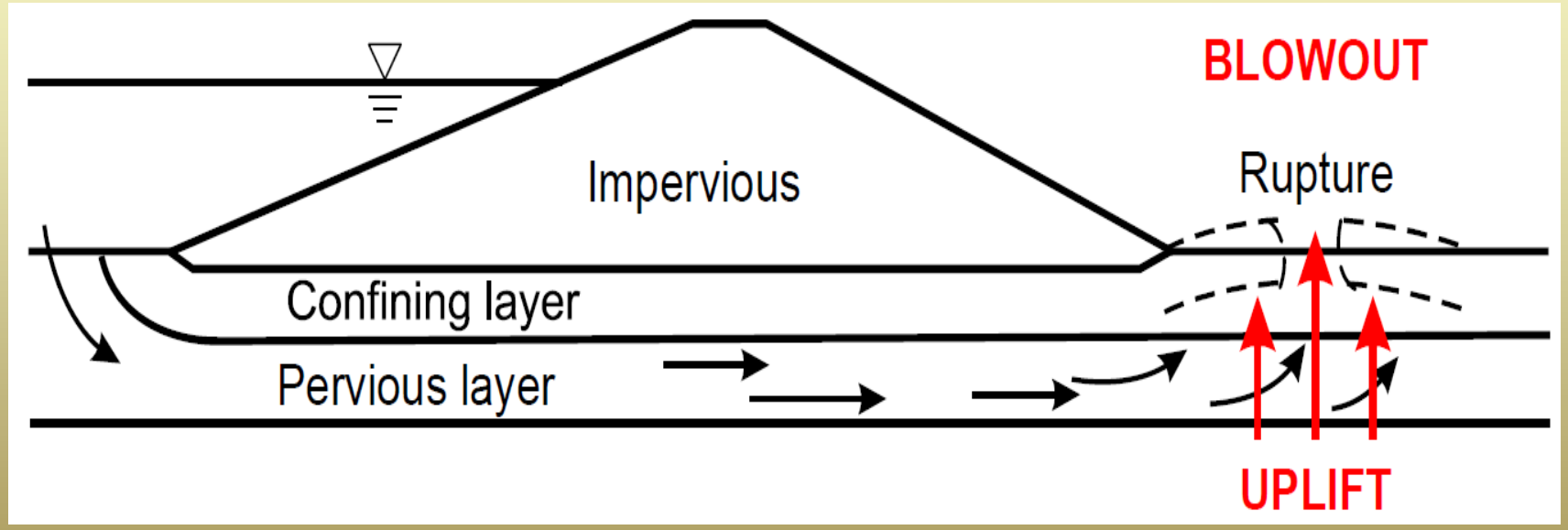


Sinkholes

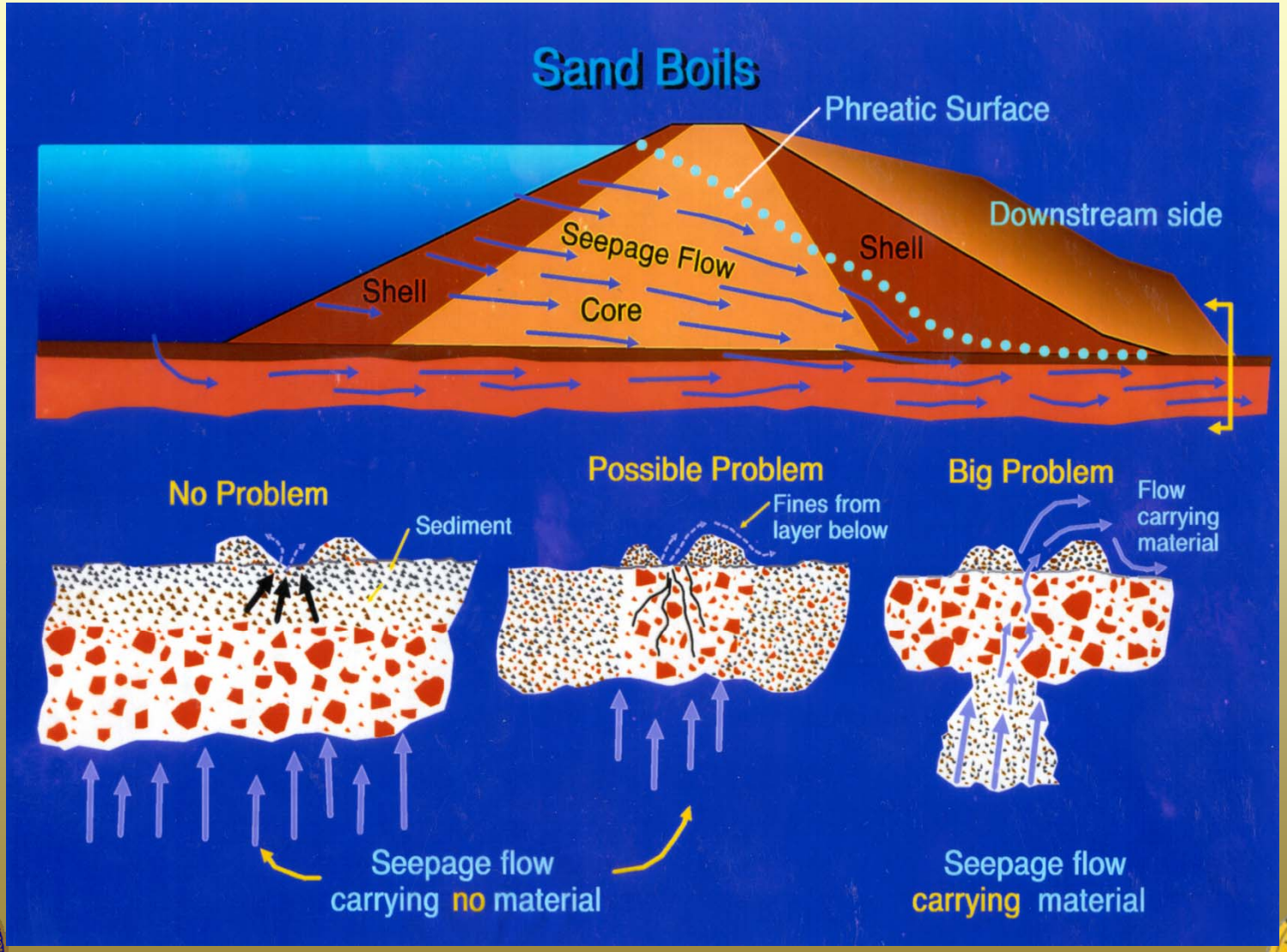
Blowout – Heave, Uplift

- 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**

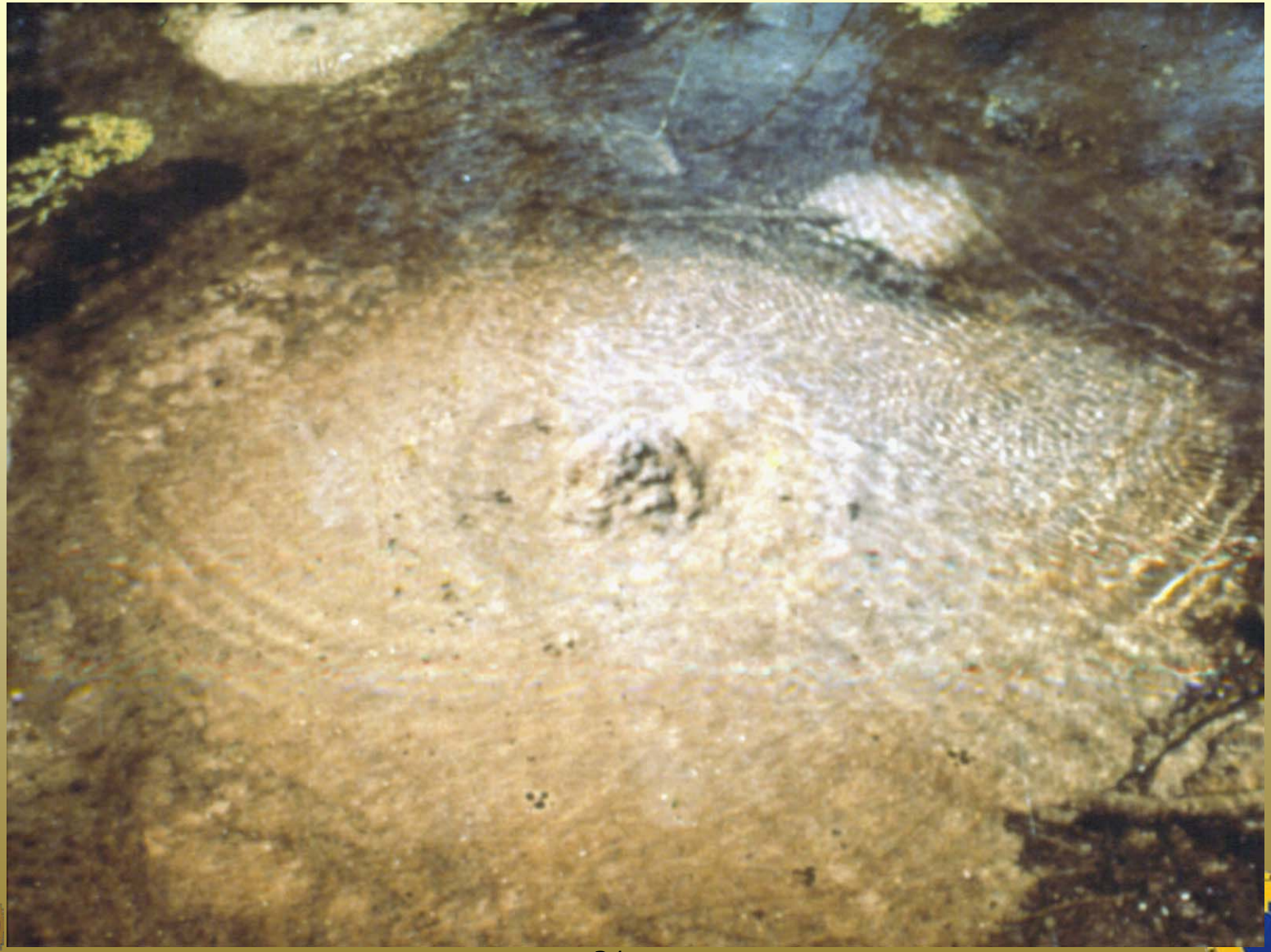
Heave


BLOWOUT
Impervious
Rupture
Confining layer
Pervious layer
UPLIFT

Sand Boils


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

Sand Boils



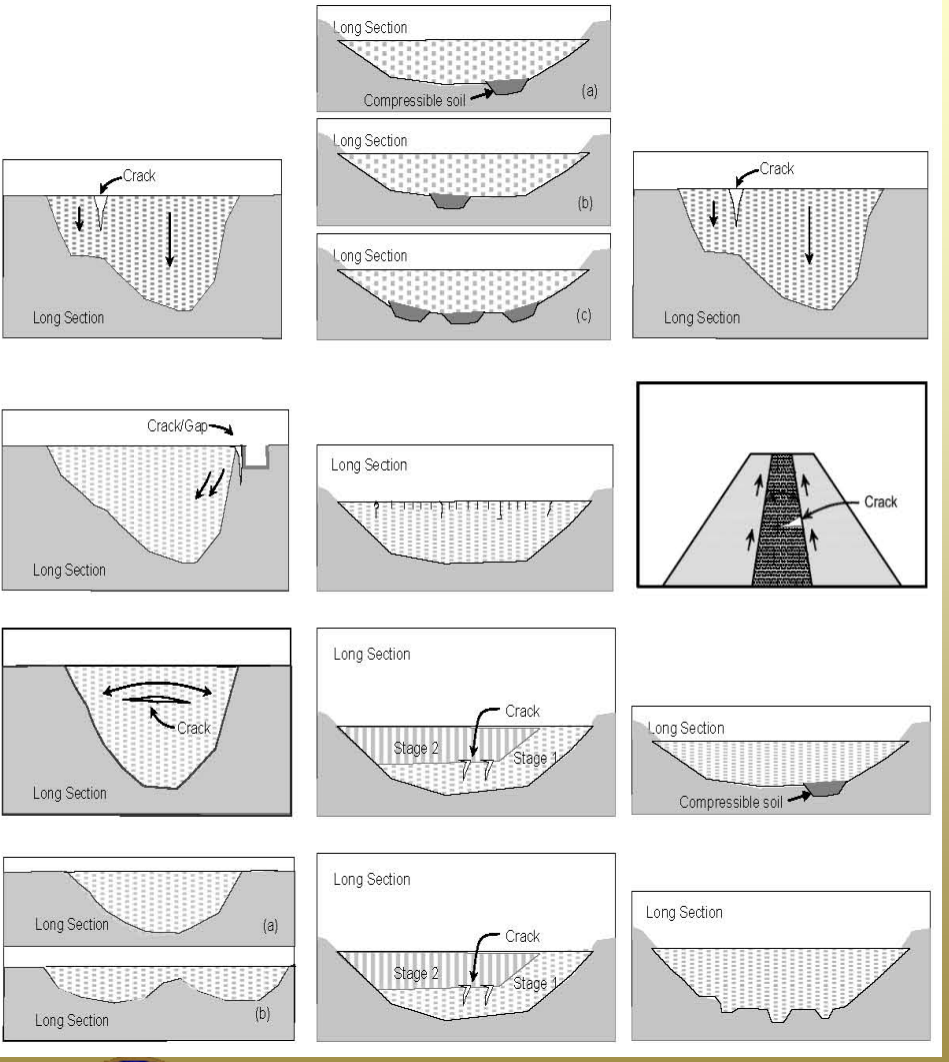
Sand Boils

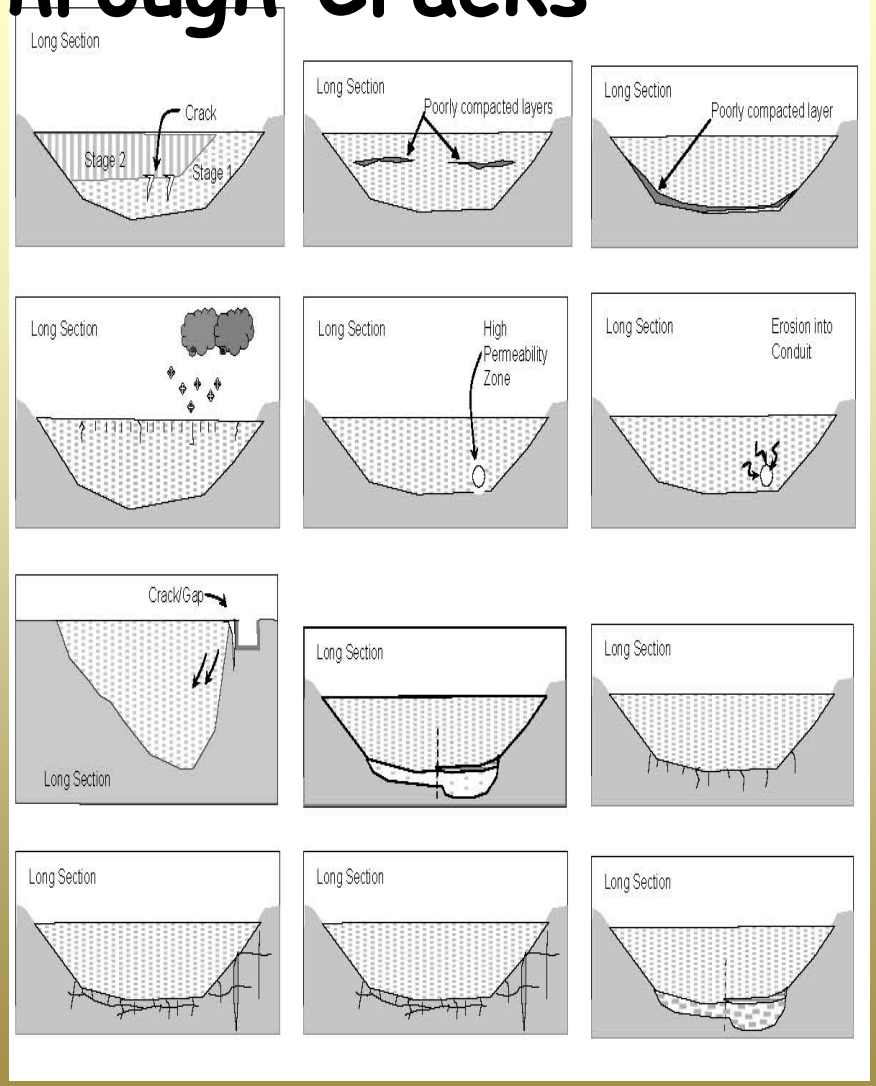
Scour

- 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**.
- **Breach** results in loss of reservoir through the eroded area.

Scour

Scour – Erosion through Cracks





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.

Suffusion

Before

After

Internal Erosion and Piping Potential Failure Modes

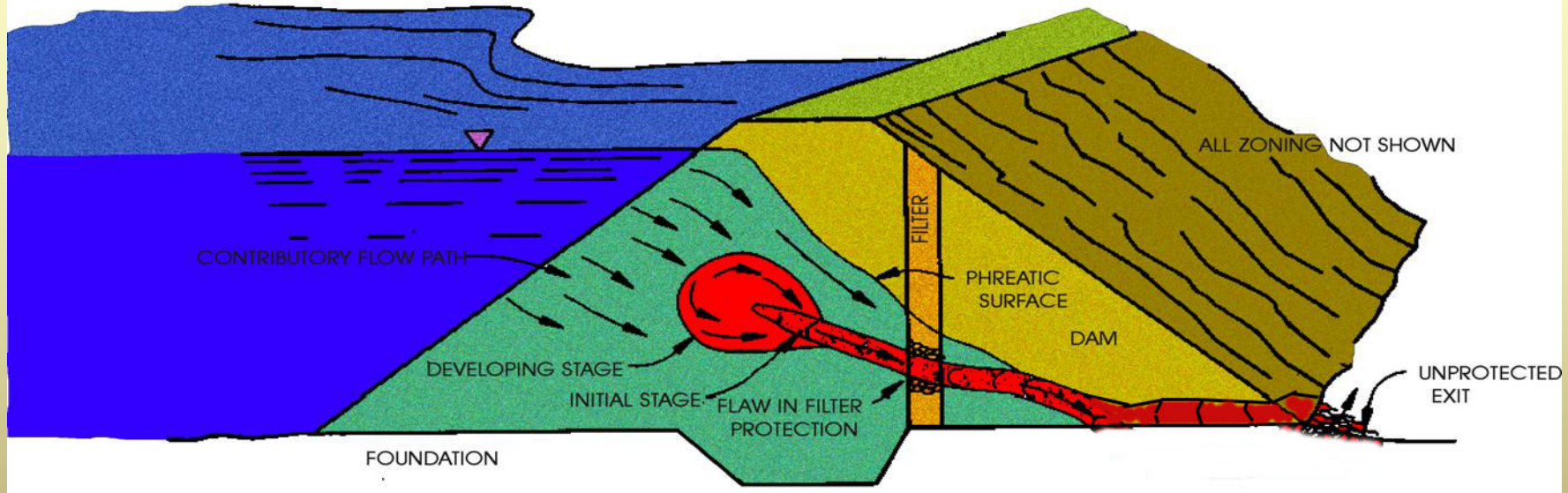
General Types of Failure Modes

- Help in understanding the **mechanisms** of internal erosion
- Note that these are "**types**" of failure modes, and definitely **not sufficient** to consider as "descriptions" of failure modes

General Types of Potential Failure Modes

- Internal erosion (piping) through embankment.

Piping through Embankment



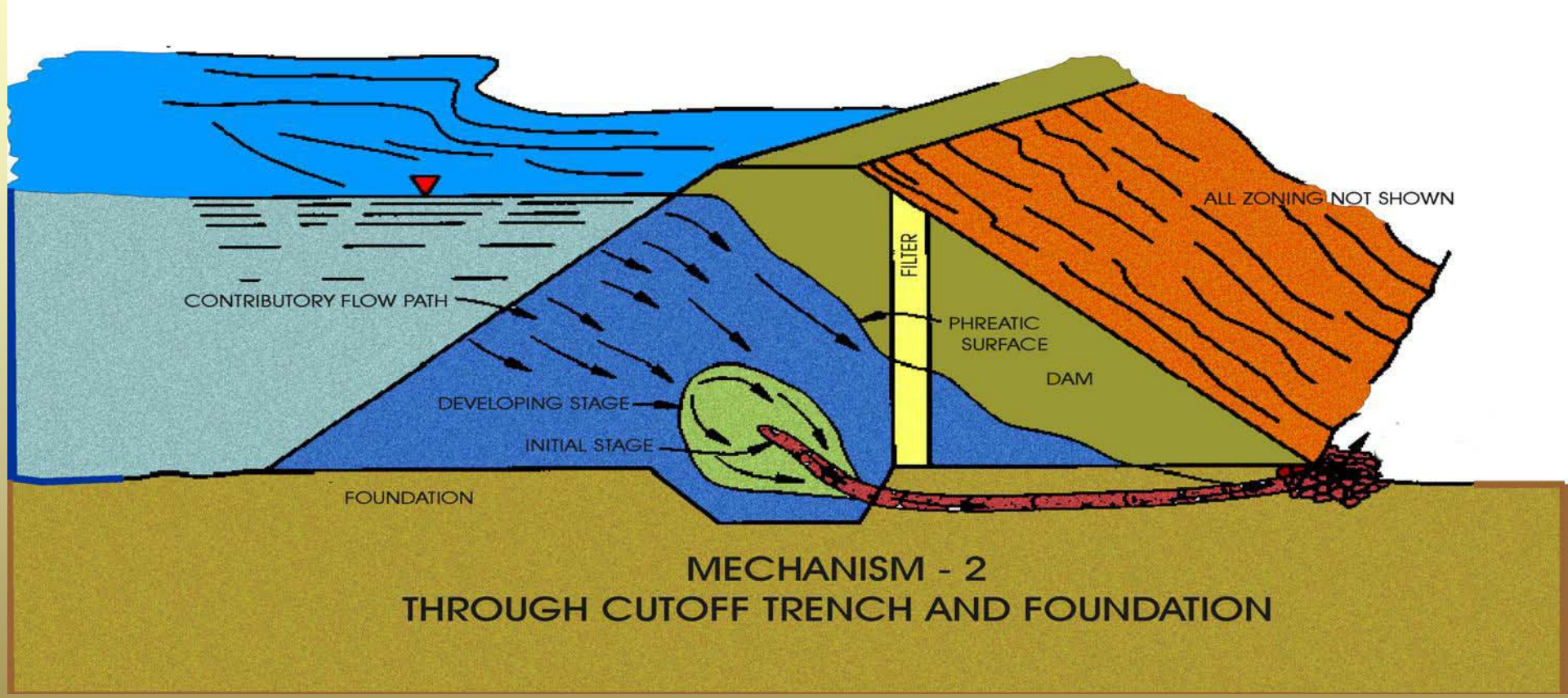
MECHANISM - 1
THROUGH EMBANKMENT

Piping through Embankment

General Types of Potential Failure Modes

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

Piping of Embankment into Foundation



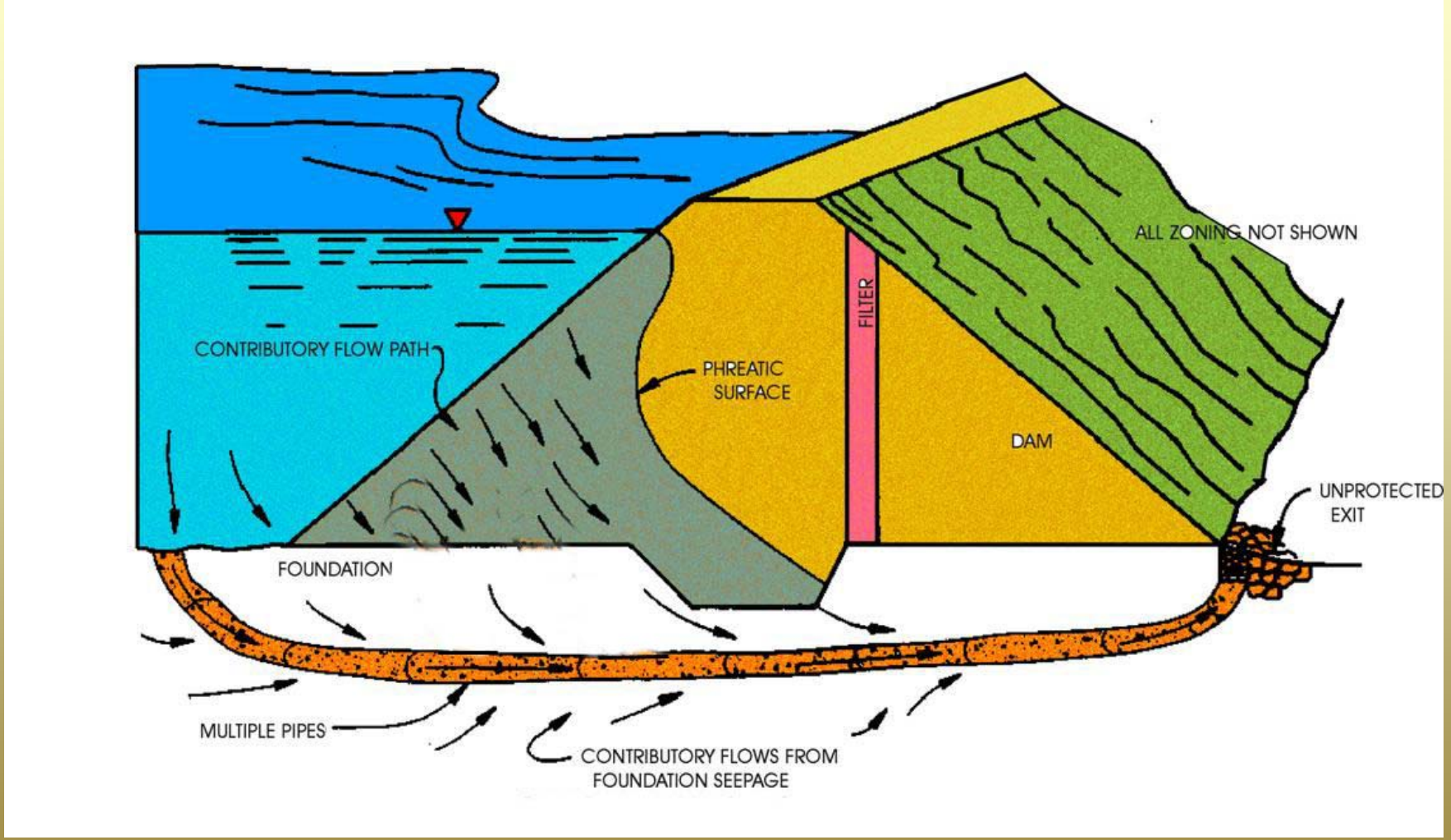
Piping of Embankment into Foundation

Swift No. 1 Dam – Lewis River, WA

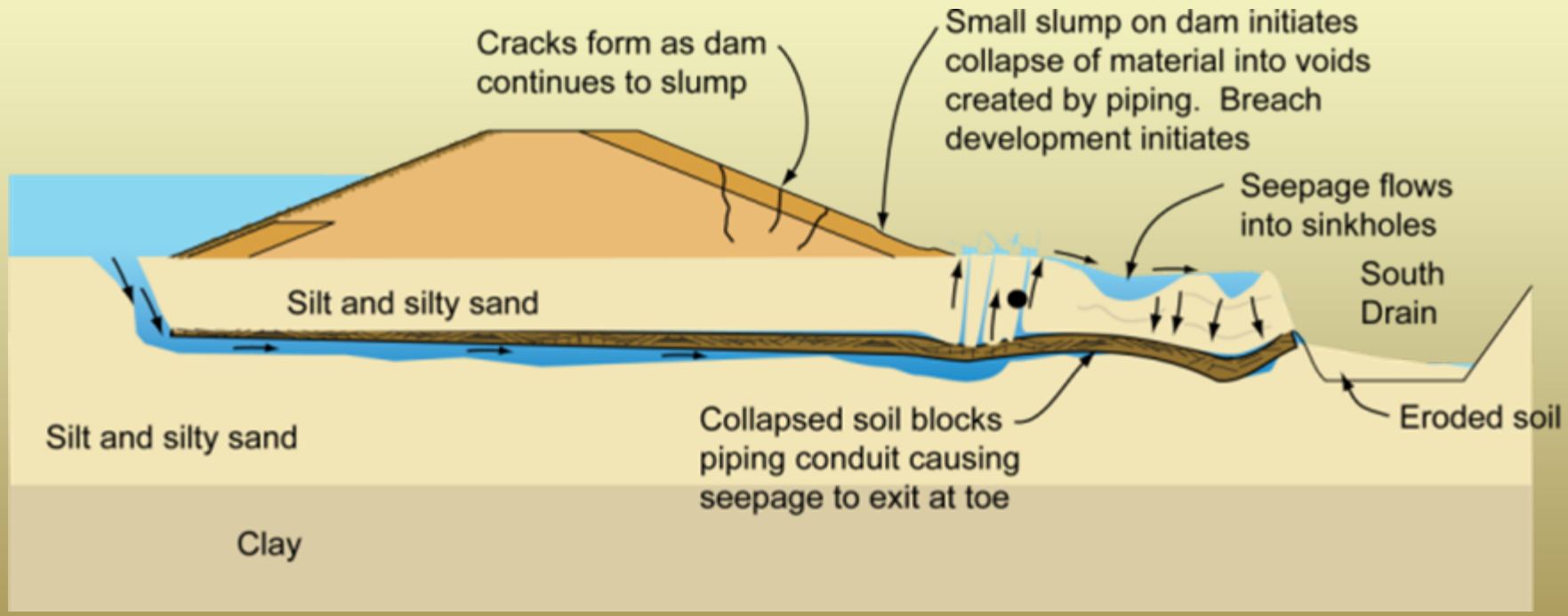
General Types of Potential Failure Modes

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

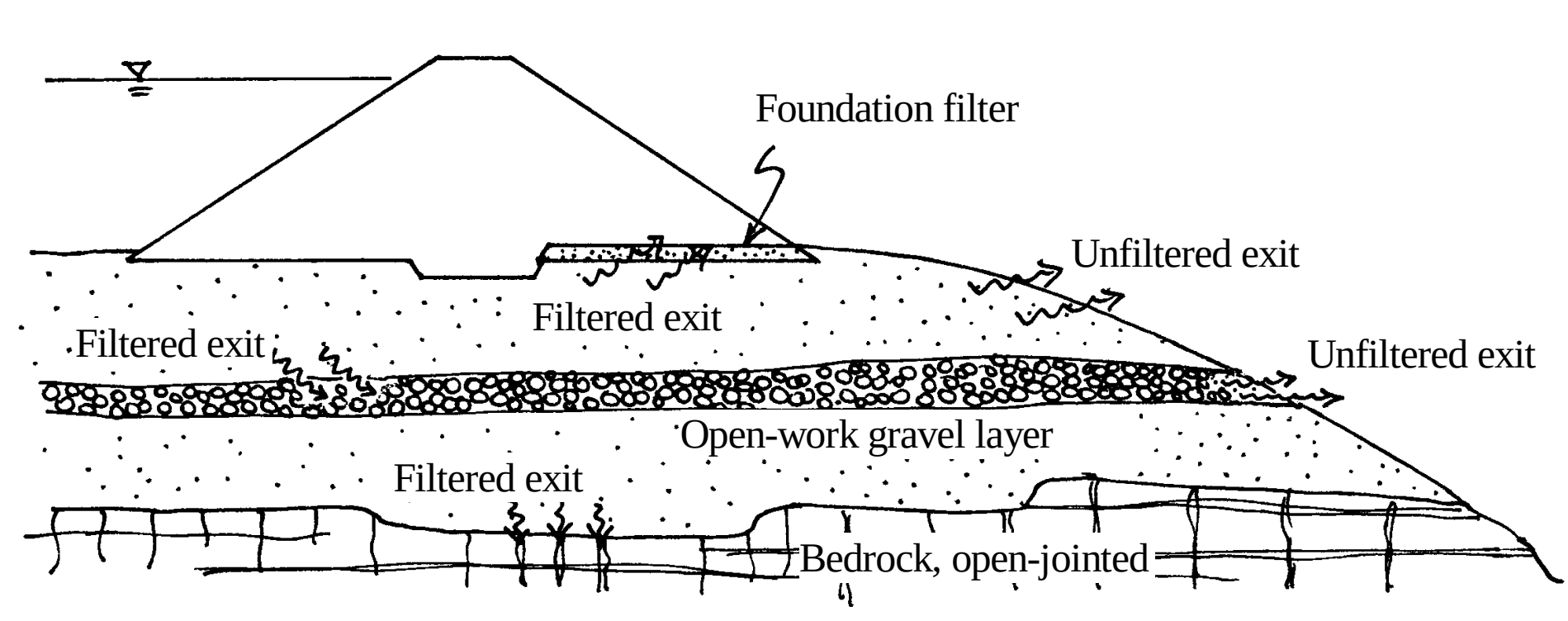
Piping Through Foundation



Piping Through Foundation



Possible Pathways/Exit Points



General Types of Potential Failure Modes

- Internal erosion (piping) through embankment.
- Internal erosion (piping) from embankment into foundation.
- Internal erosion (piping) through foundation.
- **Piping into or along embankment penetrations/walls**

Piping Along/Into Penetrations

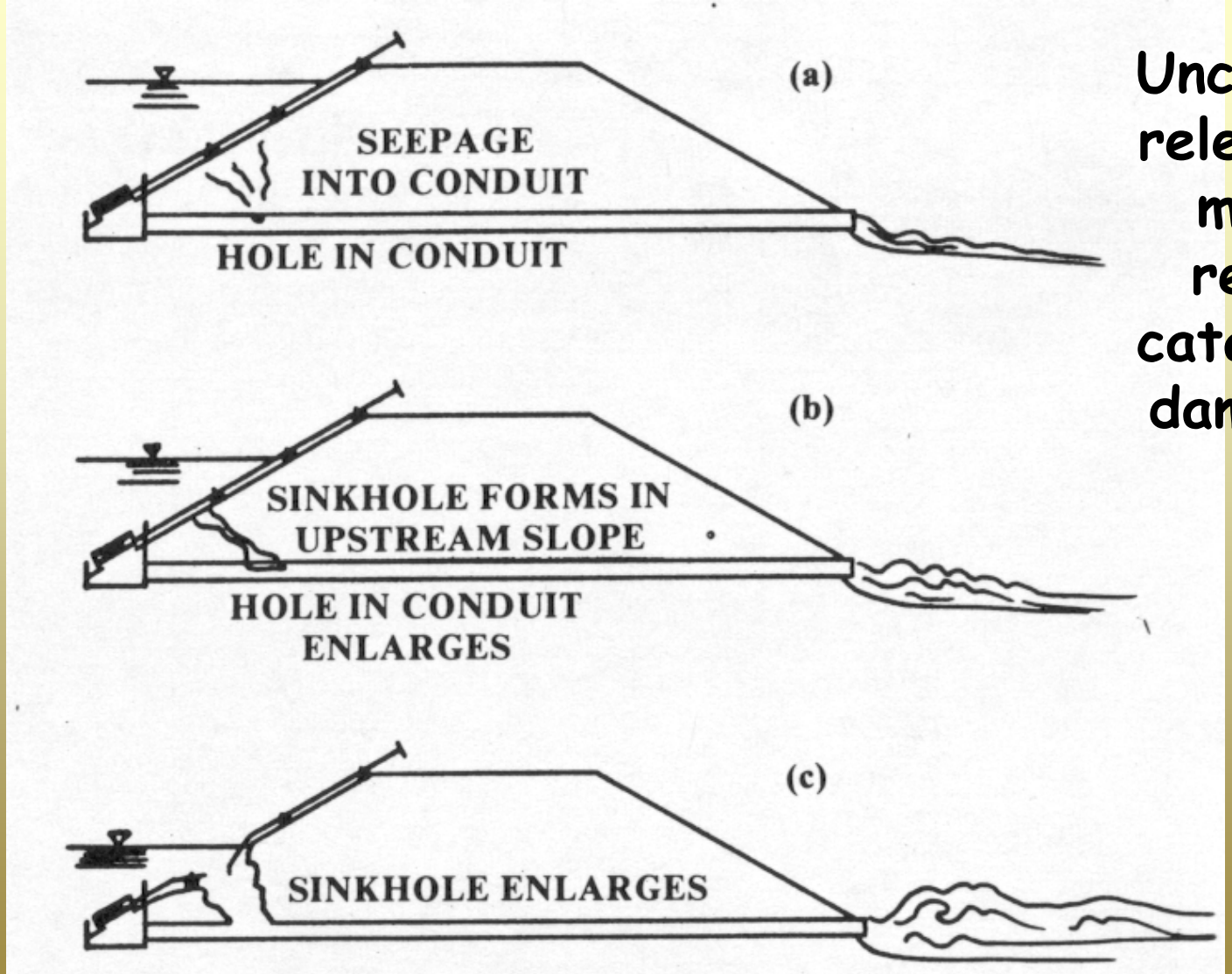


FIGURE 9.4-2 — RESERVOIR EMPTIED THROUGH THE OUTLET BECAUSE OF A HOLE IN THE UPSTREAM END OF THE PIPE.

Uncontrolled release, but may not result in catastrophic dam failure

Piping Along/Into Penetrations

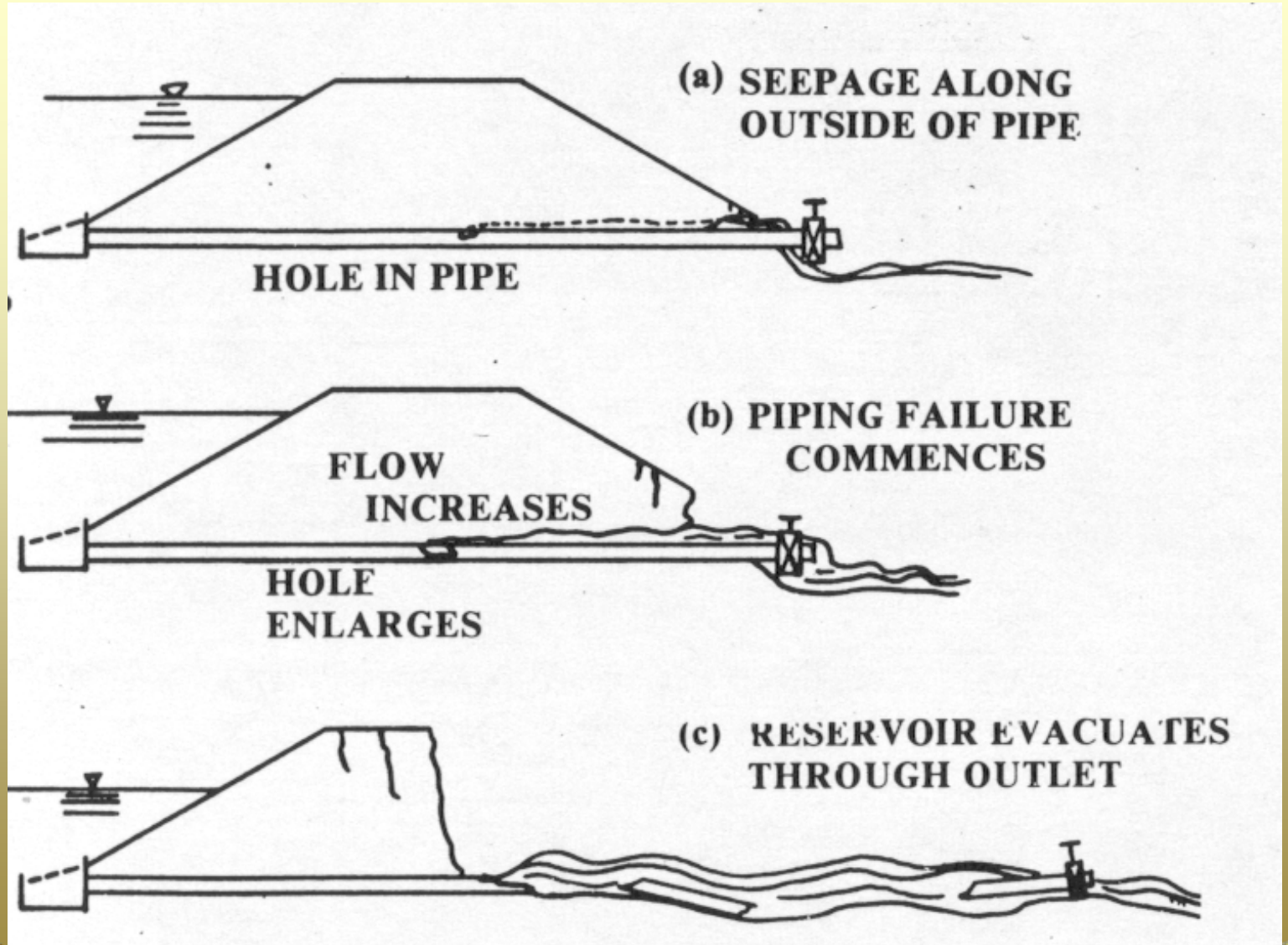
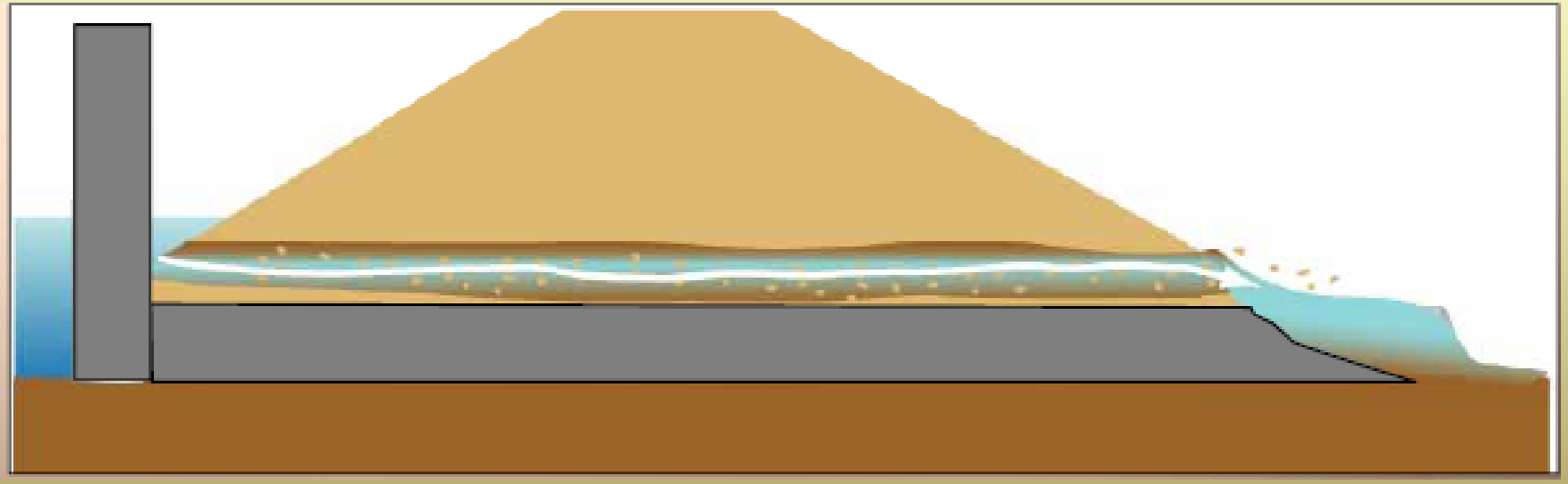


FIGURE 9.4-1 — FAILURE CAUSED BY LEAKAGE ALONG THE OUTSIDE OF THE OUTLET PIPE

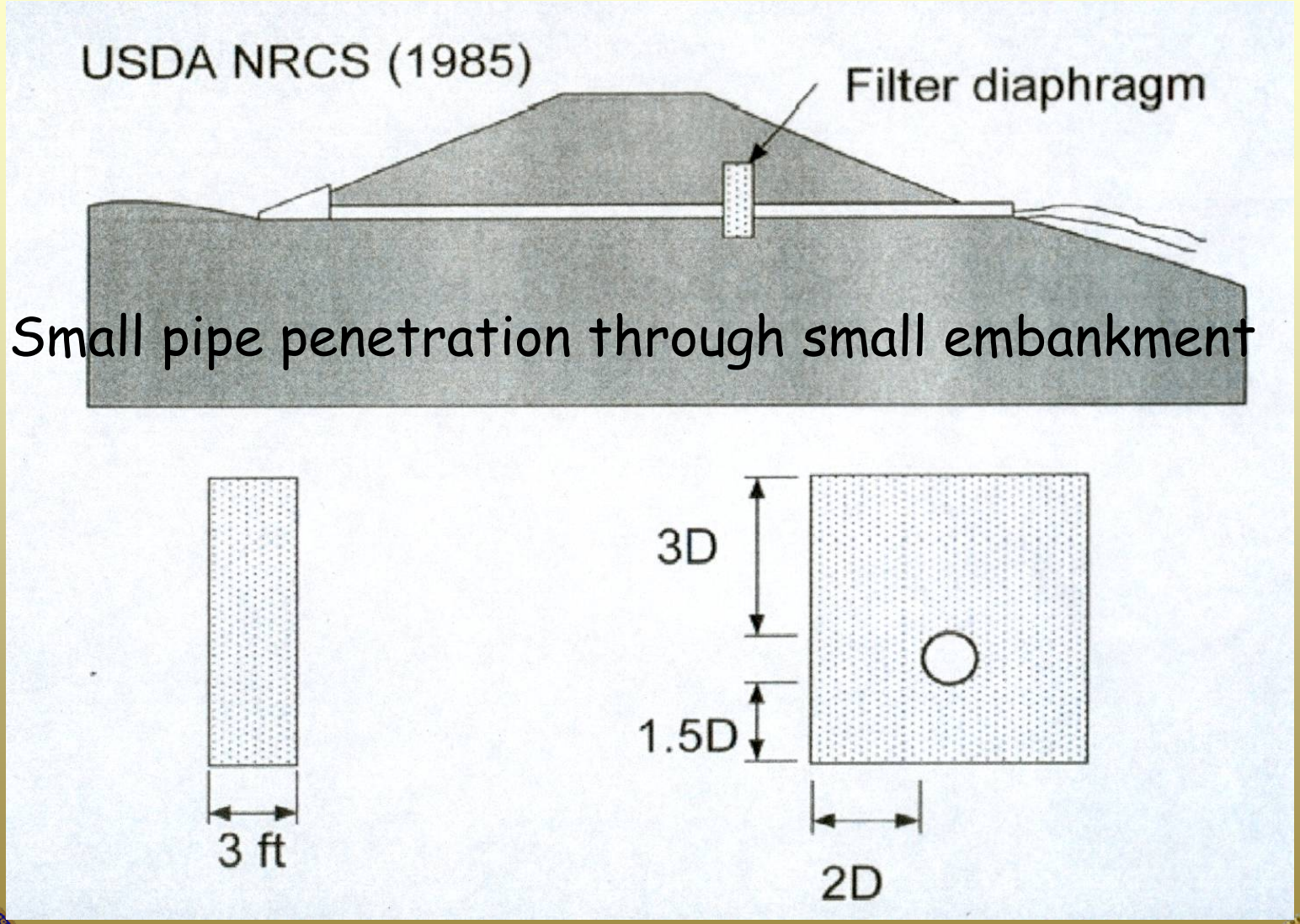
Piping Along/Into Penetrations



Piping along a conduit

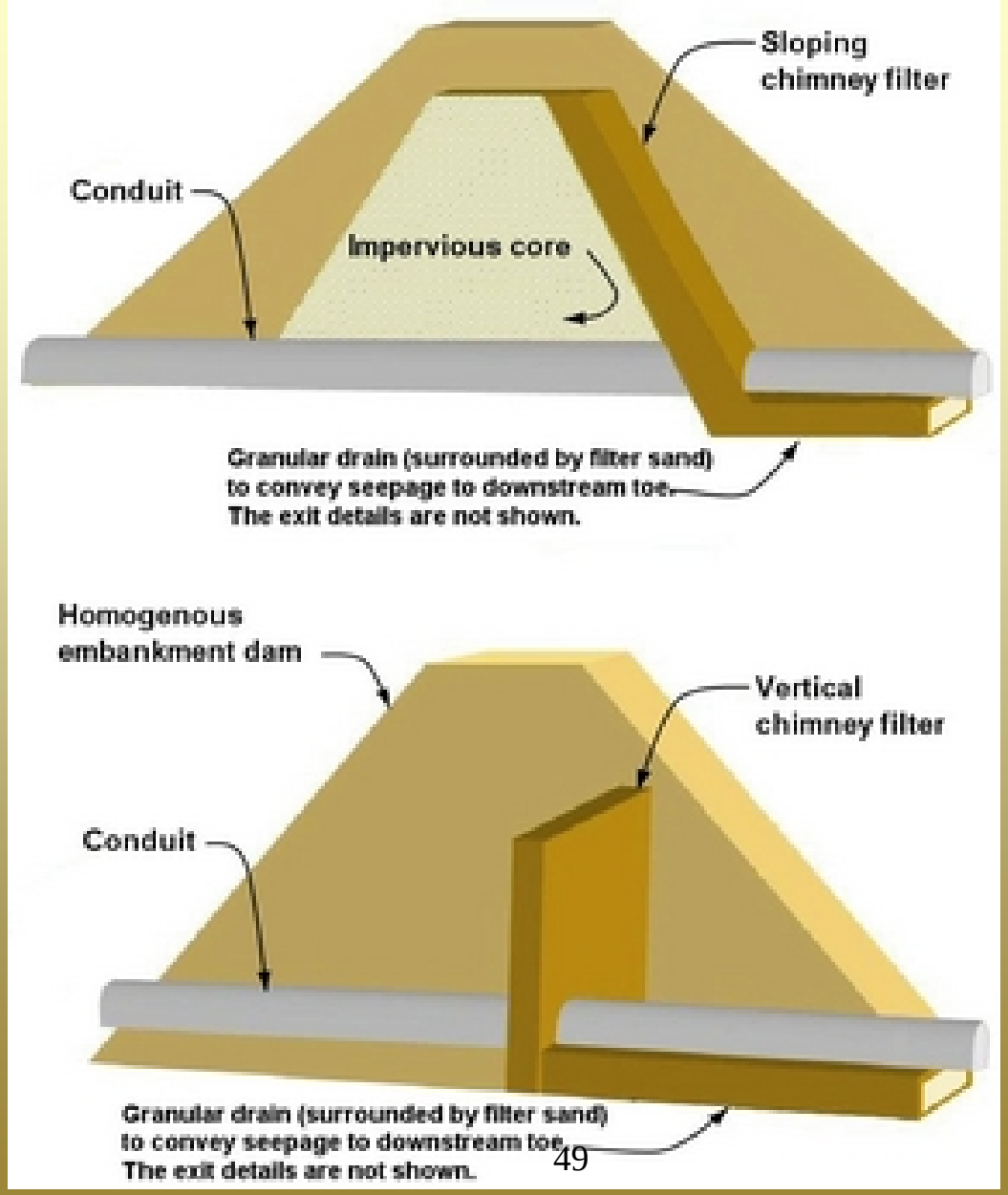
Piping Along/Into Penetrations

Proper Design Techniques



Small pipe penetration through small embankment

Proper Design Techniques

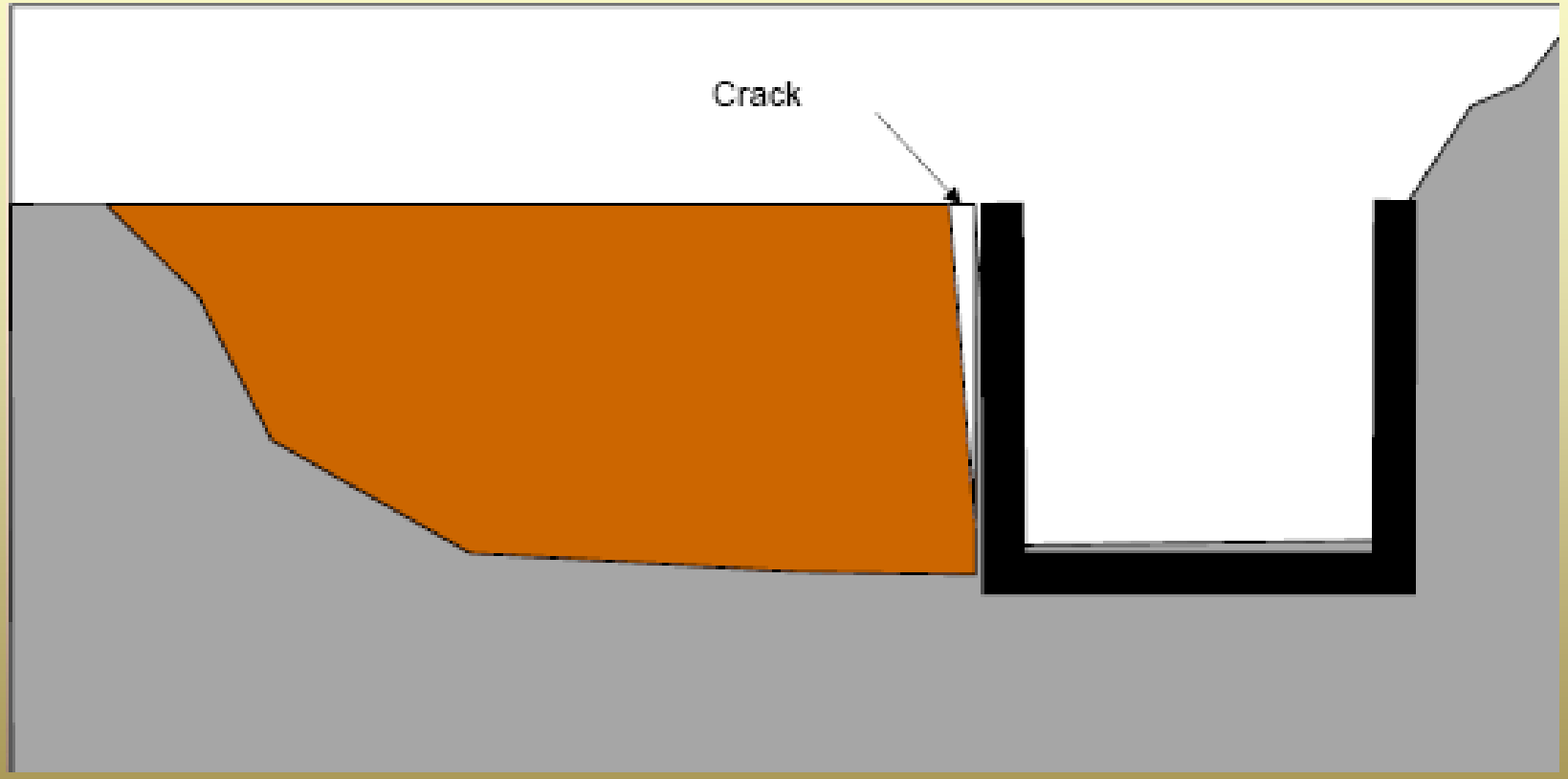


Typical filter design for larger embankment

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)

Penetrating Structures

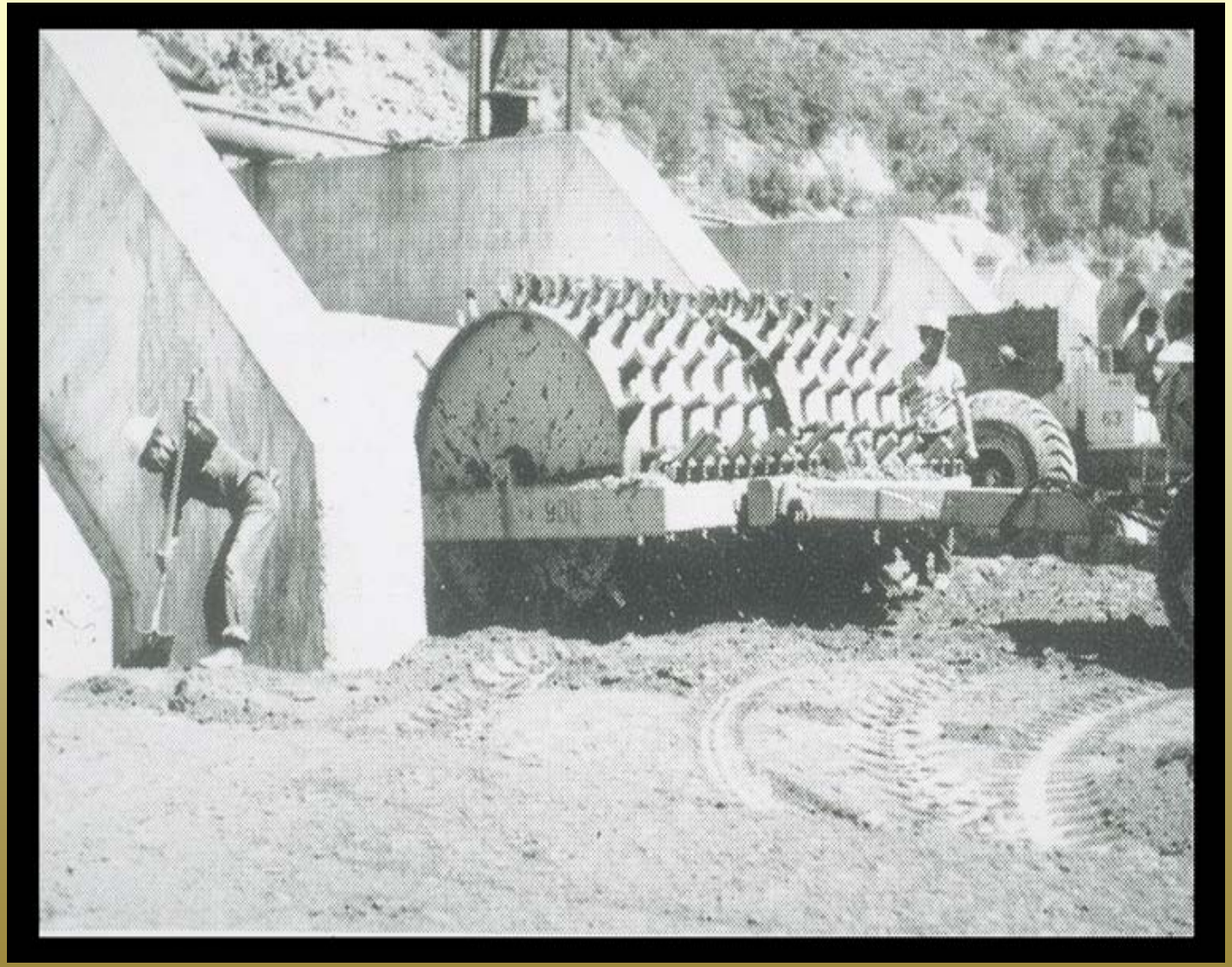


Examples of Internal Erosion and Piping

Muskrat Borrows

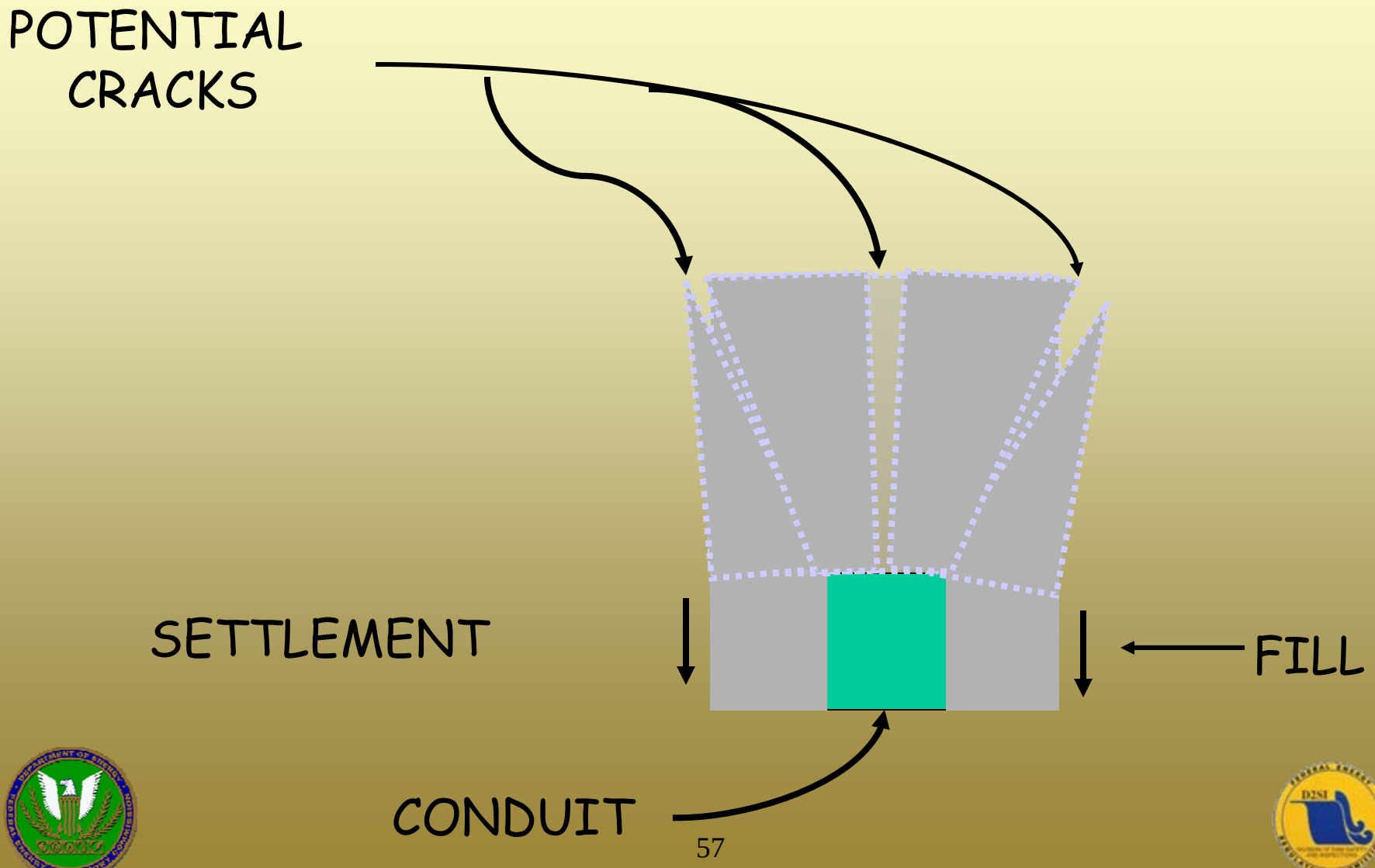
What's the Problem?

Cutoff Collars Get in the Way



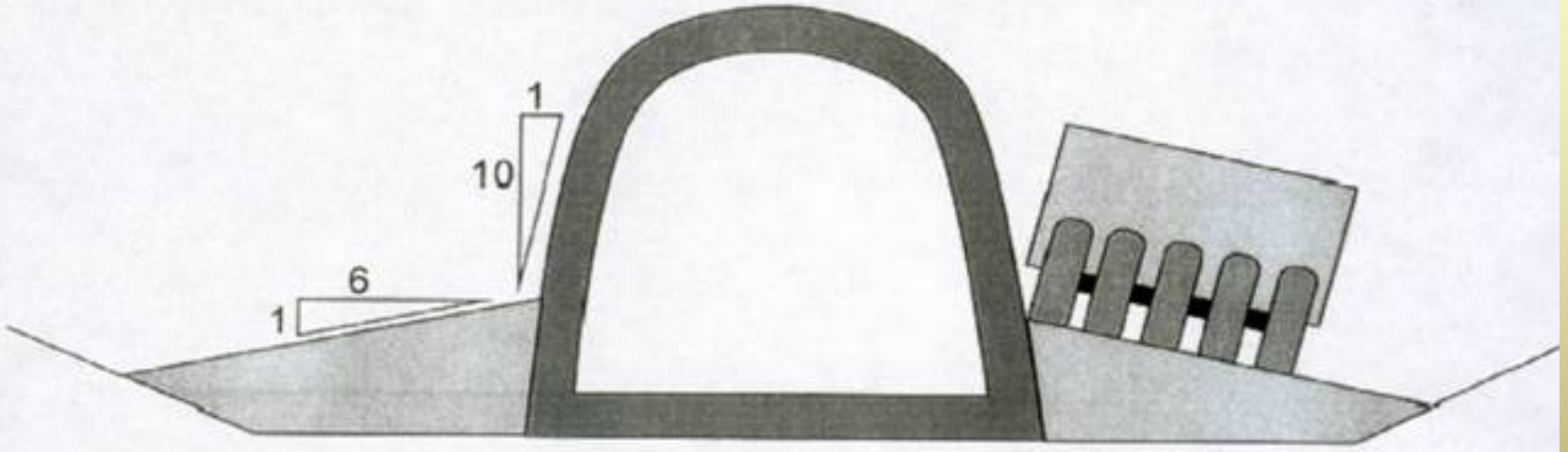
Collars Make Special Compaction Necessary

Potential for Cracking/Differential Settlement Around Conduit



Proper Design

USBR Guidelines - ACER Tech. Memo. No. 9 (1987)



1 on 10 slope on sides of conduit (concrete)

6 on 1 slope on fill against conduit

Same fill level on both sides +/– 2 feet

Adverse Foundation Conditions

Adverse Foundation Conditions

- Sand Boils
- **Open joints**, faults, shears, bedding planes at core foundation contact
  - **Indadequate Surface treatment** (slush grout/ dental concrete inadequate)
  - **Grout** effectiveness questionable
  - Traverse u/s to d/s across foundation
- **Poor cleanup** at foundation contact
- Ridges and valleys trending u/s to d/s
- Open work gravel at cutoff trench contact
- **Narrow trenches** (arching/ low vertical effective stress)

Excavation Geometry Problems

Potential Internal Erosion Avenues

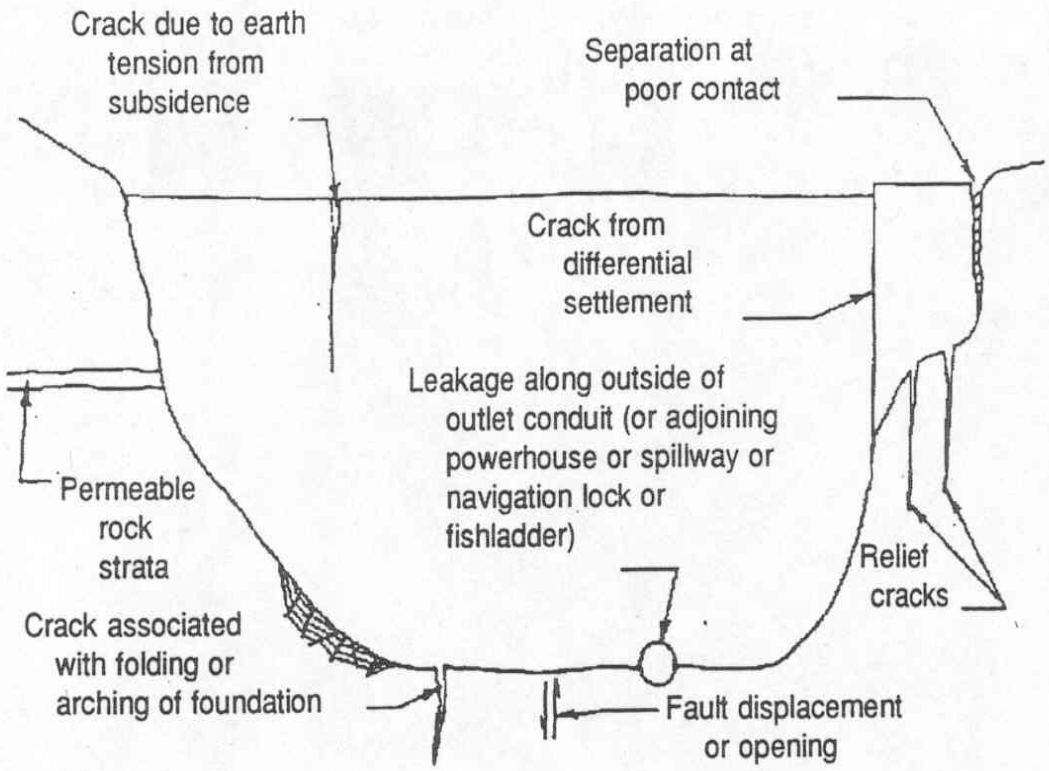


Figure 1. - Schematic illustrations of avenues for internal erosion.

Internal Erosion Potential Failure Mode

Typical Internal Erosion PFM Structure

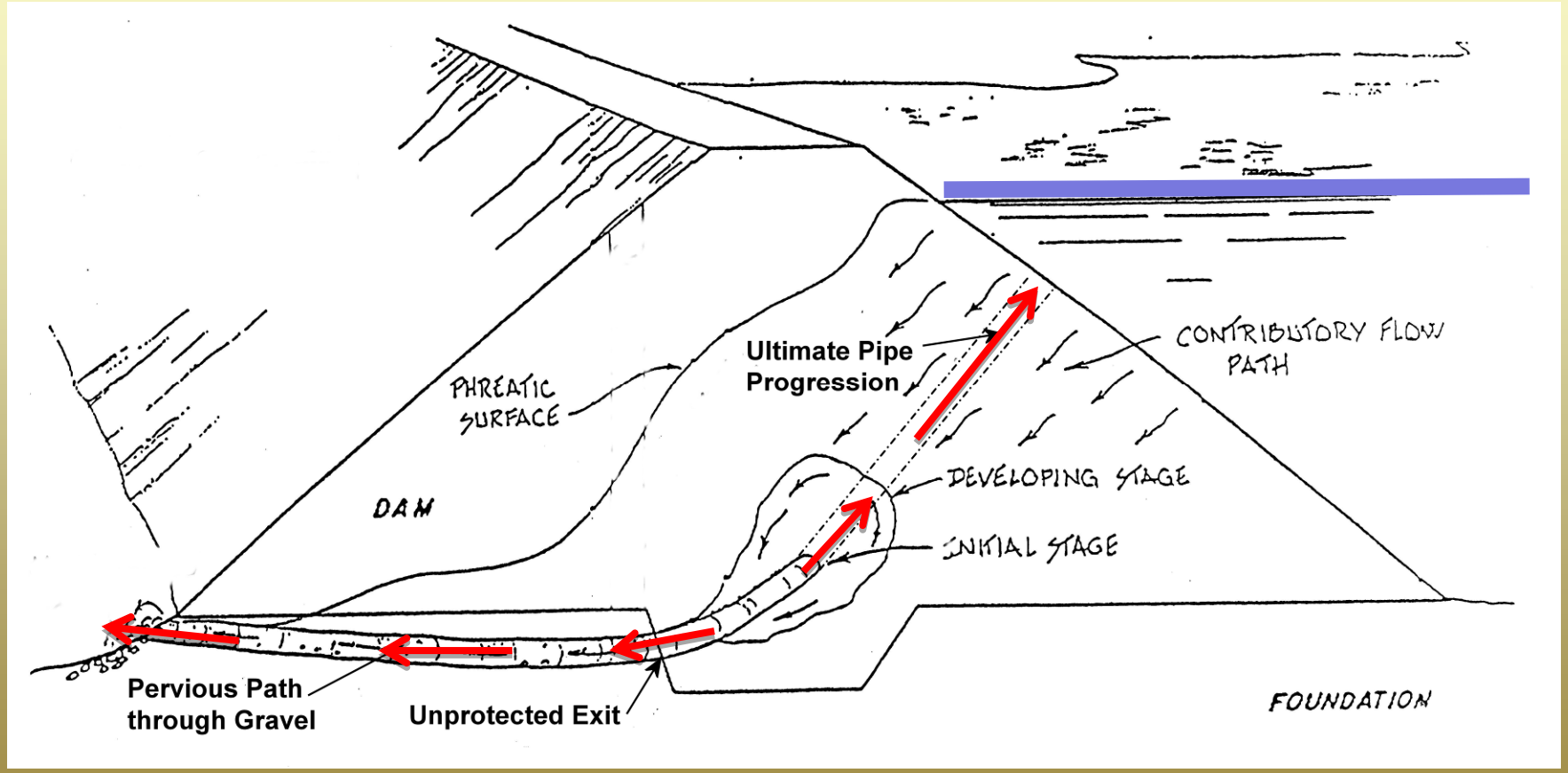
- Reservoir loading
  - Initiation – Erosion starts (Flaw and erosion)
    - Continuation – Unfiltered or inadequately filtered exit exists
      - Progression – Roof forms to support a pipe
        - Progression – Upstream zone fails to fill crack
          - Progression – Constriction or upstream zone fails to limit flows
  - Unsuccessful detection and intervention
  - Dam breaches (uncontrolled release)

Potential Failure Mode Description

- **PFM Frequently Developed:**
  - Piping from the embankment into the foundation.
- **More Appropriate PFM:**
  - When the reservoir is above elevation 5634 feet, internal erosion of the core initiates into the open-work gravel foundation at the interface of the foundation with the cutoff trench near Station 2+35, as a result of poor foundation treatment. Core material erodes into and through the foundation and exits at the toe of the dam through an unfiltered exit. Backward erosion occurs until a "pipe" forms through the core and continues upstream until reaching the reservoir. Seepage velocities increase, enlarging the pipe until a portion of the upstream face of the embankment collapses into the pipe, which continues to enlarge until the crest of the dam collapses, resulting in an uncontrolled release of the reservoir.

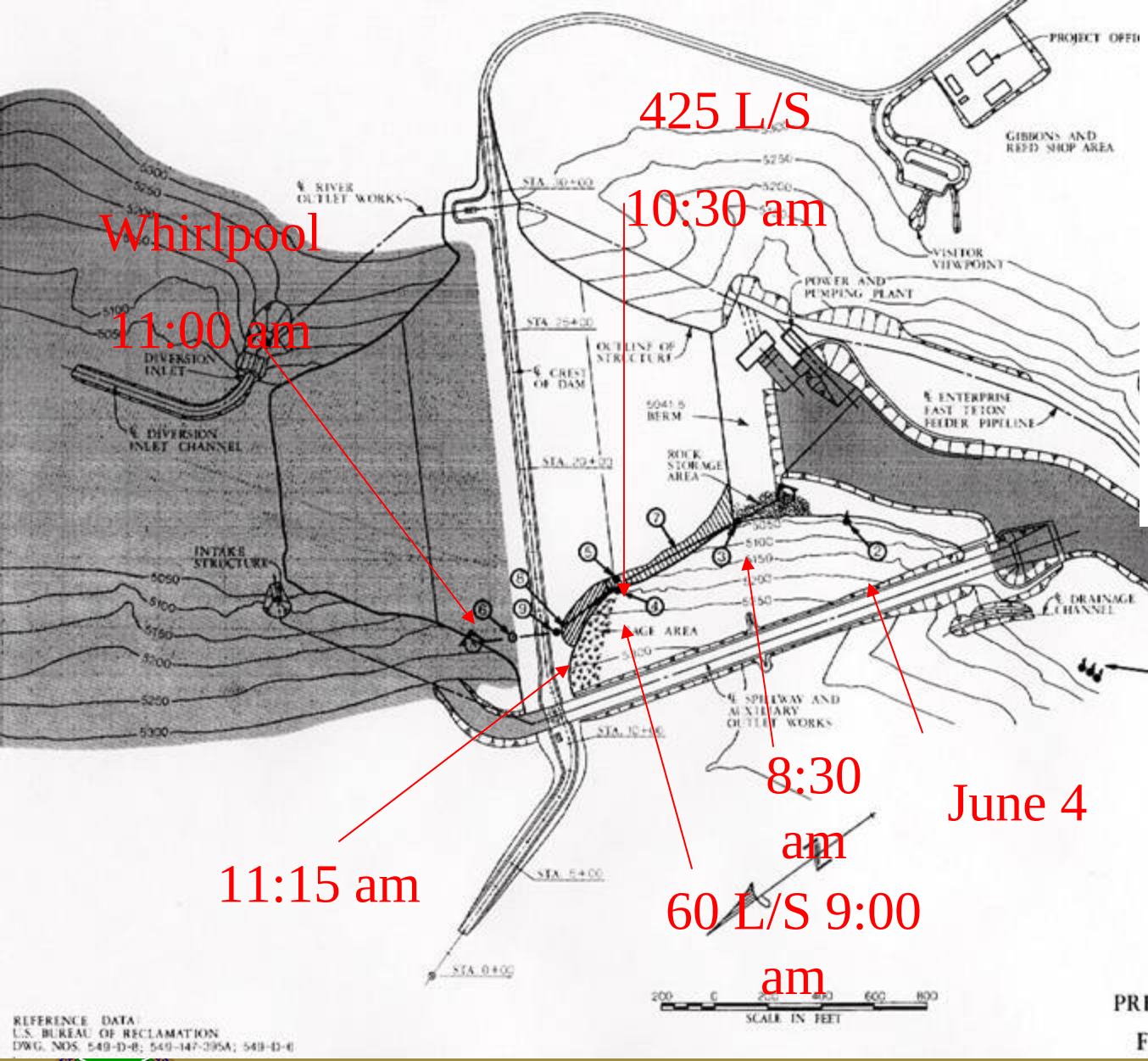
Sketch of Potential Failure Mode

Attempt to write the PFM as if you do not have a sketch.



Teton Dam

Teton Dam



1 - About 400 m downstream from Teton Dam, springs flowing clear about 6 liters/s from near vertical joints El. 5028-5035, June 3, 1976.

2 - Spring flowing clear about 1 liter/s, June 4, 1976.

3 - Muddy flow at right downstream toe estimated 600 – 800 liters/s at El. 5045, 8:30 AM.

4 - 60 liters/s flow from abutment rock at El. 5200,9 AM.

5 - Leak developing about 4.5 meters from right abutment at El. 5200. Flow about 425 liters/s. 10:30 AM.

6 - Whirlpool forming at about Sta. 14+00 (right end of dam). 11 AM

7 - Area eroded by muddy flow about 11:15 AM.

8 - Headward erosion between 11:15 – 11:50 AM.

9 - Sink hole developed about 11:50 AM.

PRE-FAILURE LEAKAGE ON JUNE 5, 1976

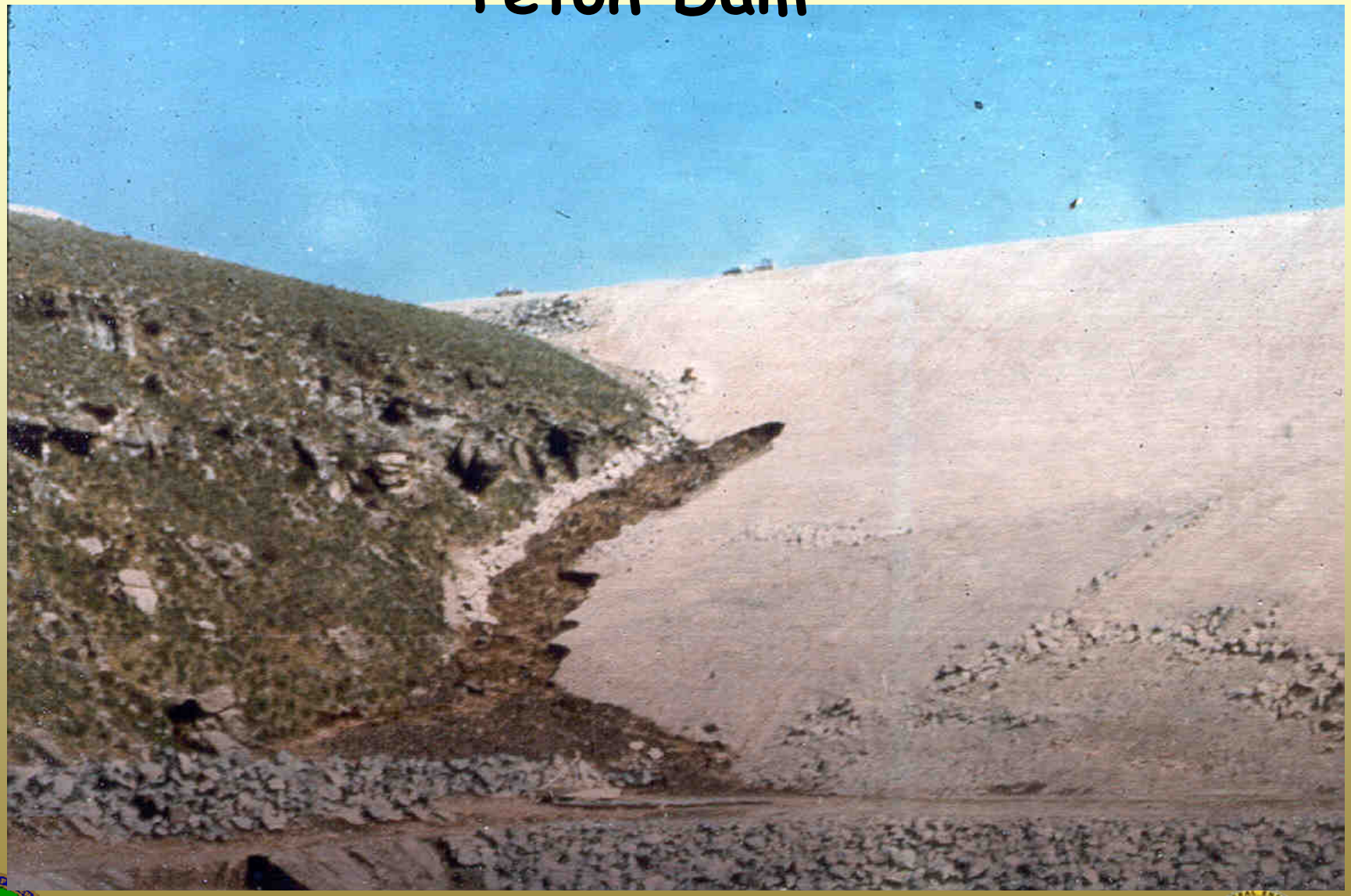
FIG. 2-1. U.S. DEPARTMENT OF THE INTERIOR — STATE OF IDAHO INDEPENDENT PANEL TO REVIEW CAUSE OF TETON DAM FAILURE

Pre-Failure Seepage

Teton Dam

Pre-Failure Seepage

Teton Dam



Seepage Moving Into Embankment
About 10:45 am, June 5, 1976

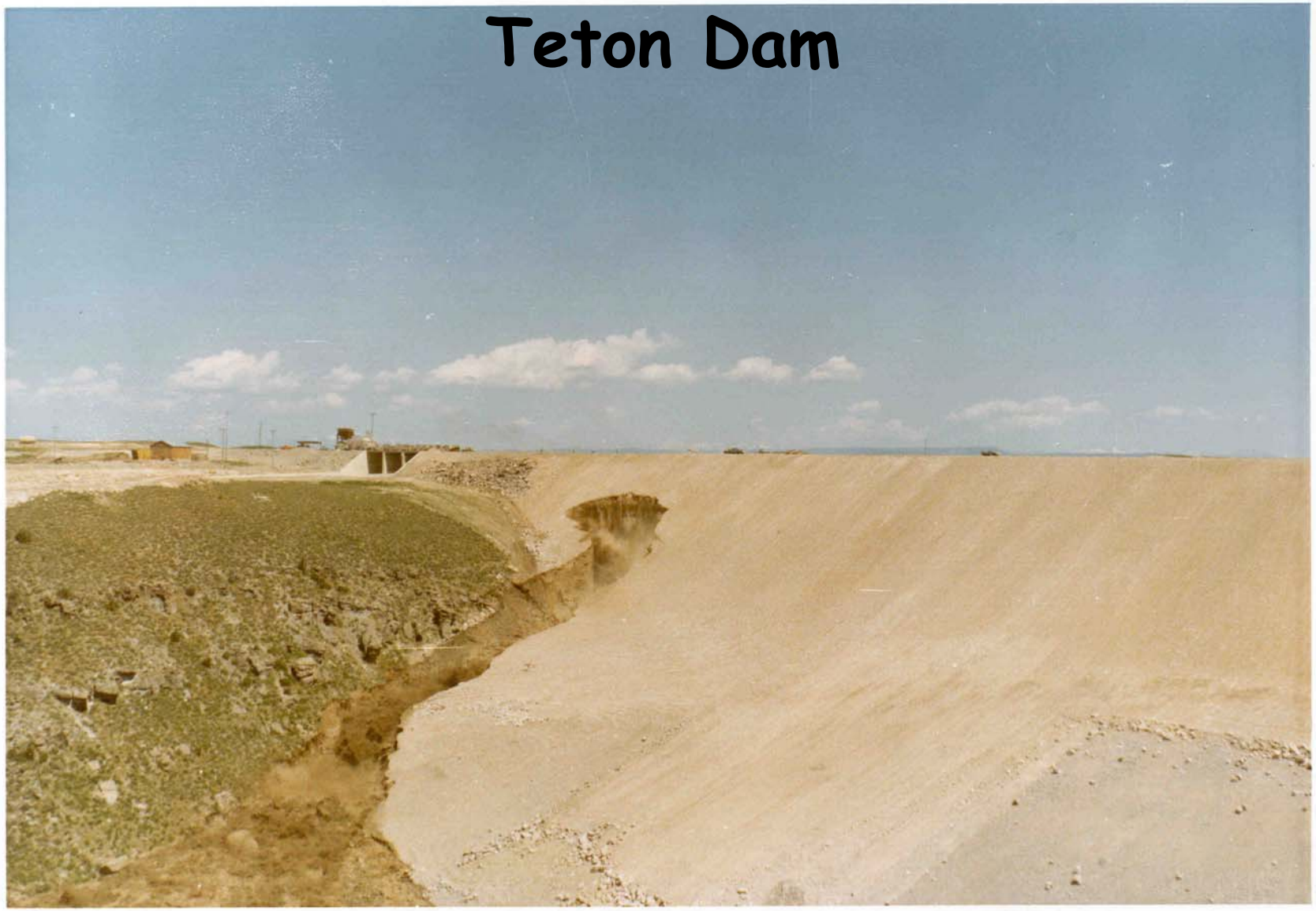
Teton Dam

Flow Increasing, Dozers Sent to Fill Hole at Elevation 1585 m

Teton Dam

Dozers
Lost in Hole
about 11:20 a.m.

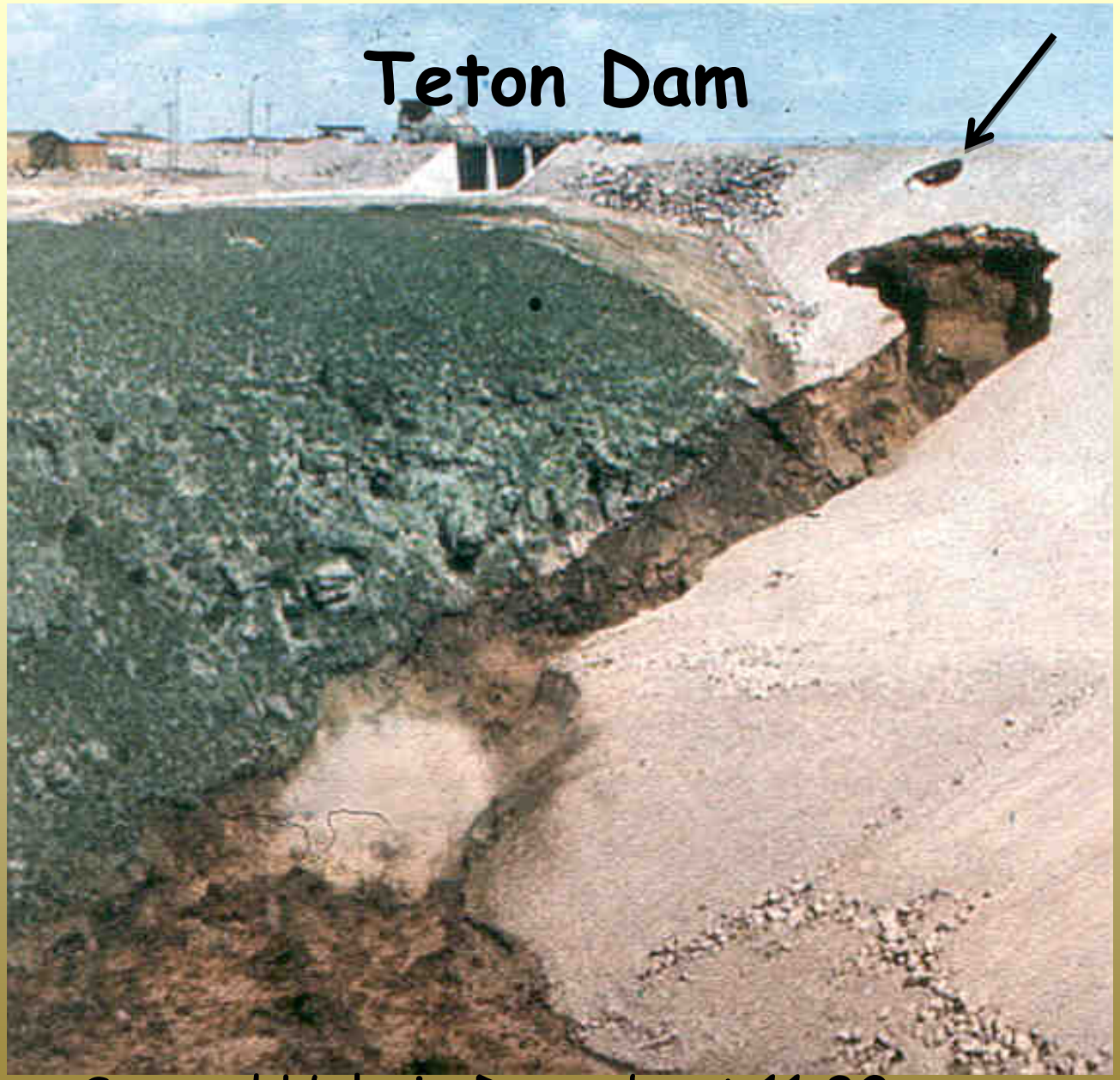
Teton Dam



B-14

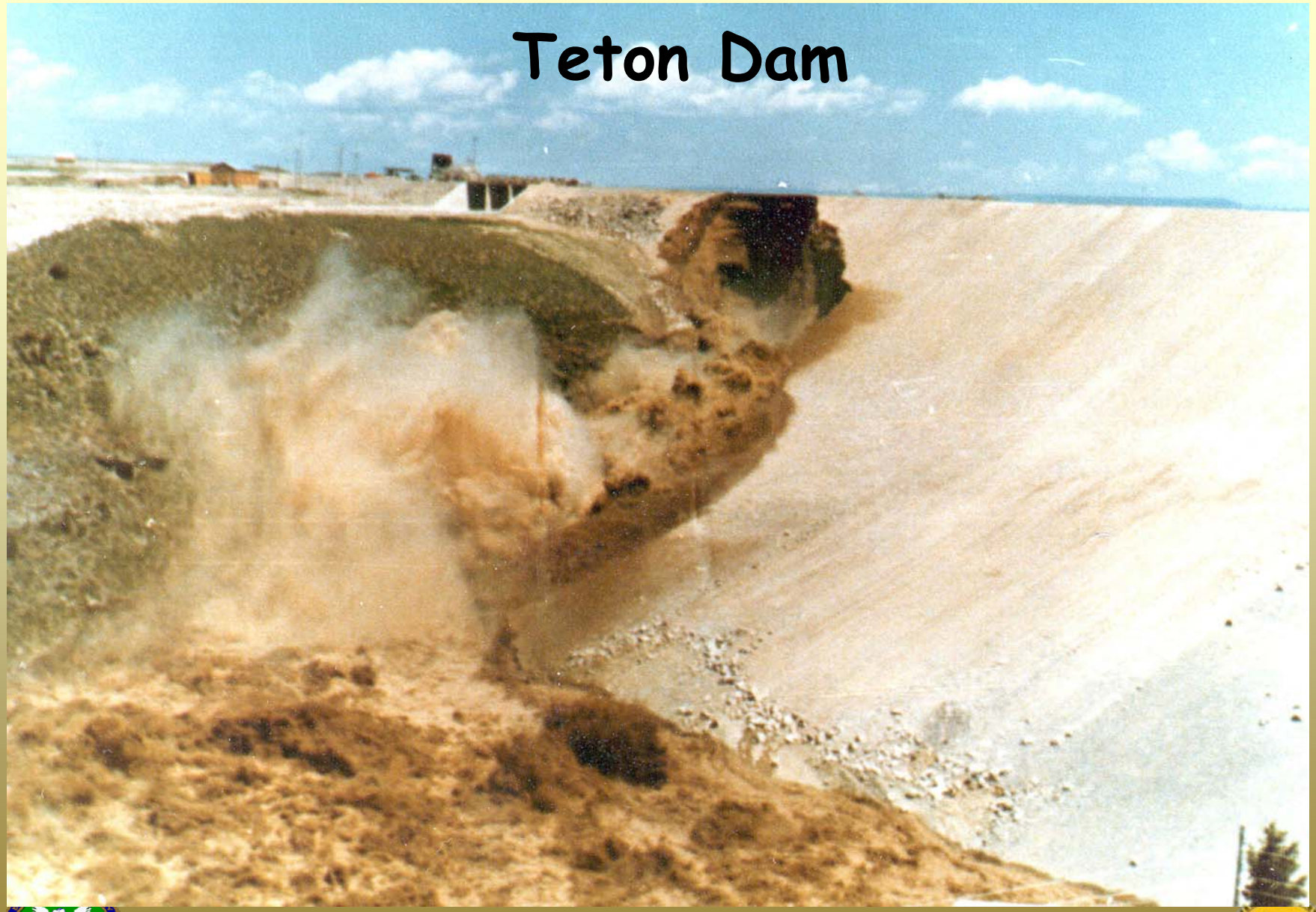
Approximately 11:30 am, June 5, 1976

Teton Dam



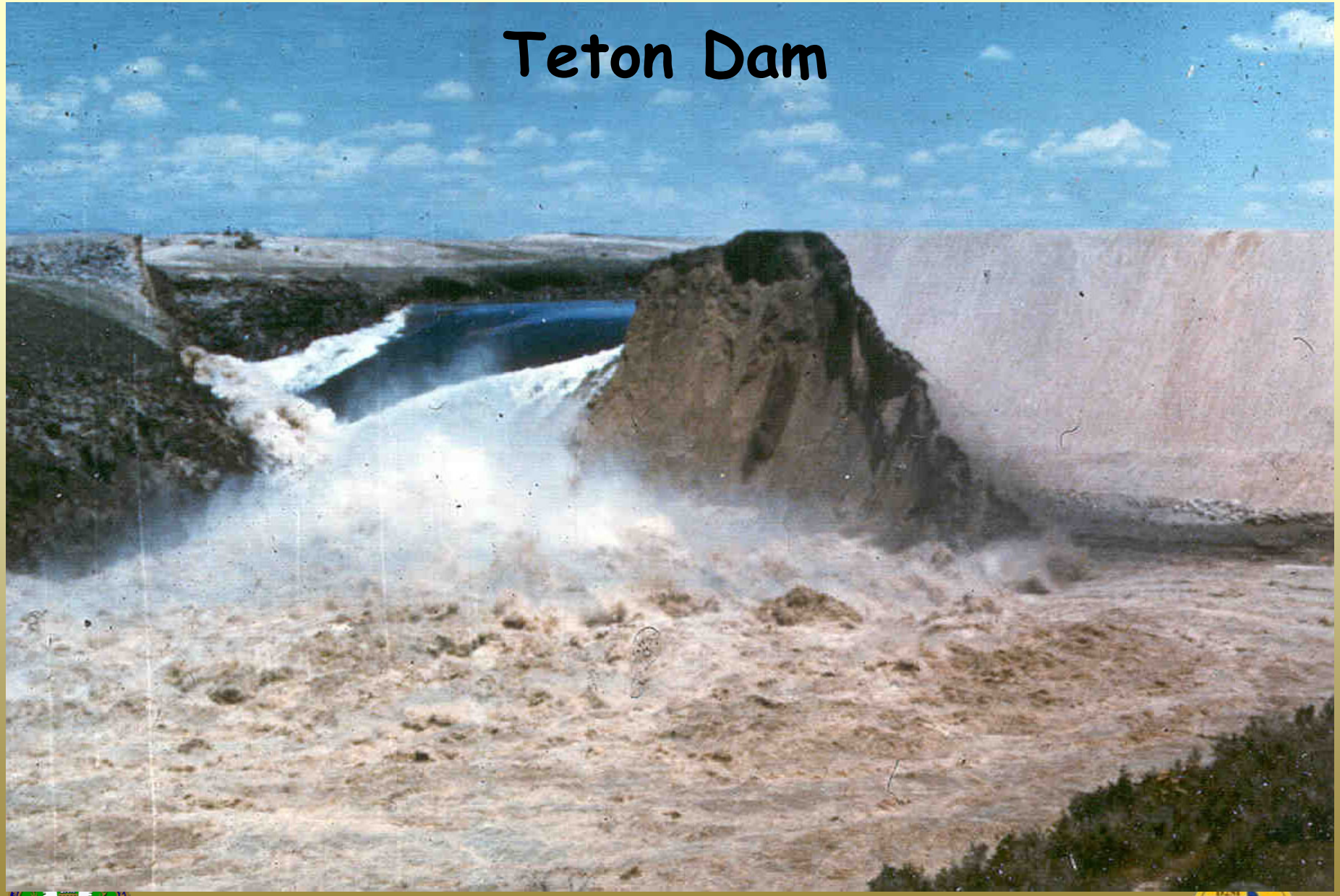
Second Hole in Dam about 11:32 am, June 5, 1976

Teton Dam



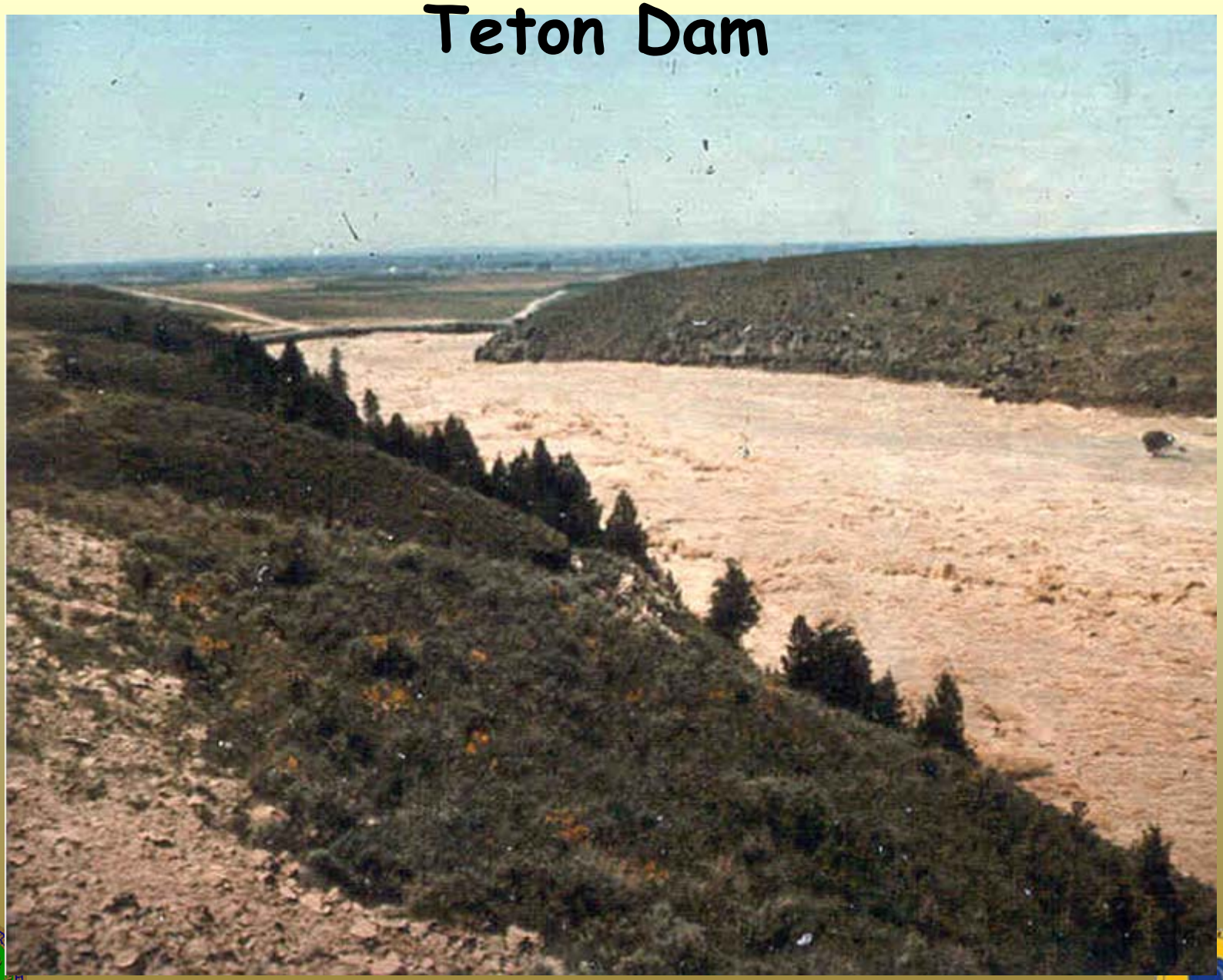
Dam Crest Breaching at 11:55 am, June 5. 1976

Teton Dam



Maximum Flow about 1 Million cfs

Teton Dam



Rexburg, Idaho

11 Fatalities

Could have been much worse if failure had occurred at night

Teton Dam

- Contributing factors
  - Low permeability transition zones with too high fines content
  - Lack of foundation filters or treatment of open joints
  - Erodible core material
  - Rapid filling with no outlet works

- Bottom line – joints, fractures and openings in the downstream wall of the cutoff trench and the remaining foundation downstream of the trench were severely incompatible with respect to filtering and retention of the very fine grained, erodible core materials, as well as the silt infillings in some of the joints themselves

Teton Dam

Teton Dam Abument

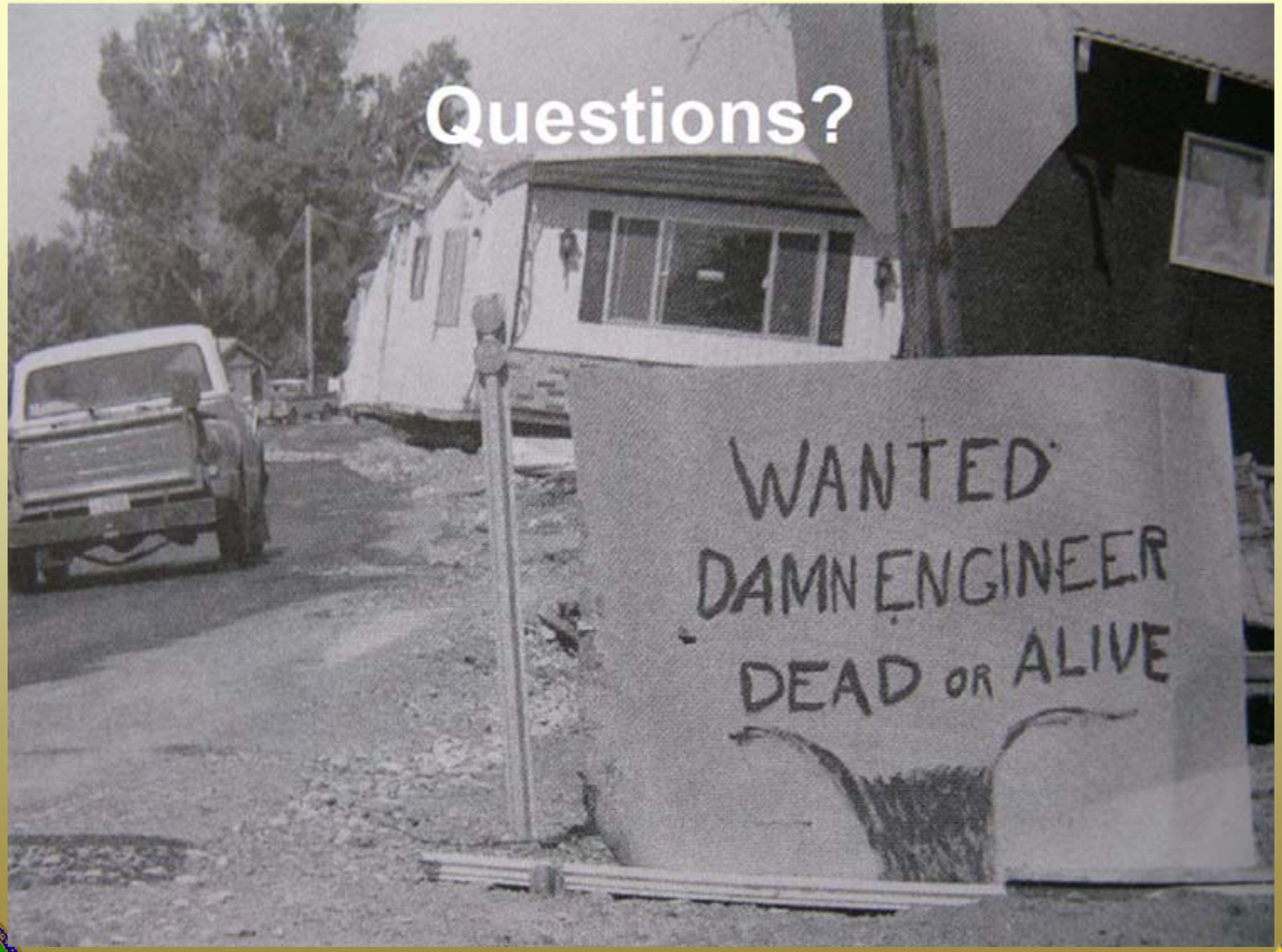
Teton Dam

2012

Teton Dam

2012

Public Perception of Failed Dam Safety Program



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

Federal Energy Regulatory Commission

Potential Failure Modes for Piping and Internal Erosion

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QUESTIONS?

2013 Oregon Dam Safety Conference
February 26, 2013