Seepage Detection and Monitoring

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Maryland Dam Safety Training
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Presentation Outline

- Failure and incident (accident) statistics
- Internal erosion mechanisms and pathways
- Methods for identifying seepage concerns
- Two examples (if time allows)

ICOLD Embankment Dam Failure Statistics

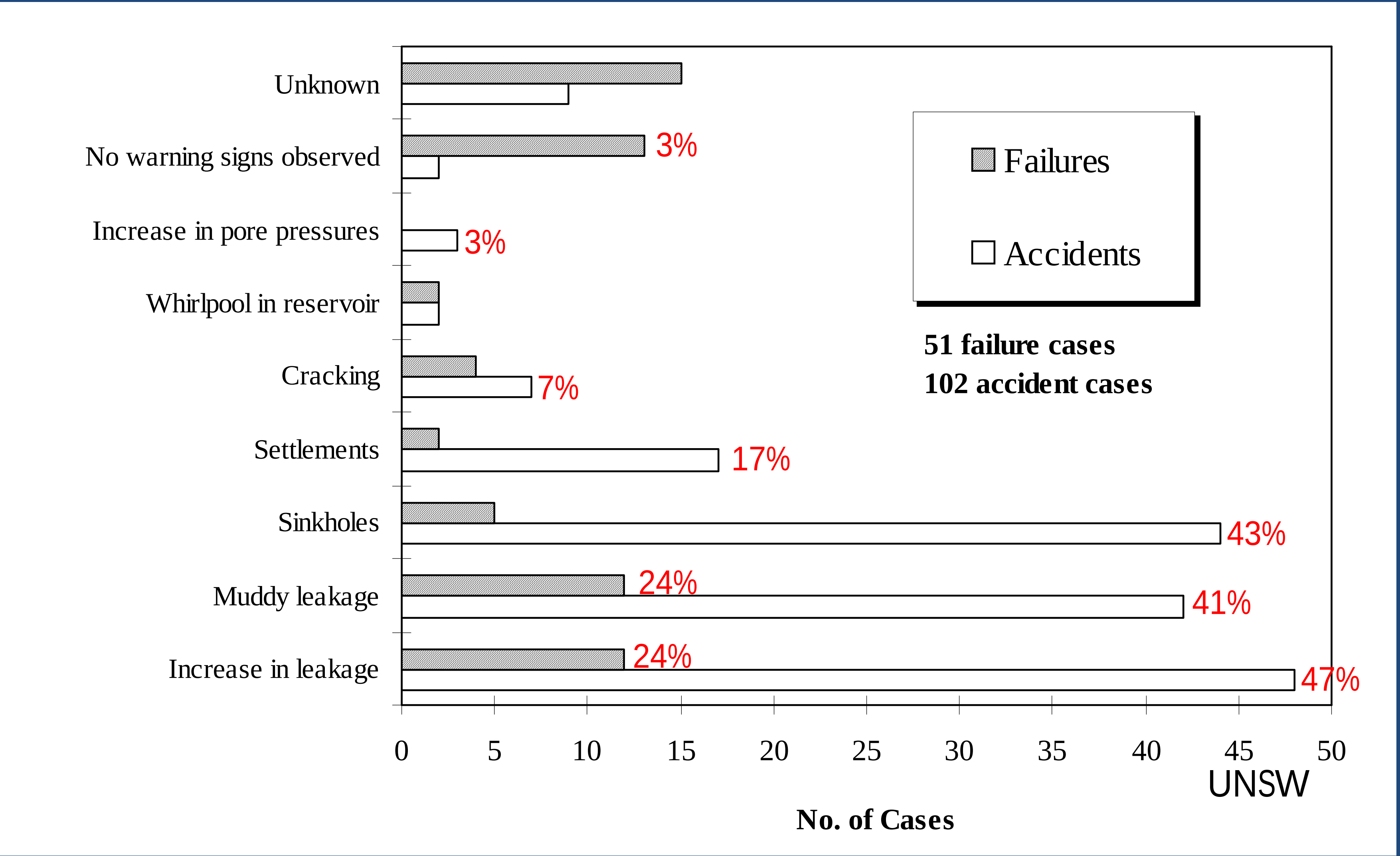
Failure Mechanism	Erosion		Embankment Sliding	
Mode of Failure:	External Erosion (Overtopping)	Internal Erosion	Static Instability	Seismic Instability
% Over the World:	48%	46%	4%	2%
% Over the World:	94%		6%	

ICOLD Statistics

Mode of Failure	No of Cases	% Failures (where known)
Inadequate spillway capacity	46	36
Malfunction of gate	16	12
Subtotal overtopping & appurtenant failures	**62**	**48**
Internal erosion through embankment	39	30
Internal erosion through foundation	19	15
Internal erosion from embankment into foundation	2	1.5
Subtotal internal erosion(1)	**59**	**46.5**
Downstream slides	6	5
Upstream slides	1	1
Subtotal slides	**7**	**6**
Earthquake/liquefaction	**2**	**1.5**
Unknown mode	8	
Total no. of failures (1)	136	
Total no. of failures (where mode of failure known)	128	
No of embankment dams	**11192**	

Notes: 1) Subtotals and totals do not necessarily sum to 100% as some failures were classified as multiple modes of failure.

Observations During Internal Erosion Incidents



Internal Erosion Mechanisms and Pathways

- Best Overview References
  - Internal Erosion of Existing Dams, Levees And Dikes, And Their Foundations, Bulletin 164, ICOLD (2015)
  - Best Practices in Dam and Levee Safety Risk Analysis, Chapter IV-4, Internal Erosion Risks for Embankments and Foundation, Bureau of Reclamation, U.S. Corps of Engineers, (2015)

    https://www.usbr.gov/ssle/damsafety/risk/BestPractices/Chapters/IV-4-20150617.pdf

Internal Erosion Mechanisms

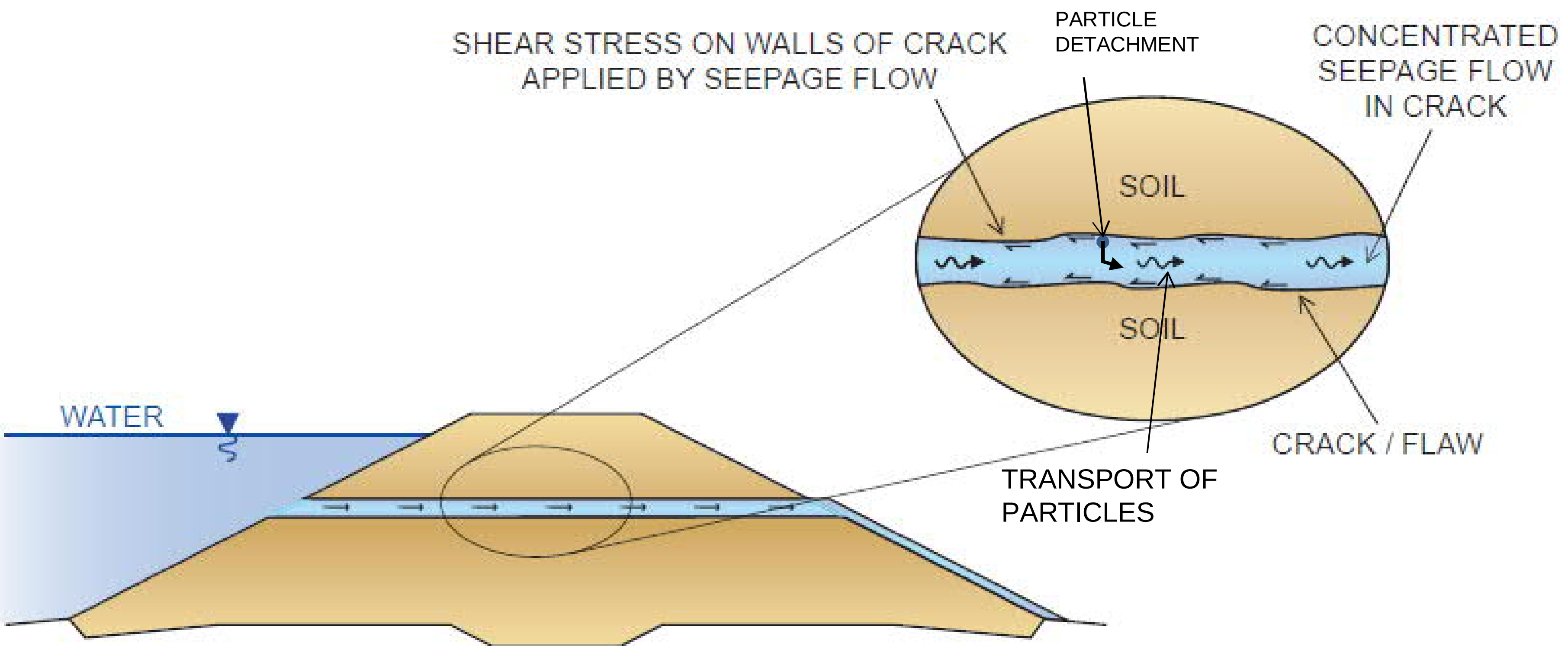
- Concentrated Leak Erosion
- Backward Erosion Piping (BEP)
- Contact Erosion
- Suffusion/Suffosion

Internal Erosion Pathways

- IE Through Embankment
- IE Through Foundation
- IE of Embankment Into Foundation
- IE Along/Into/Out Of Embedded Structures, such as Spillway Walls and Outlet Conduits

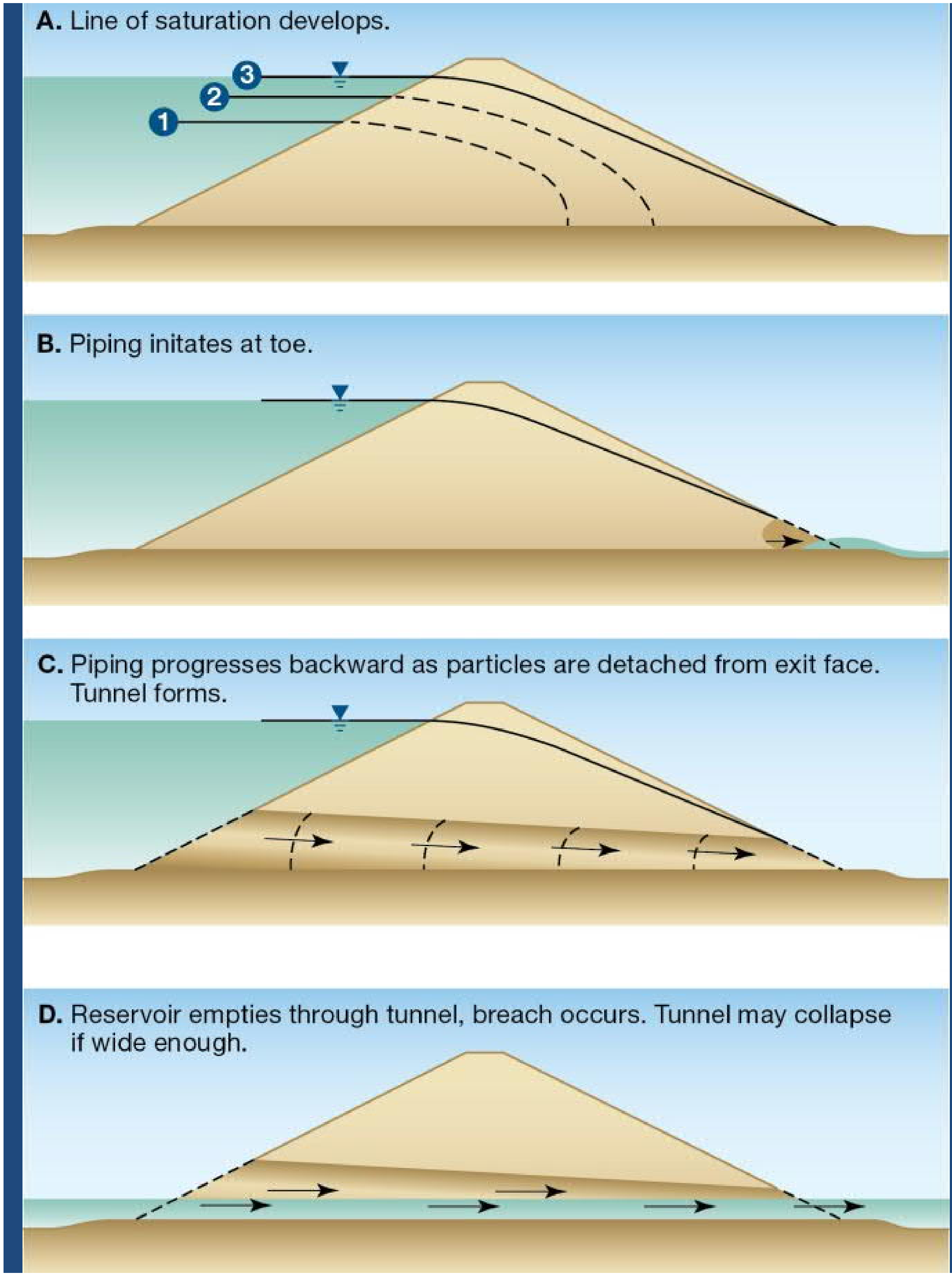
Above as defined in ICOLD Bulletin 164, Internal Erosion of Existing Dams, Levees, and Dikes, 2015; definitions in other publications may vary

Concentrated Leak Erosion



Adapted from slide by Robin Fell, UNSW

- Erosion along sides of an opening (crack). Erosion initiates if hydraulic shear stress > critical shear stress of the soil.



Backward Erosion Piping

- Detachment/erosion of particles at exit of seepage path(s)
- Usually occurs in non-plastic soils
- Two kinds of BEP:
  - BEP beneath a roof
  - Global BEP (Unraveling or Stoping)

Contact Erosion

- Coarse material in contact with finer material
- Flow path is parallel (along) the interface of the different materials
- Flow through the more pervious coarse material scours or erodes the finer material

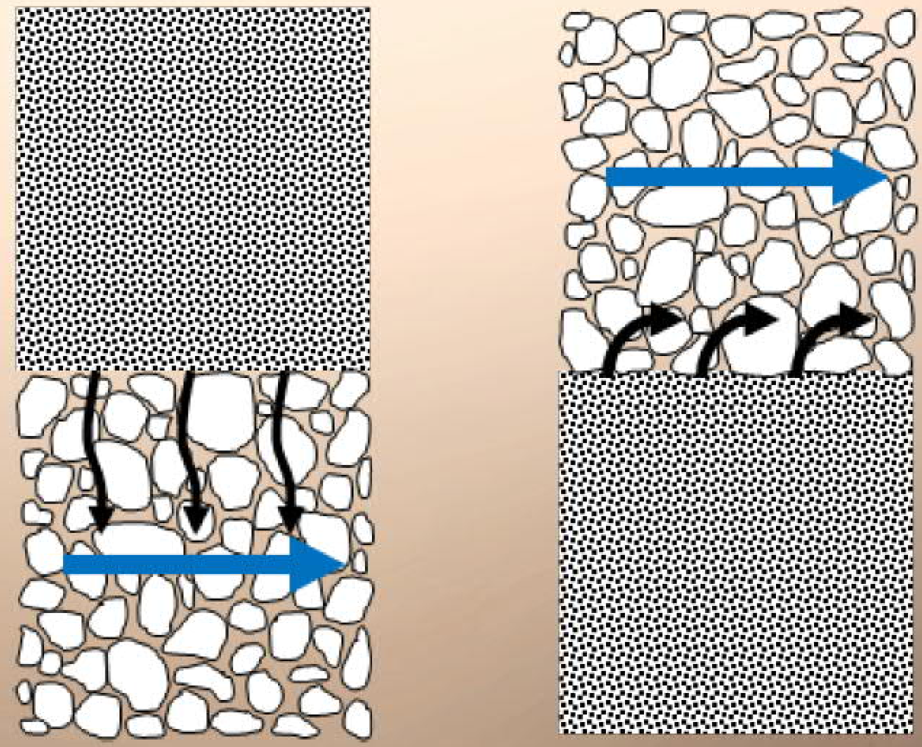
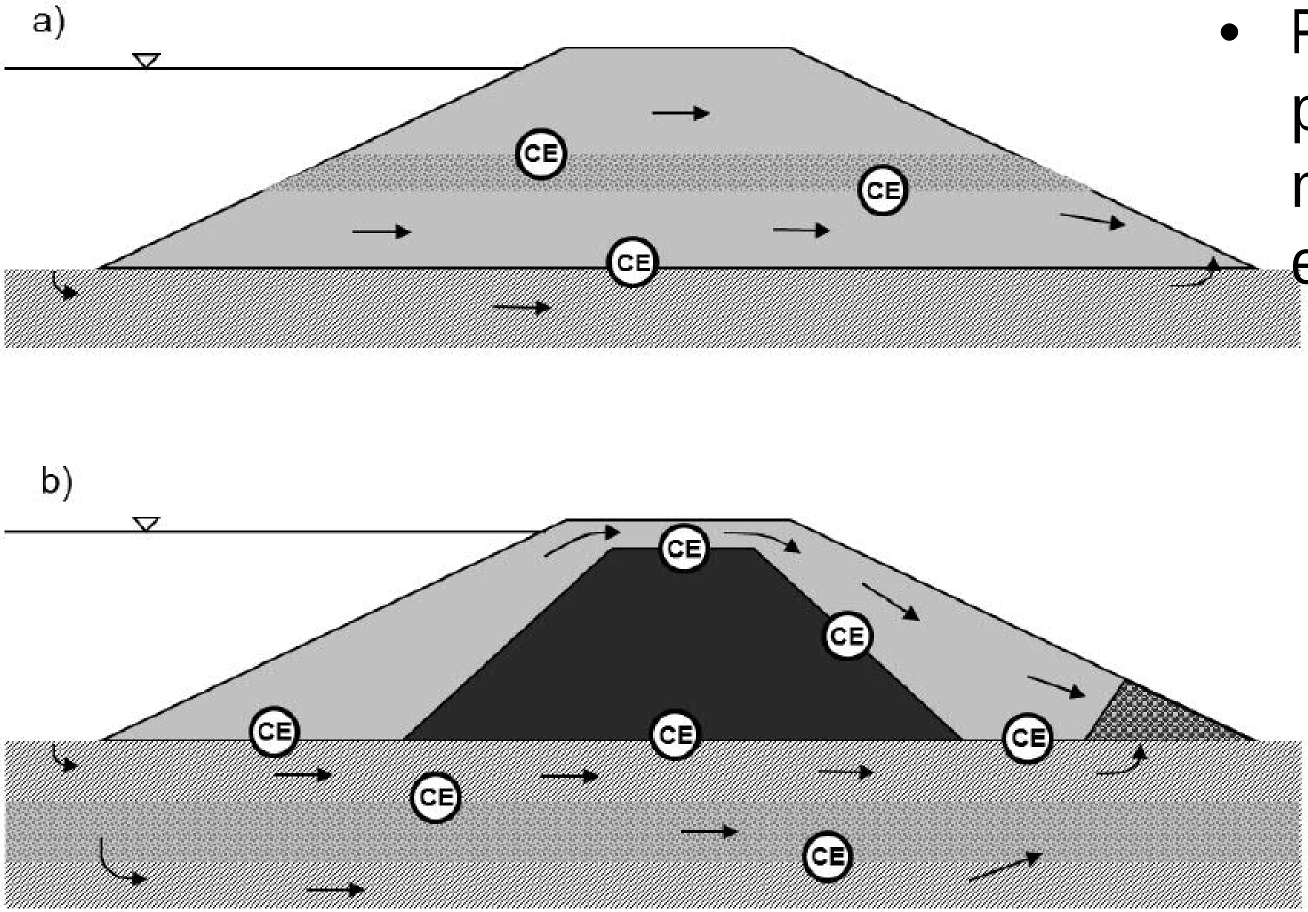
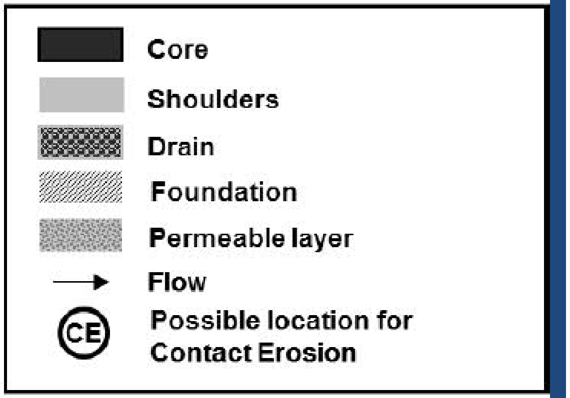


Figure 26-28. Contact Erosion Process (adapted from ICOLD, 2012 Draft)

Contact Erosion



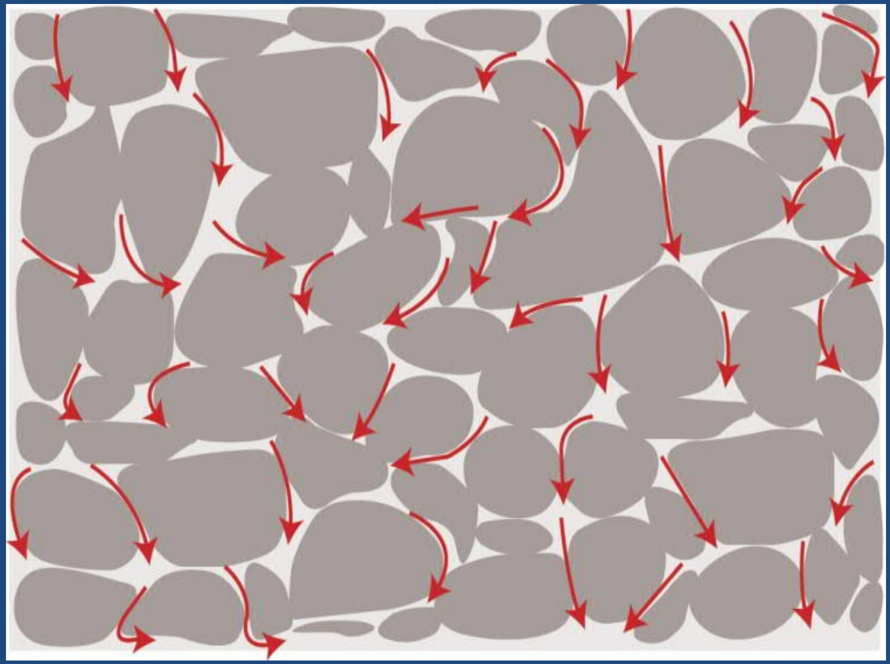
- Flow through more pervious coarse material scours or erodes finer material



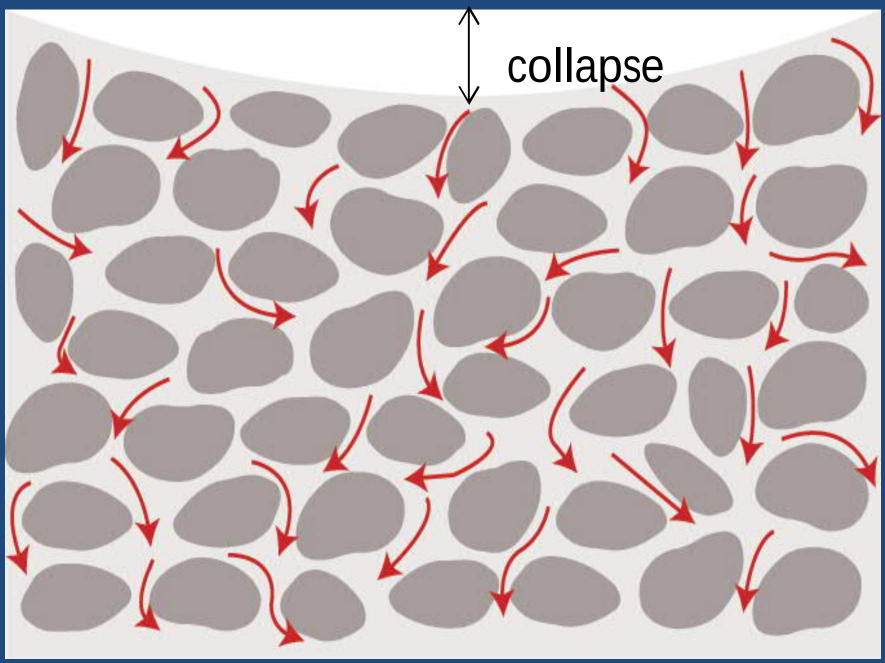
From Béguin et al 2009

Suffusion/ Suffosion

- Internal instability
- Finer soil particles eroded from within matrix of coarser soil particles

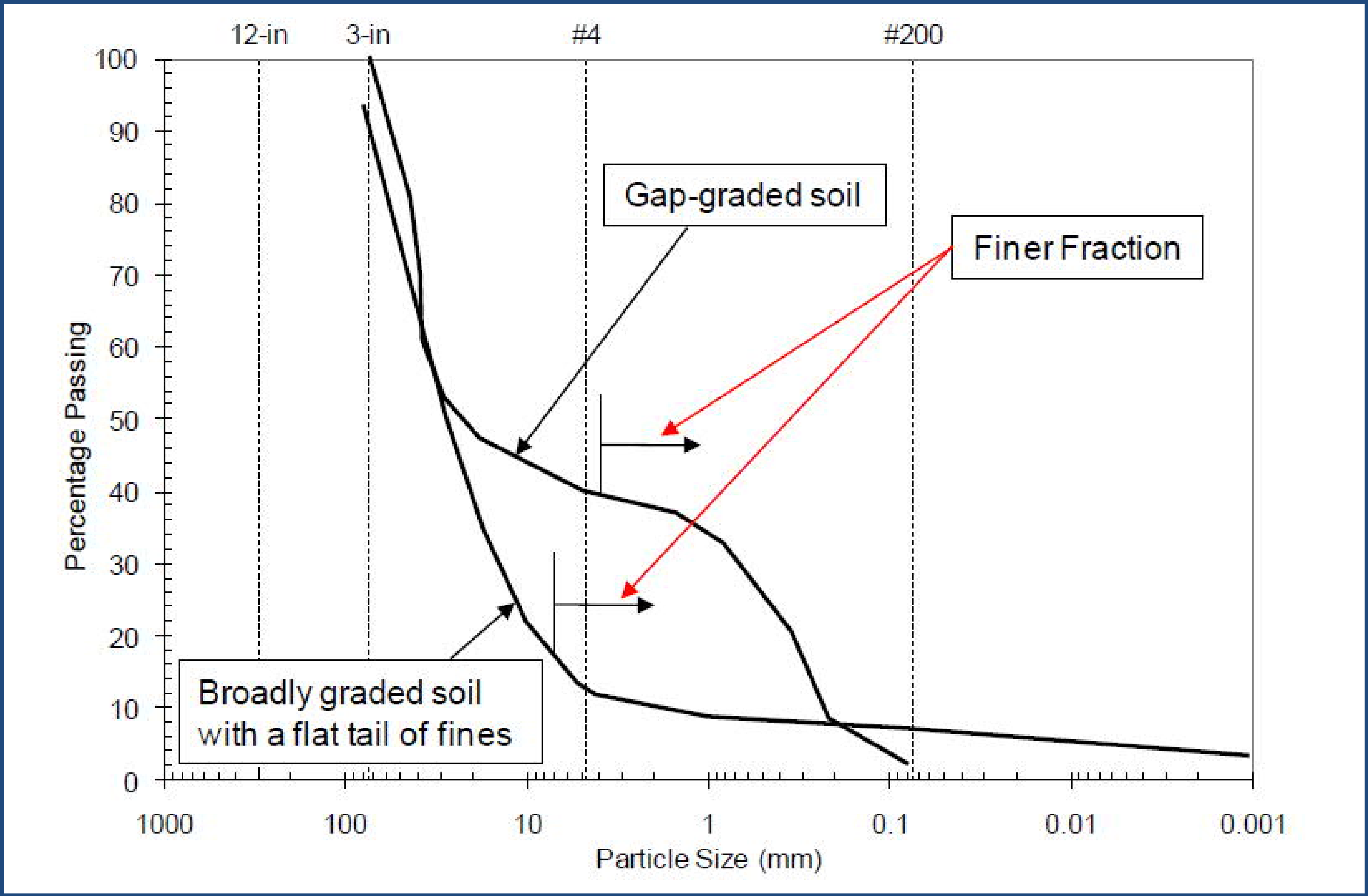


Suffusion – Point-to Point Contact

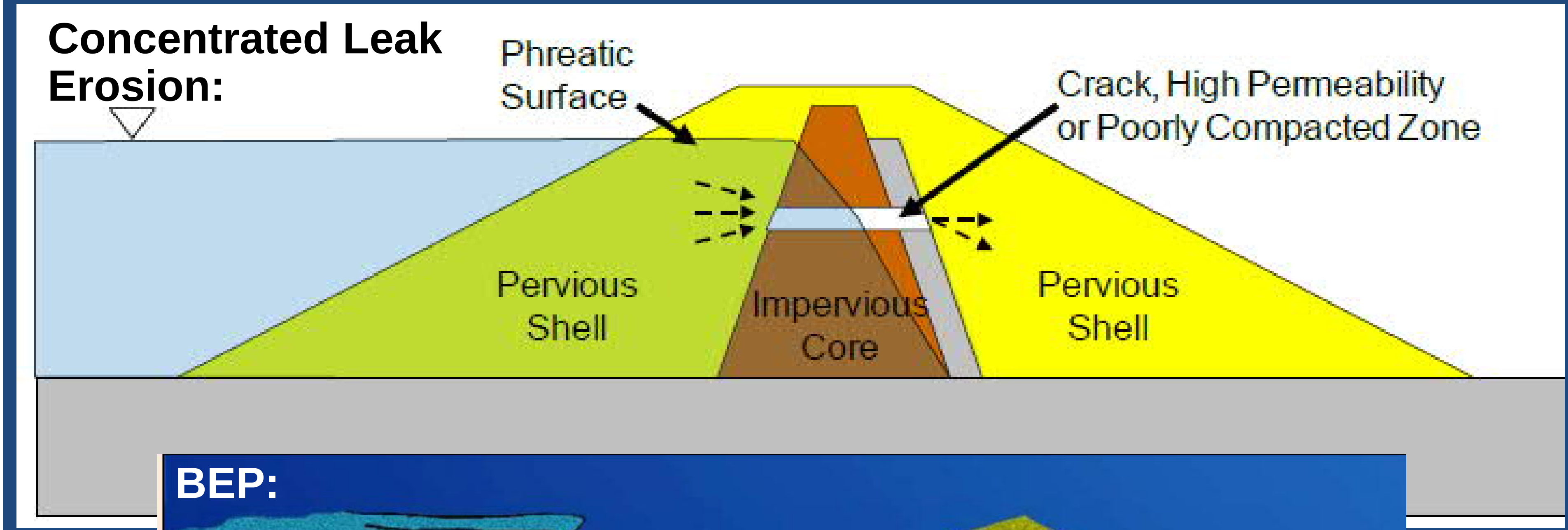


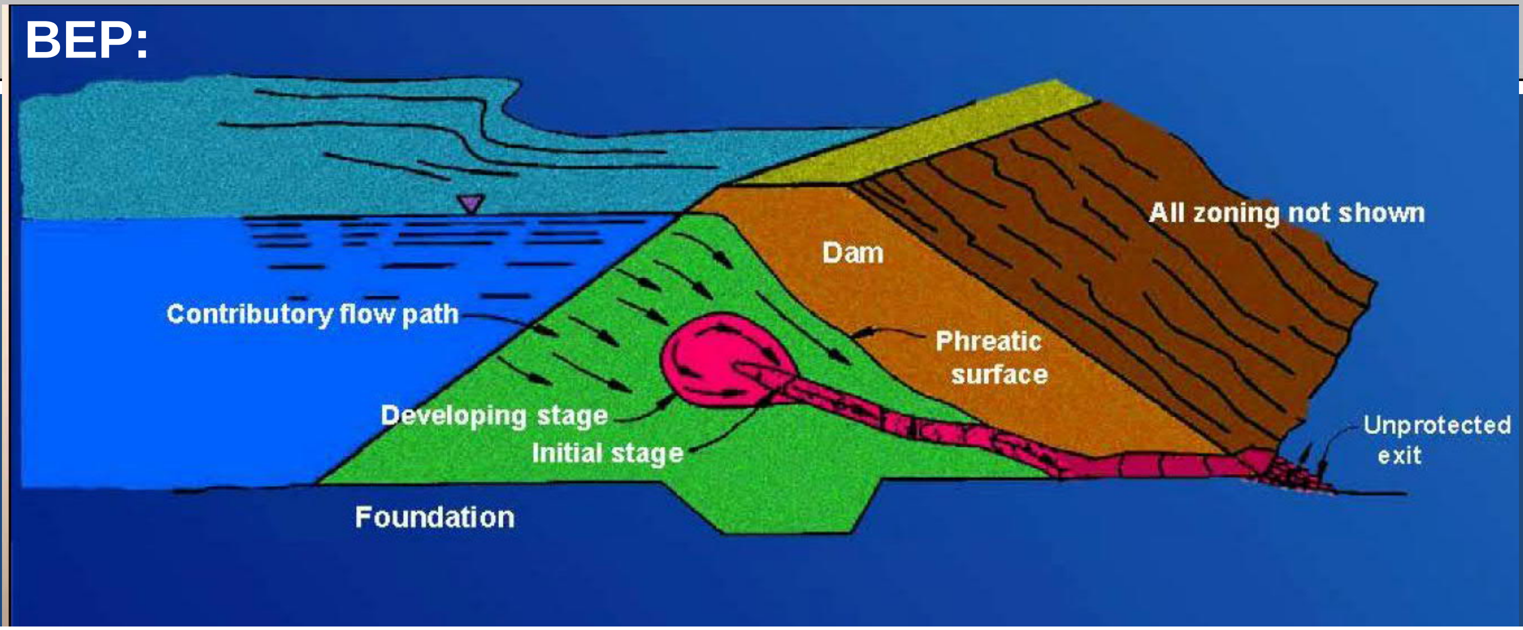
Suffosion – No Point-to Point Contact

Internally Unstable Soils



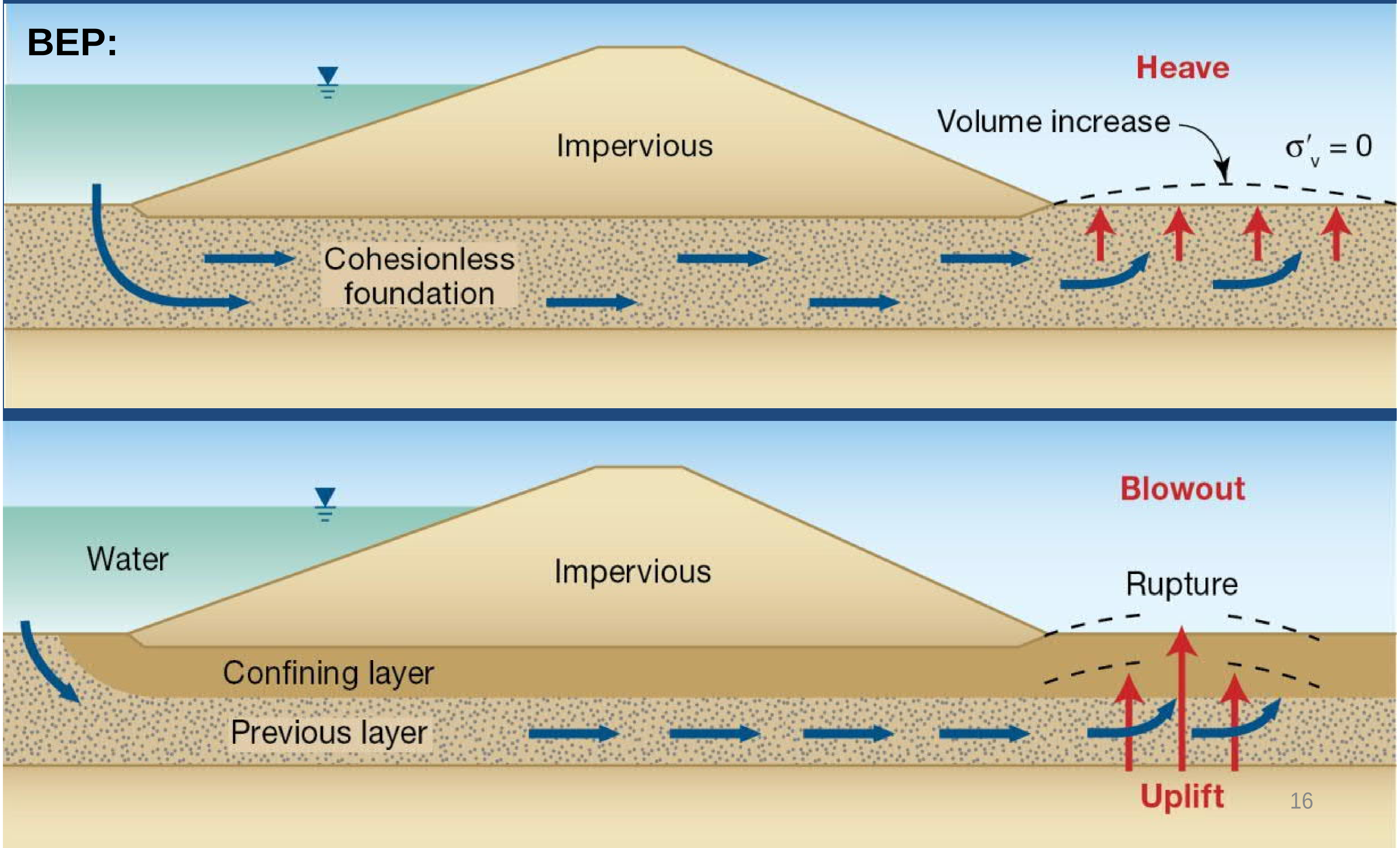
IE Through Embankment





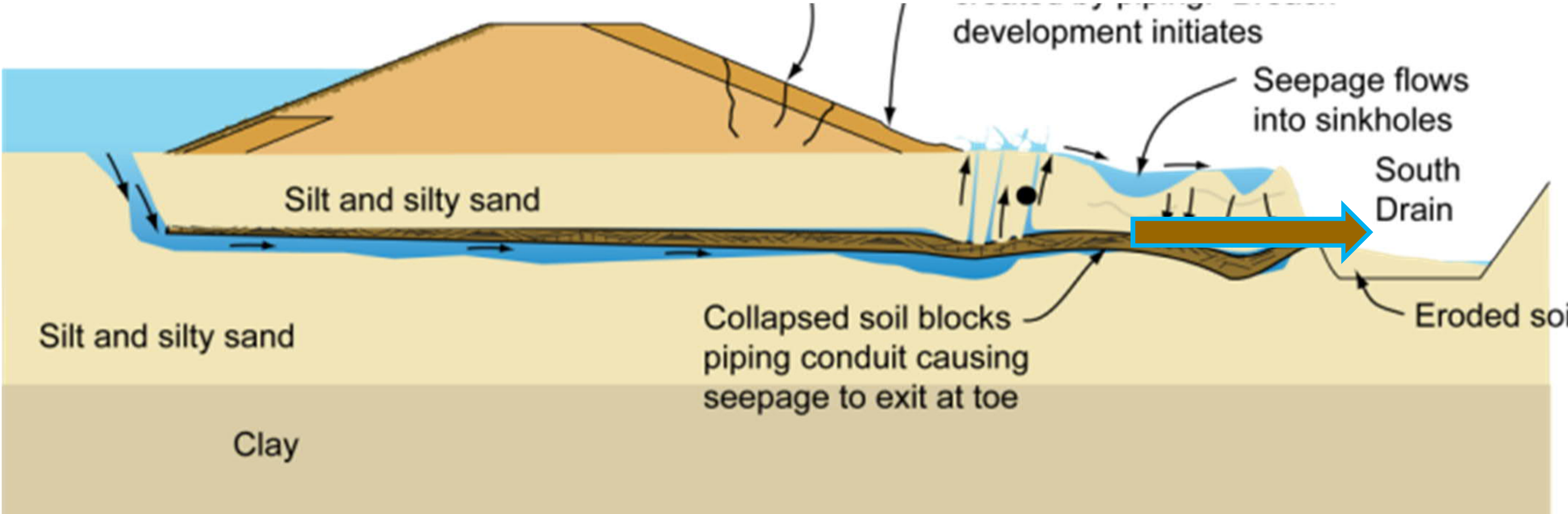
IE Through Foundation

BEP:



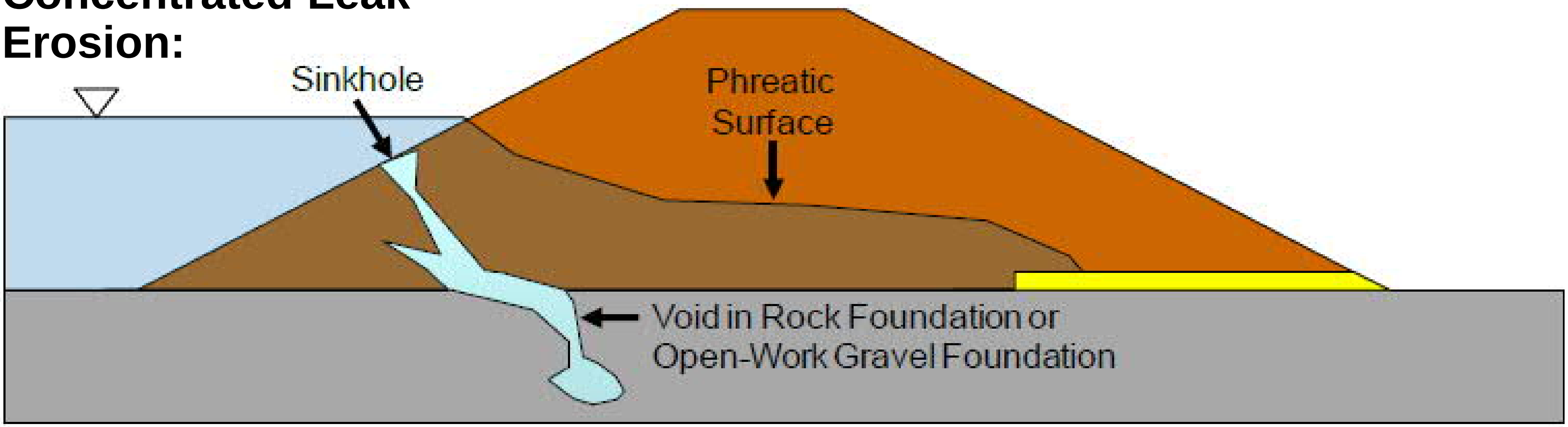
IE Through Foundation

BEP (horizontal exit most dangerous):

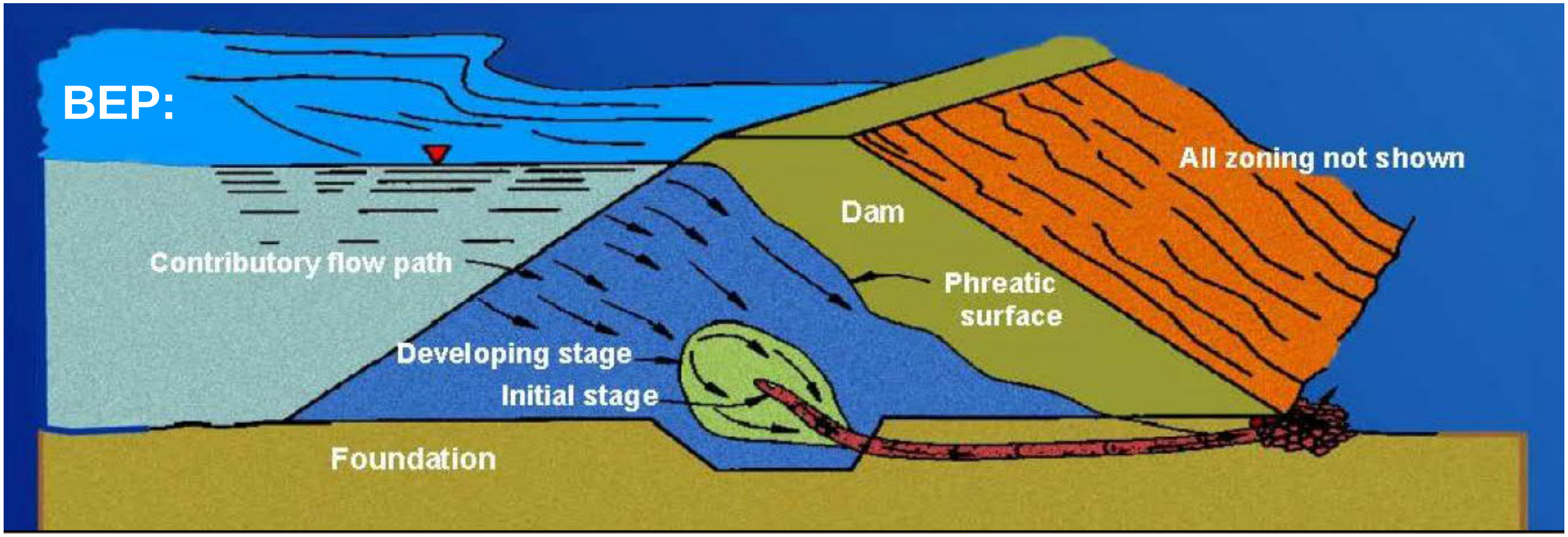


IE of Embankment Into Foundation

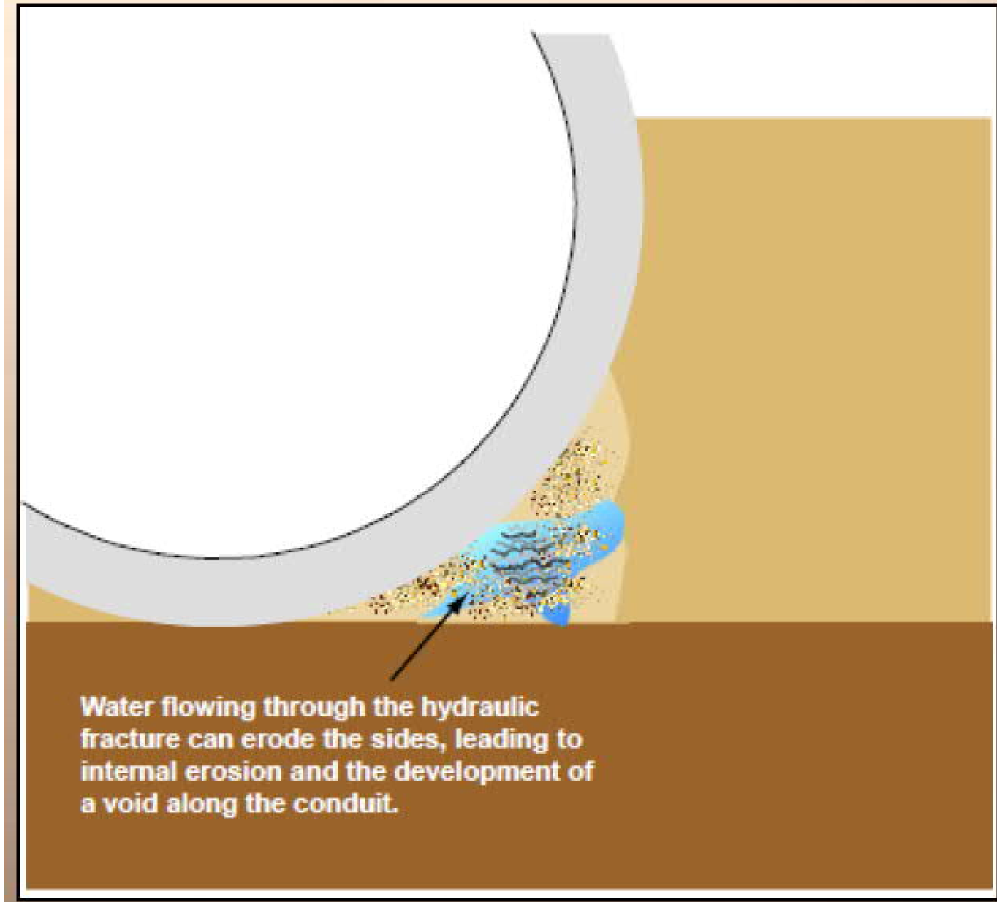
Concentrated Leak Erosion:

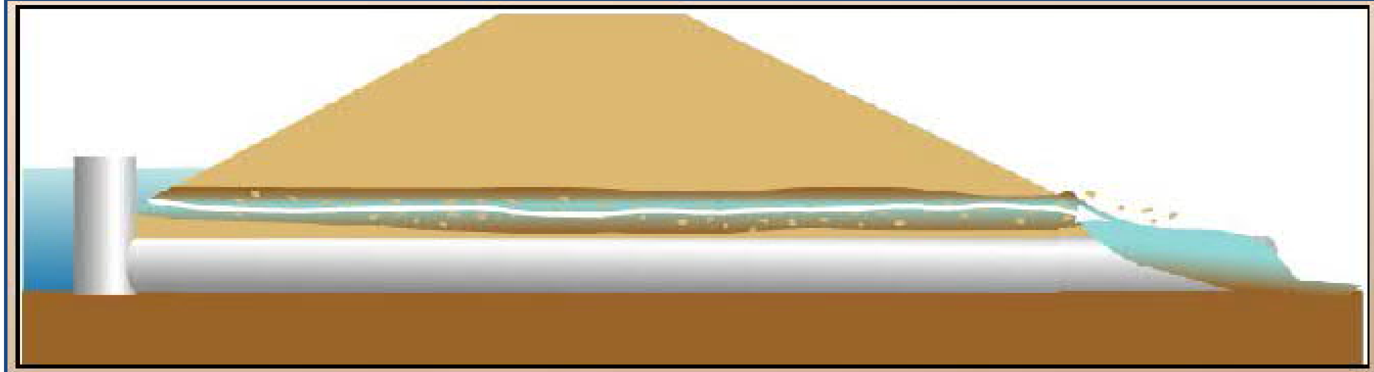


BEP:

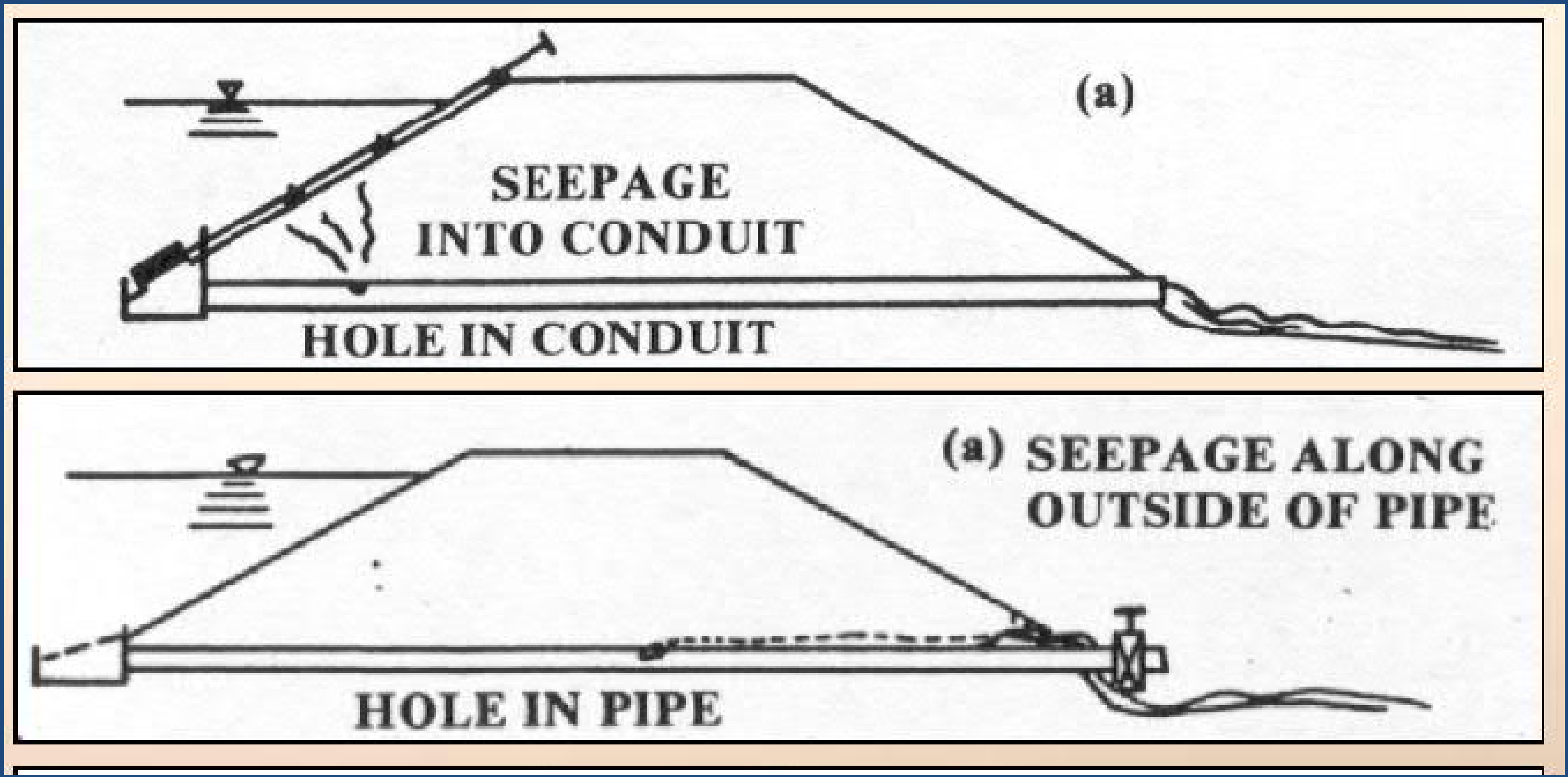


IE Along Outlet Conduit

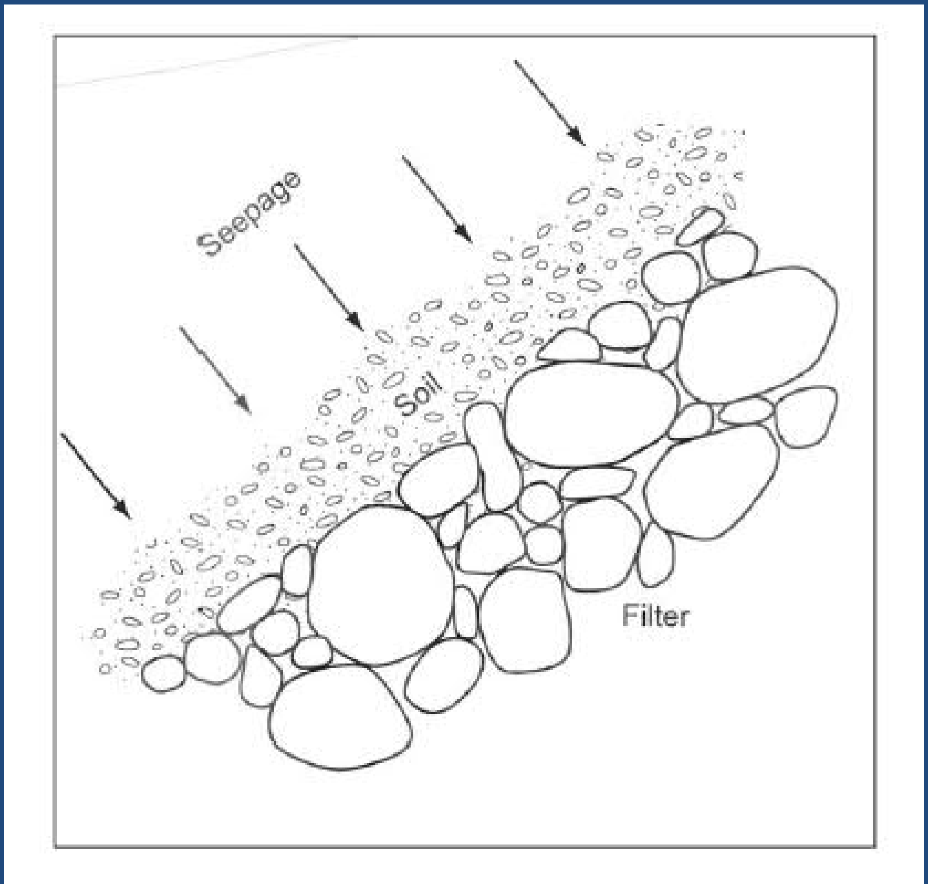




IE Into or Out of Outlet Conduit

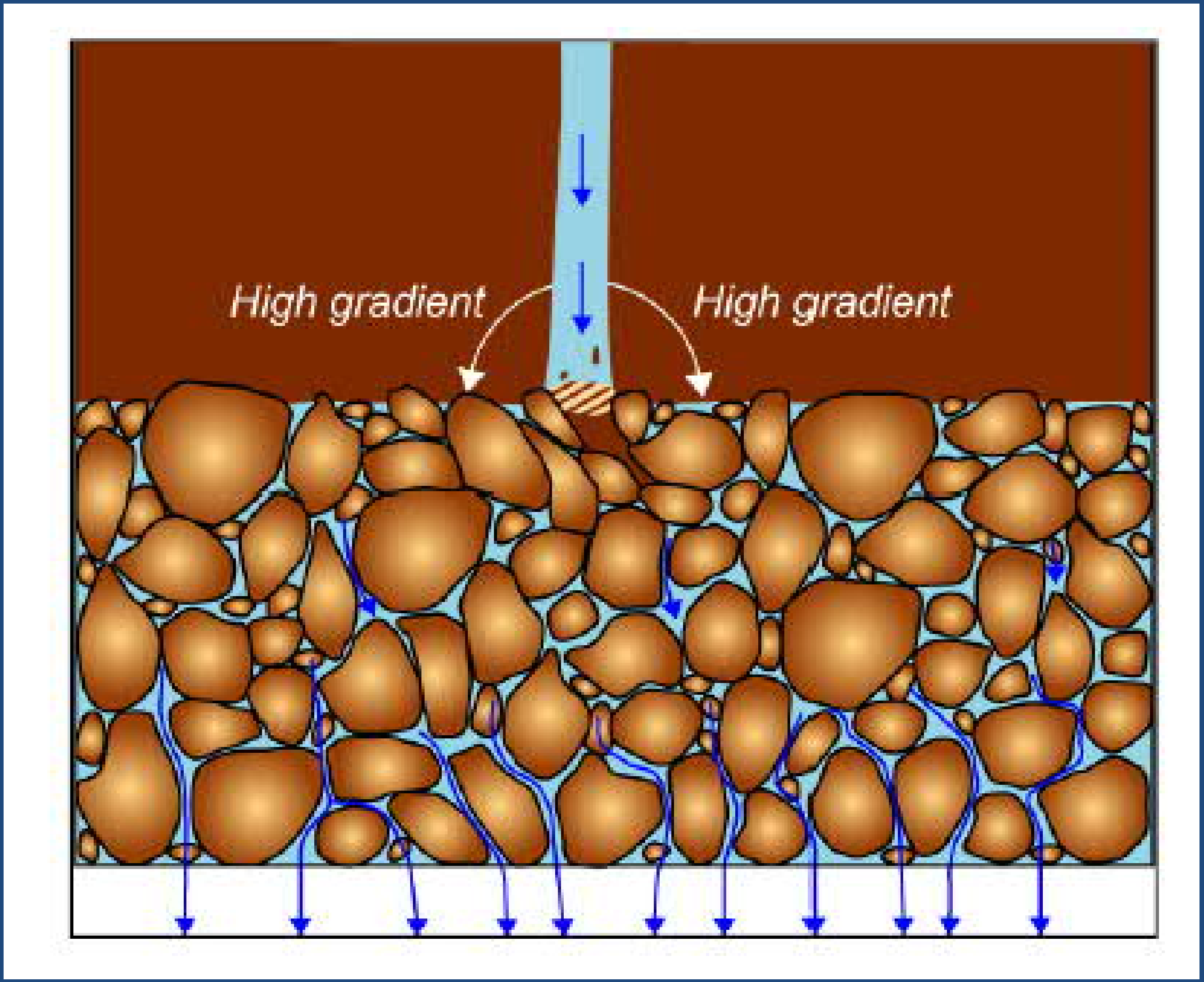


Filters are a Defense Against IE Mechanisms



- Filters can arrest almost all IE mechanisms / failure modes
- Exception may be IE through large openings in rock

Eroded Soil in Crack Caught by Filter



Seepage Detection

- Visual inspection/observation
- Monitoring instruments
  - Flow measurement
  - Piezometers
- Water properties
  - Turbidity measurements
  - Temperature studies
  - Chemistry studies
- Non-intrusive investigations

Inspection versus Monitoring

Visual inspection tells you very little about what is inside the dam, but usually provides the first indicator of adverse performance

Seepage Detection

- Developing seepage failure modes are most often first detected with visual clues:
  - New or increased seepage discharge
  - Muddy or discolored seepage
  - Sand boils, blowouts
  - Sinkholes or settlement
- Instruments and measurements can also assist in detection, but are no substitute for visual observation

Visual Observation

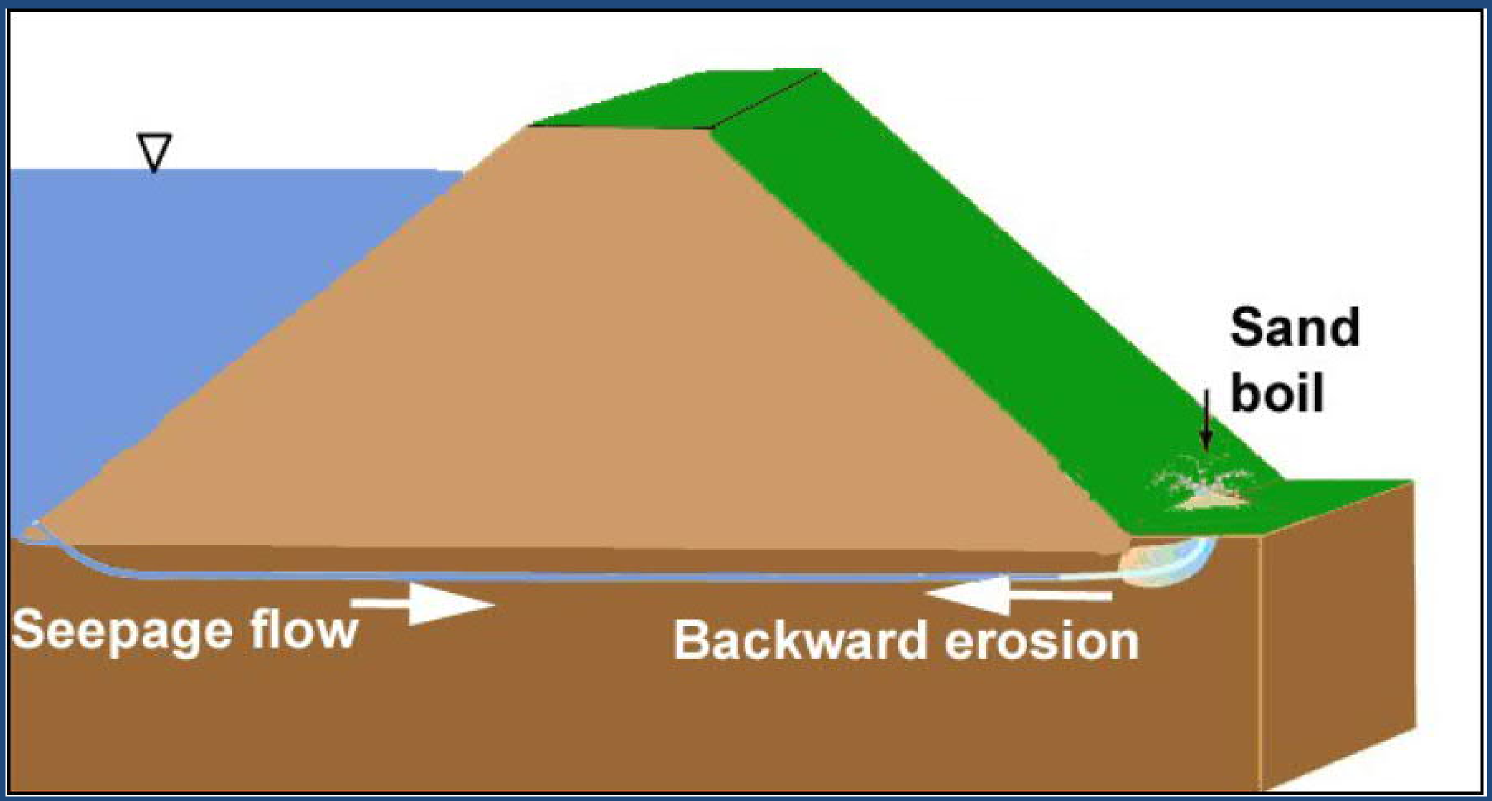
- First line of defense
- Look for changes
- Both trained and untrained eyes

Early Signs of Piping

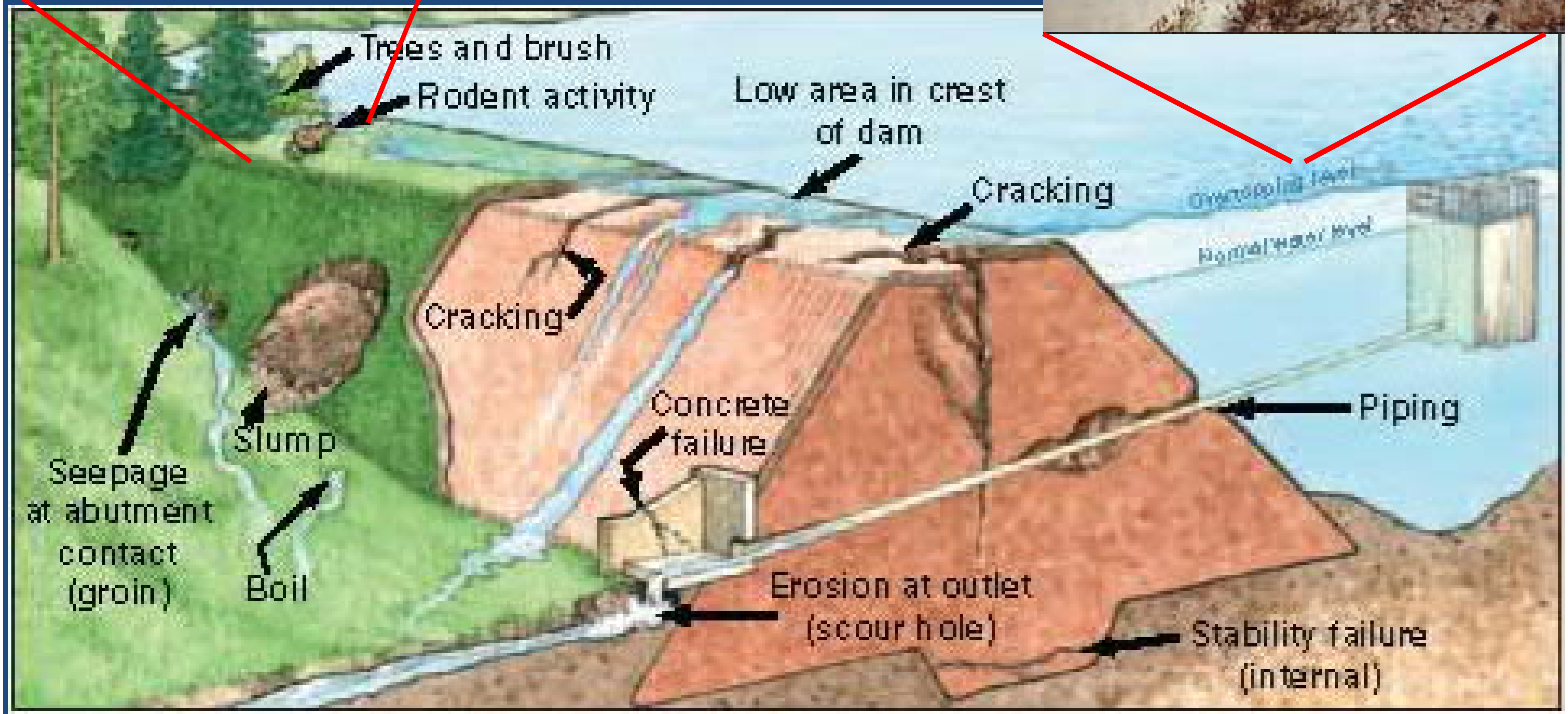
- Wet spots or flowing seepage on downstream slopes or abutment areas of the dam. May be turbid, but not all the time – episodic.
- Sand boils or excessive seepage at or beyond the downstream toe of the dam.
- When early signs of seepage appear, it is always good to start some type of monitoring or way to determine changes in flow, turbidity, or sediment discharge

Visual Observations

- Visual observations provide clues as to what IE failure mode may be developing

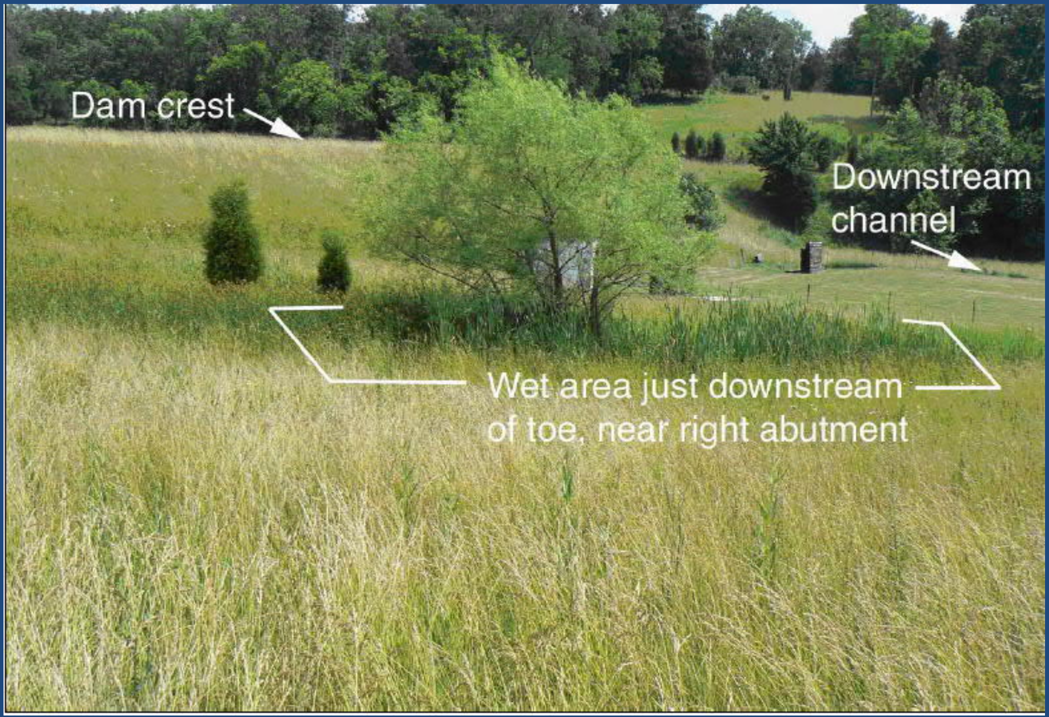


Items for Visual Observation



Visual Observation

- Saturated ground
- Wetlands
- Willows
- Staining

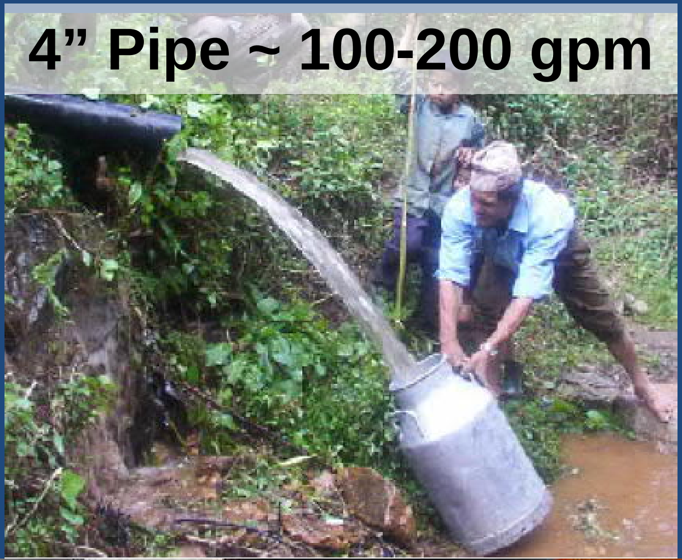


Reference: FEMA, Dam Safety: Seepage Monitoring, 2015

Visual Observations

- New/increasing seepage and sediment deposition

Visually Estimating Seepage Discharge Volumes



Visual Observations

- Cloudy discharge
- Pluming

Beginning of Piping – Sand Boil Example

Sand boils just beyond downstream toe of embankment with substantial seepage through the foundation collecting along the downstream area. No drain to intercept seepage.

Visual Observations

- Sinkholes
- Depressions
- Reservoir whirlpools or vortices

Visual Observation

- Boils
- Settlement
- Sinkholes

Visual Observations

- Sand boils

  - Often slightly submerged on downstream toe
  - Detectable by water ripples (a)
  - May start as very small deposit (b)
  - Often sandbagged to help limit progression (c)

Visual Observations

- Sand boils

4-ft-diameter sand boil at downstream toe of dam

Actively piping sand boil at downstream toe of dam

Visual Observations

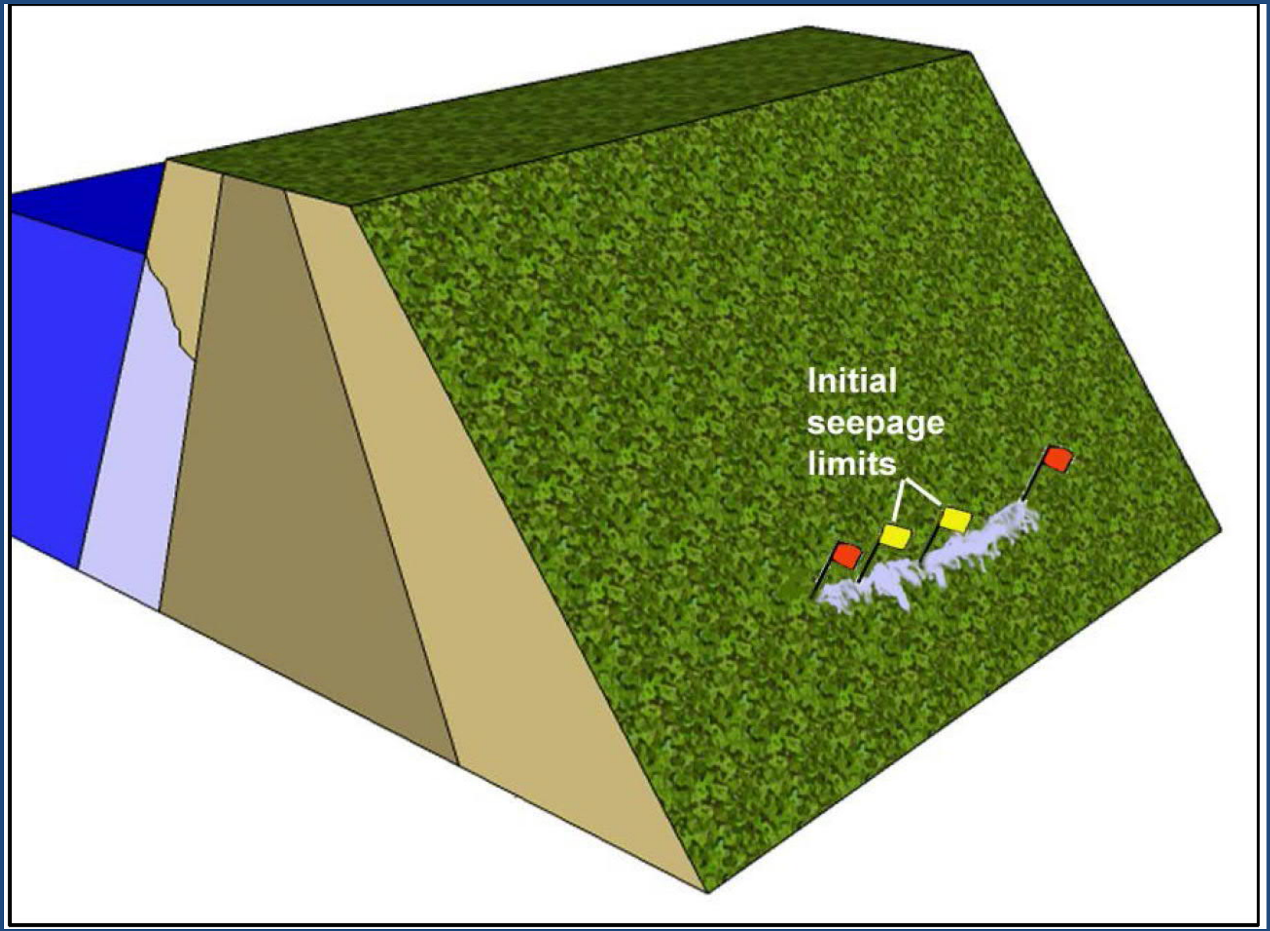
- Blowouts

Rupture of confining layer at downstream toe of dam

Sand deposit/flow out of rupture

Visual Observation

- Use Visual Markers to help detect change



Reference: FEMA, Dam Safety: Seepage Monitoring, 2015

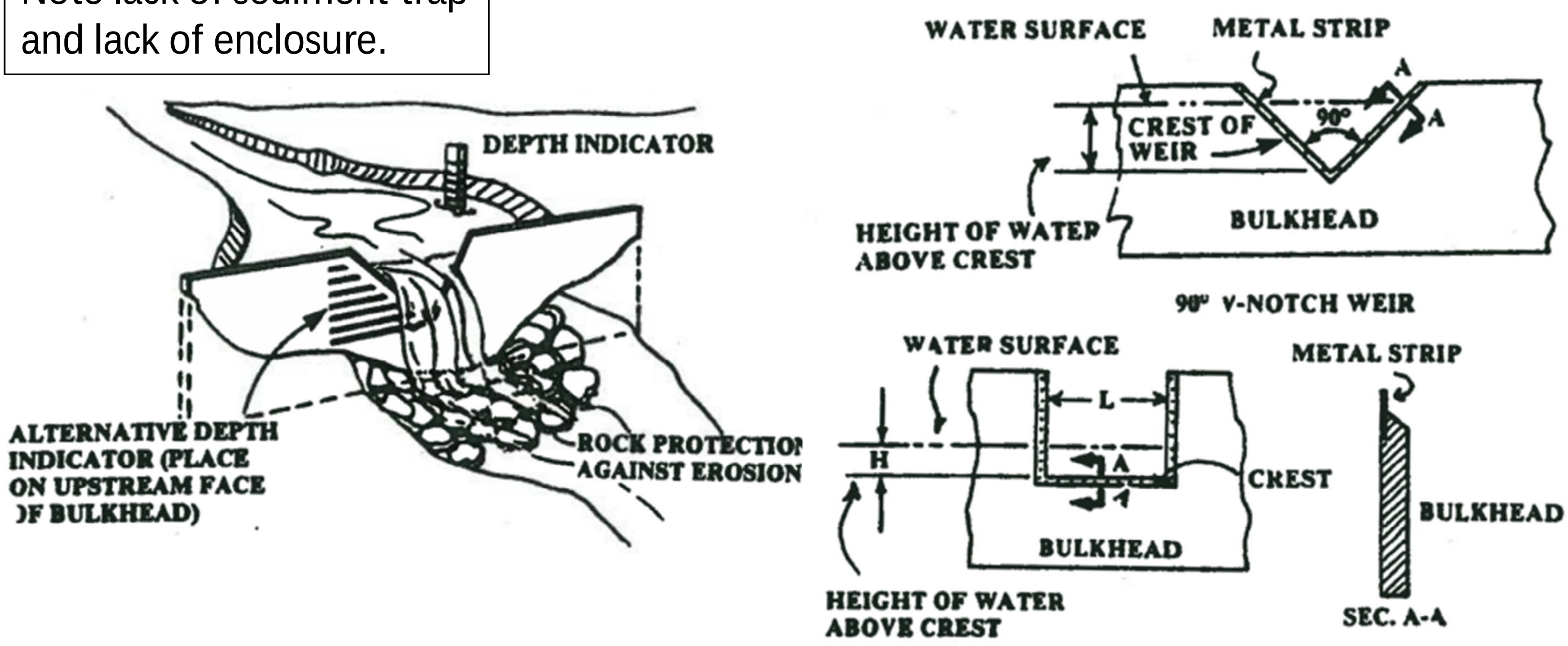
Flow Measurement

- Type of Flow Measuring Devices:
  - Weirs
  - Flumes
  - Flowmeters
- Purpose:
  - Measure seepage
  - Monitor turbidity / sediment transport

Seepage Weirs and Flumes

Weirs

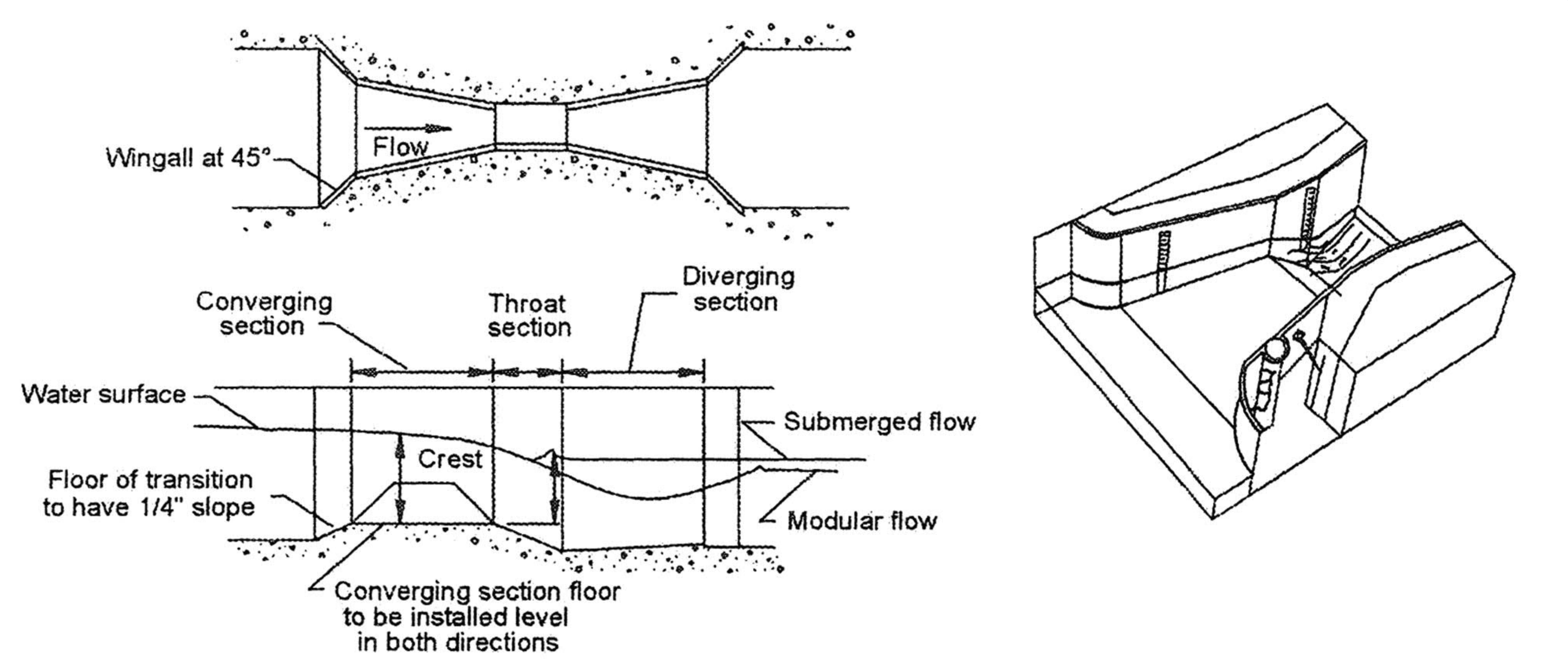
Note lack of sediment trap and lack of enclosure.



Reference: FEMA, Dam Safety: An Owner's Guidance Manual, 1987

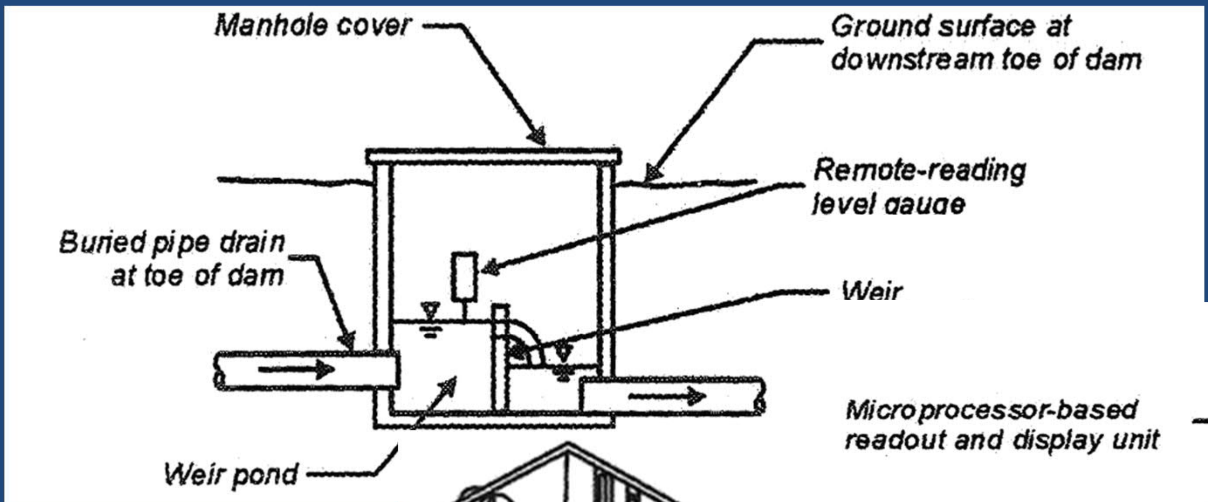
Seepage Weirs and Flumes

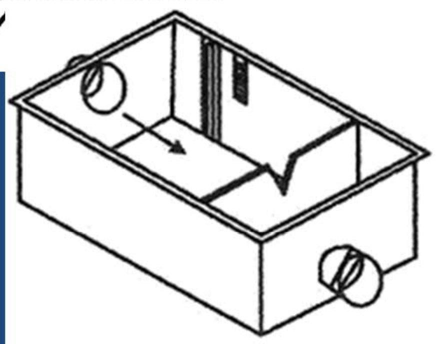
Parshall flume

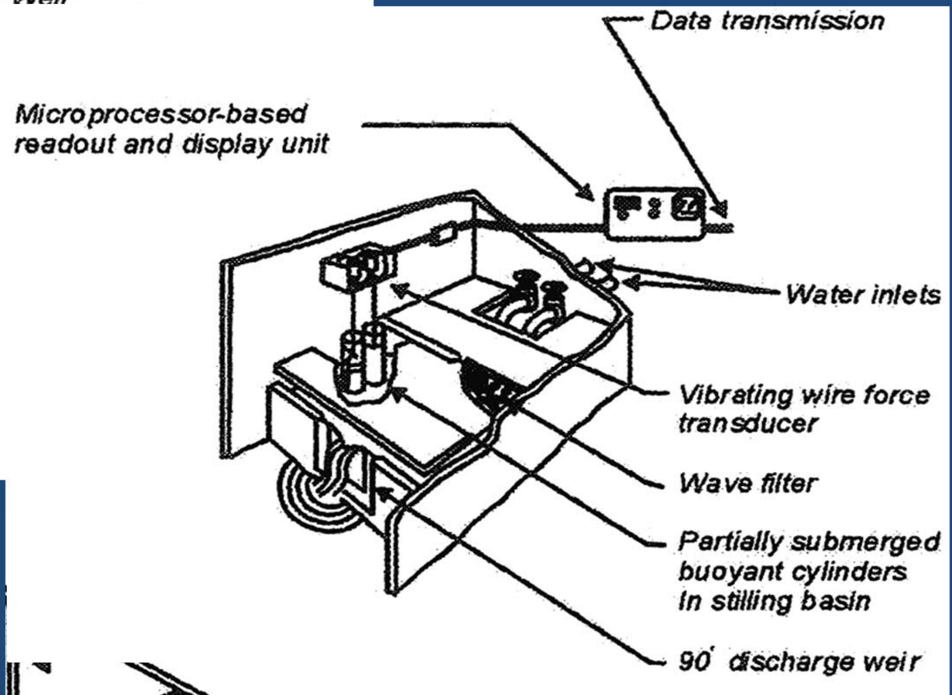


Reference: ASCE, Guidelines for Instrumentation and Measurement for Monitoring Dam Performance, 2000

Seepage Weirs and Flumes







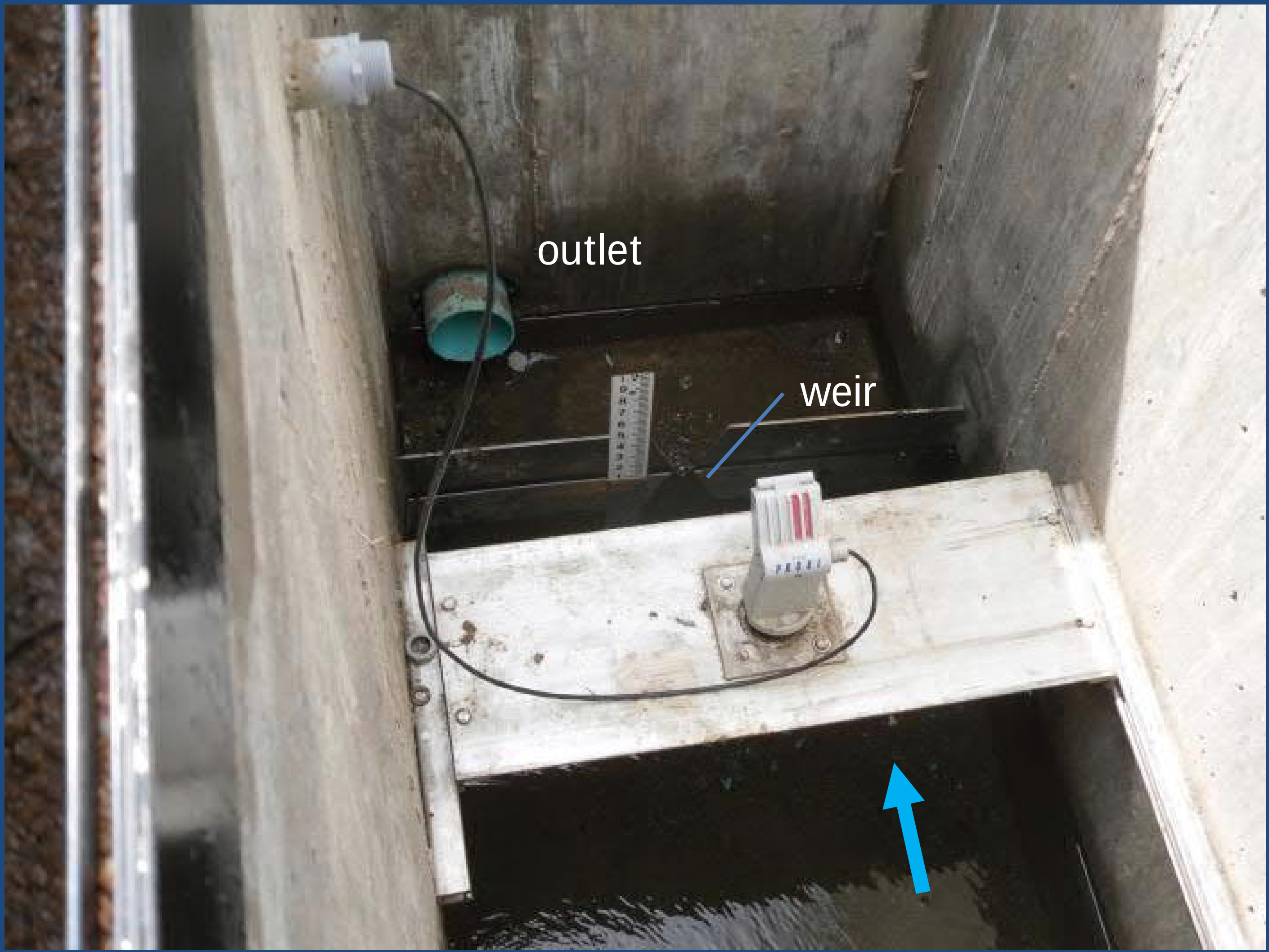
Inspection well installation

Reference: ASCE, Guidelines for Instrumentation and Measurement for Monitoring Dam Performance, 2000

Seepage Weirs and Flumes

Seepage Weirs and Flumes

Seepage Weirs and Flumes



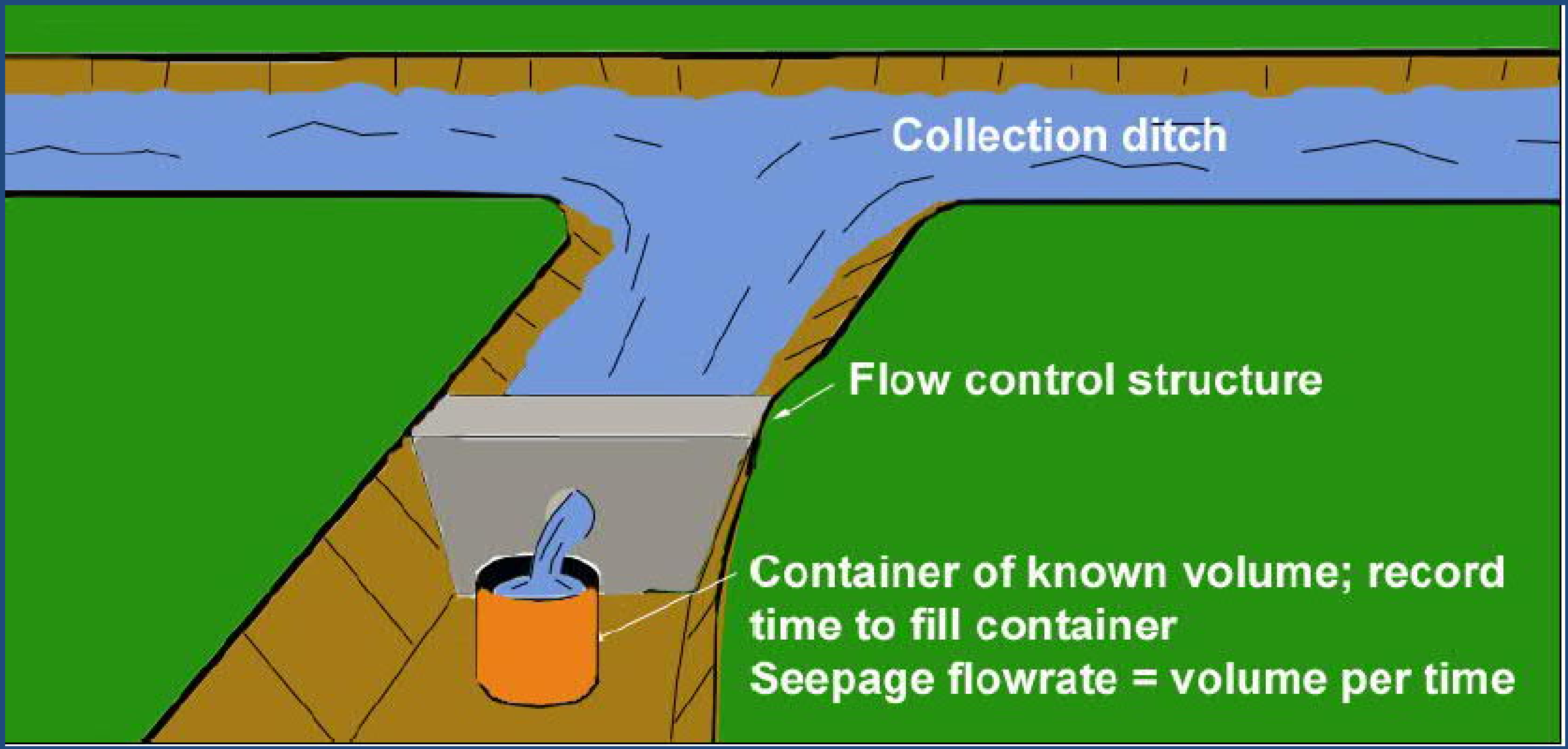
Seepage Weirs and Flumes

Seepage Weirs and Flumes

- Sediment monitoring

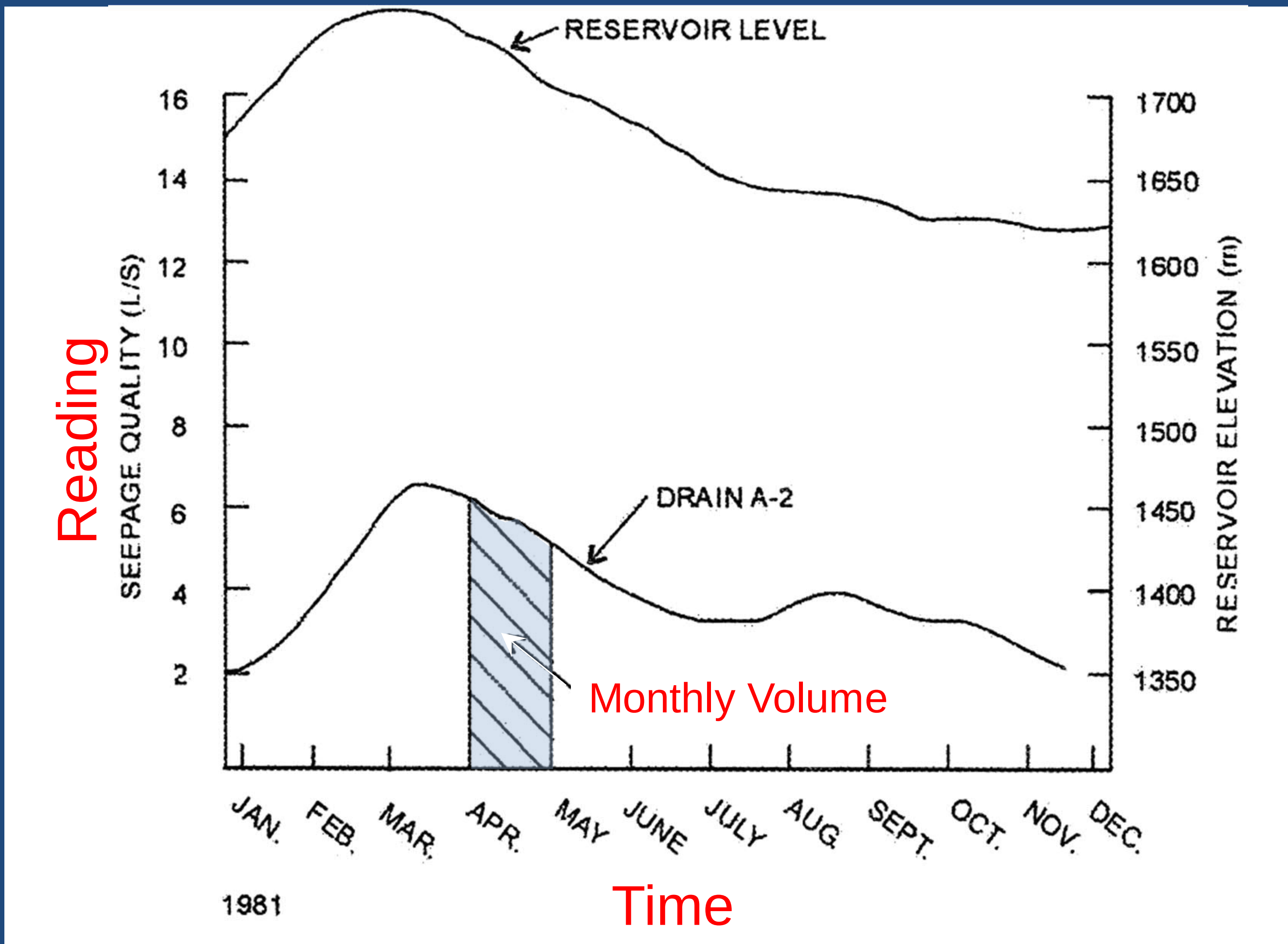
Seepage Weirs and Flumes

Bucket and stopwatch



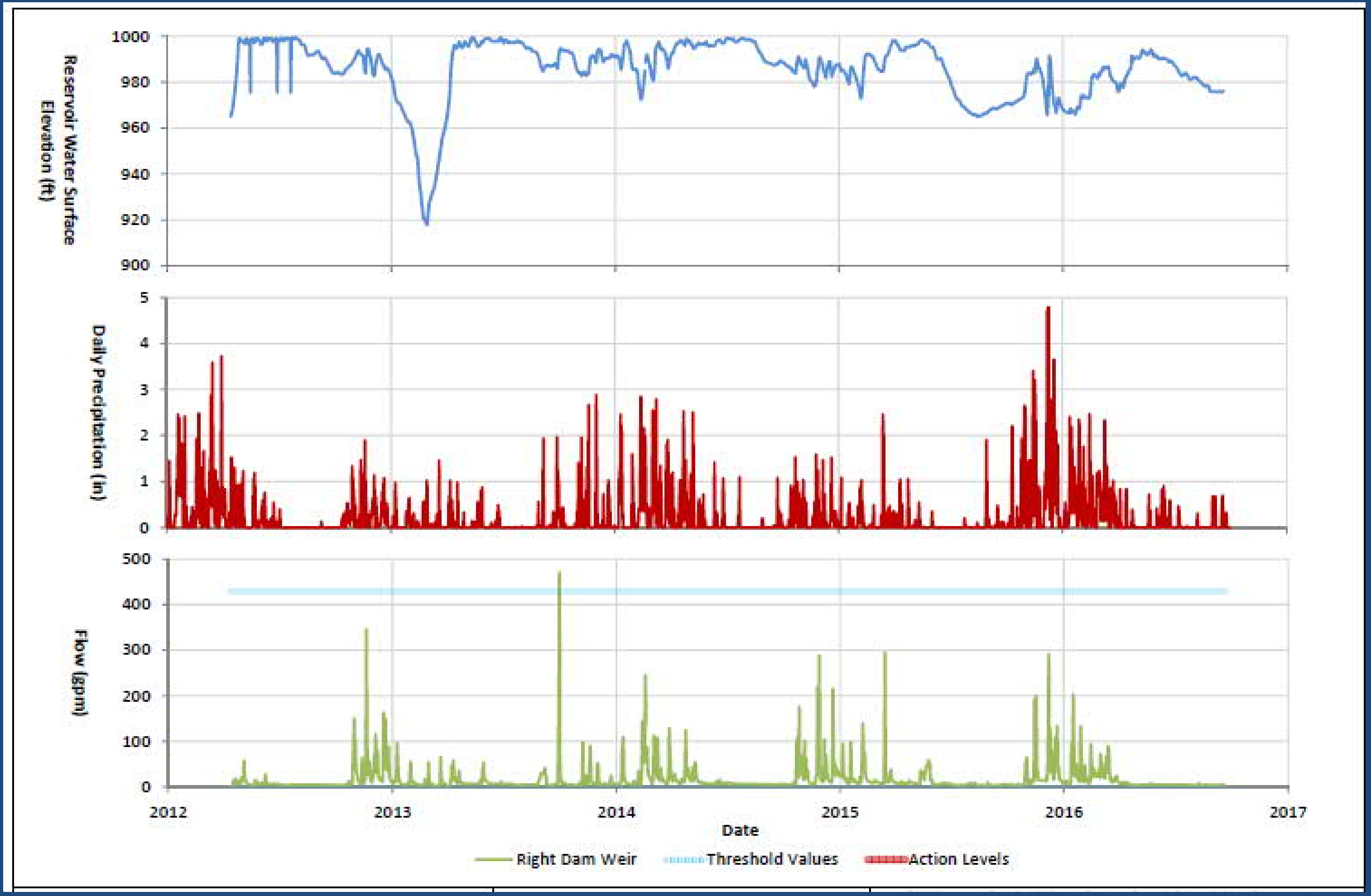
Reference: FEMA, Dam Safety: Seepage Monitoring, 2015

Flow: Time vs. Reading Plot

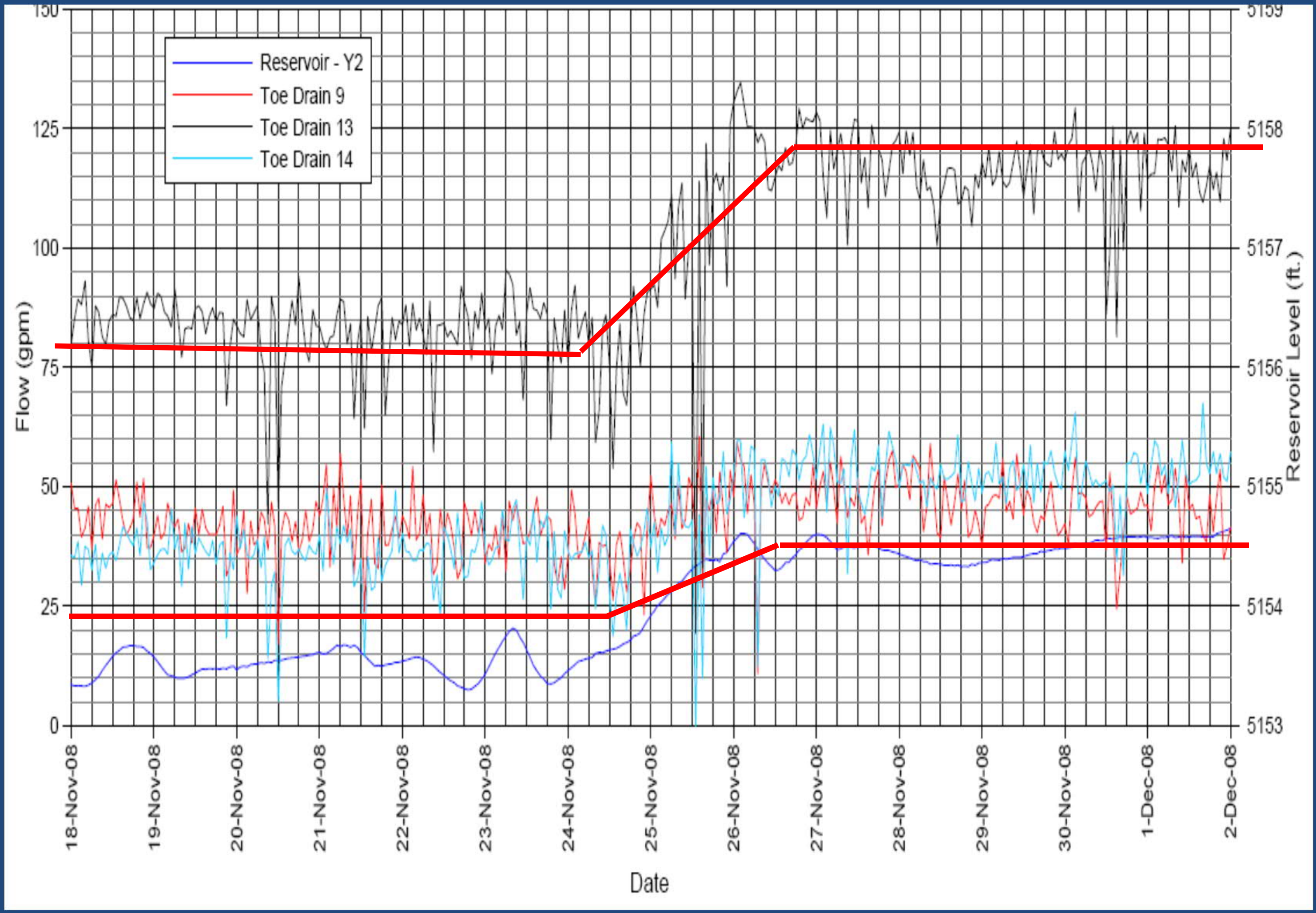


Reference: ASCE, Guidelines for Instrumentation and Measurement for Monitoring Dam Performance, 2000

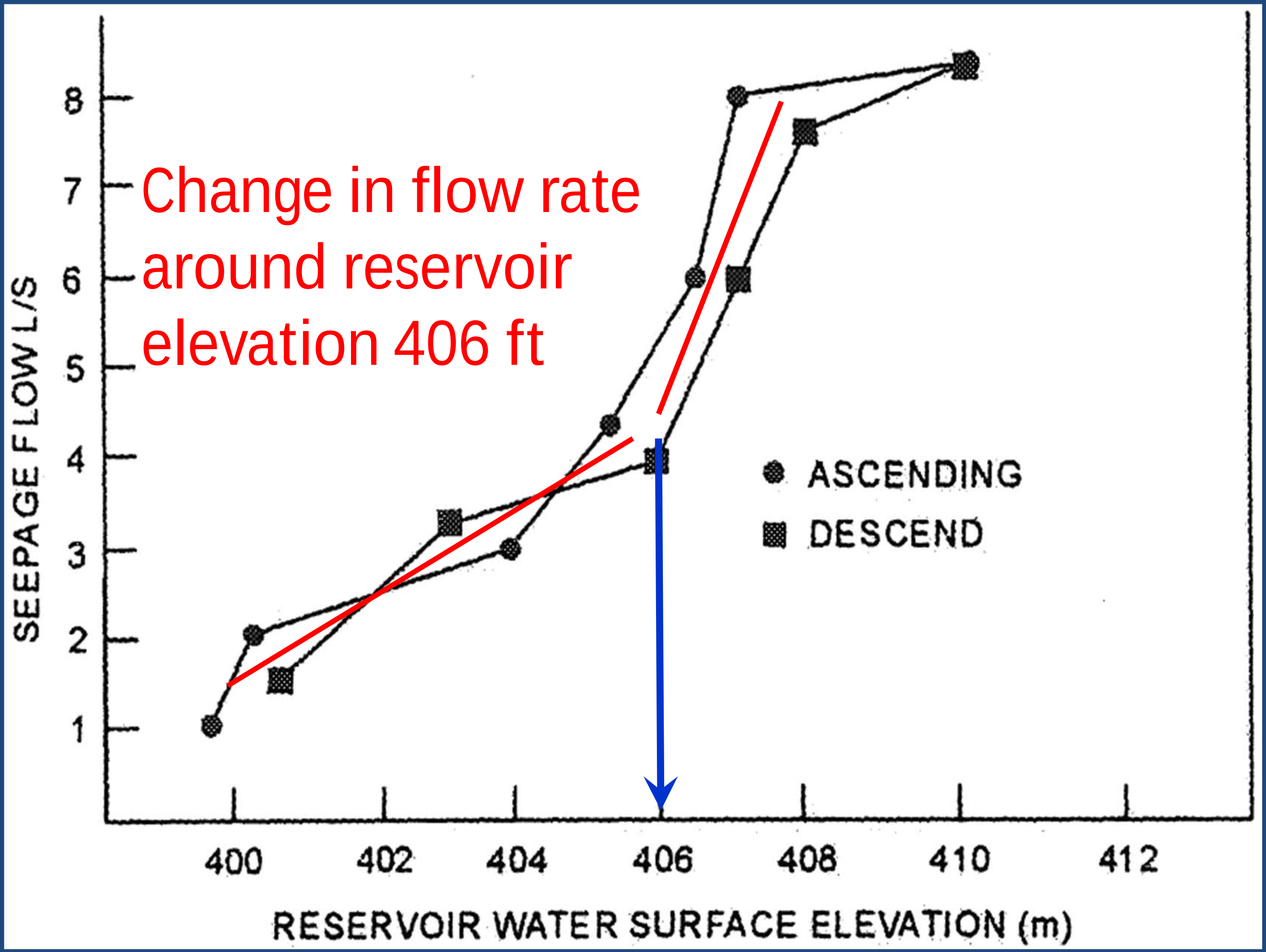
Flow: Time vs. Reading Plot



Toe Drain Flow Meters



Flow: Non-linear Flow Behavior



Flow: Data Evaluation

Things to consider

- Reservoir elevation and its variation
- Precipitation
- Seasonal changes
- Time

Instrumentation data does not replace visual observations; it supplements those observations

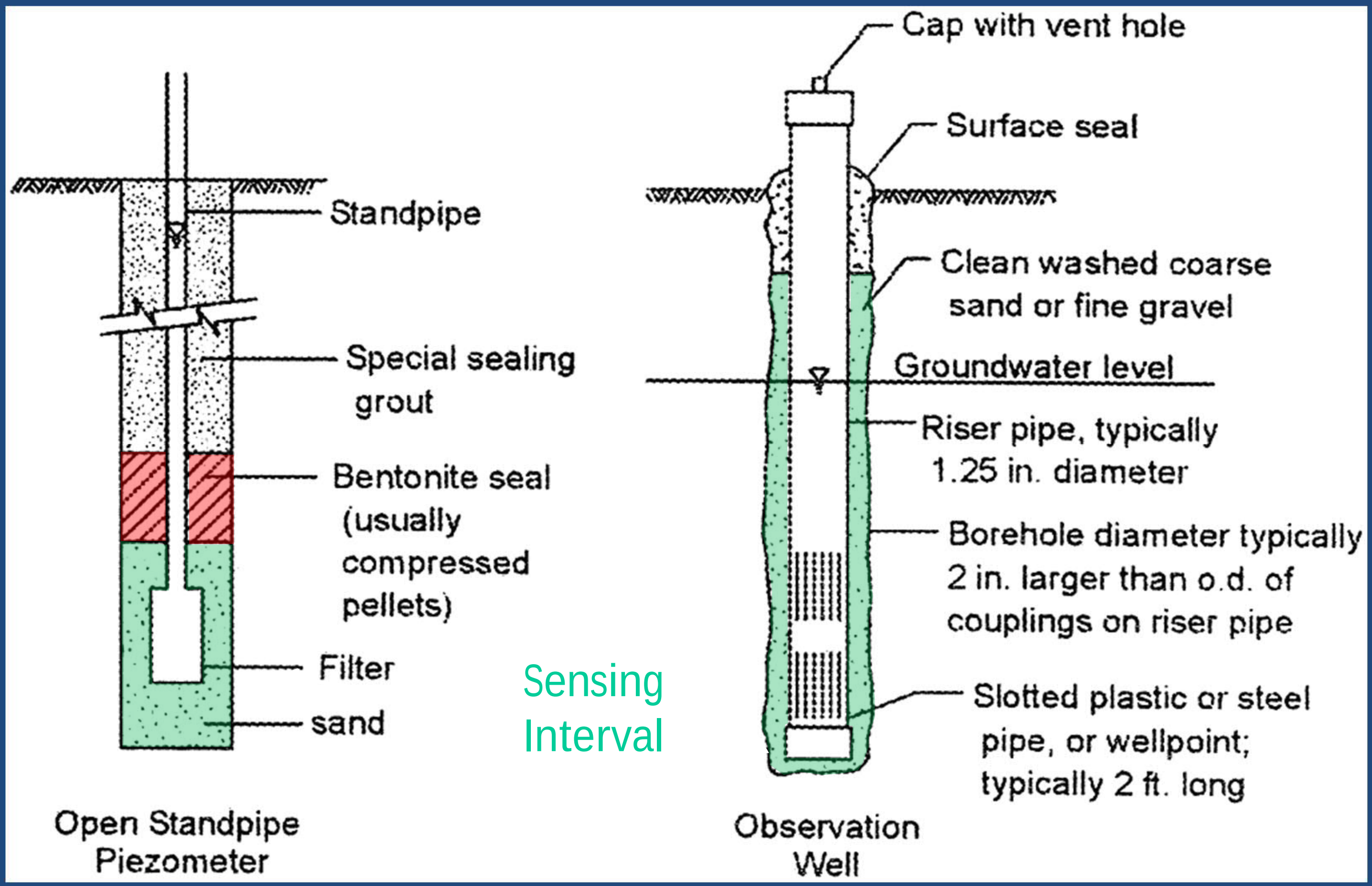
Piezometers

- Purposes
  - Piezometric levels in embankment and foundation
  - Phreatic surface in embankment
  - Gradient estimation
  - Provides means for measuring response times
  - Trends can be used for extrapolation of piezometric performance (with apropriate caution)

Piezometers

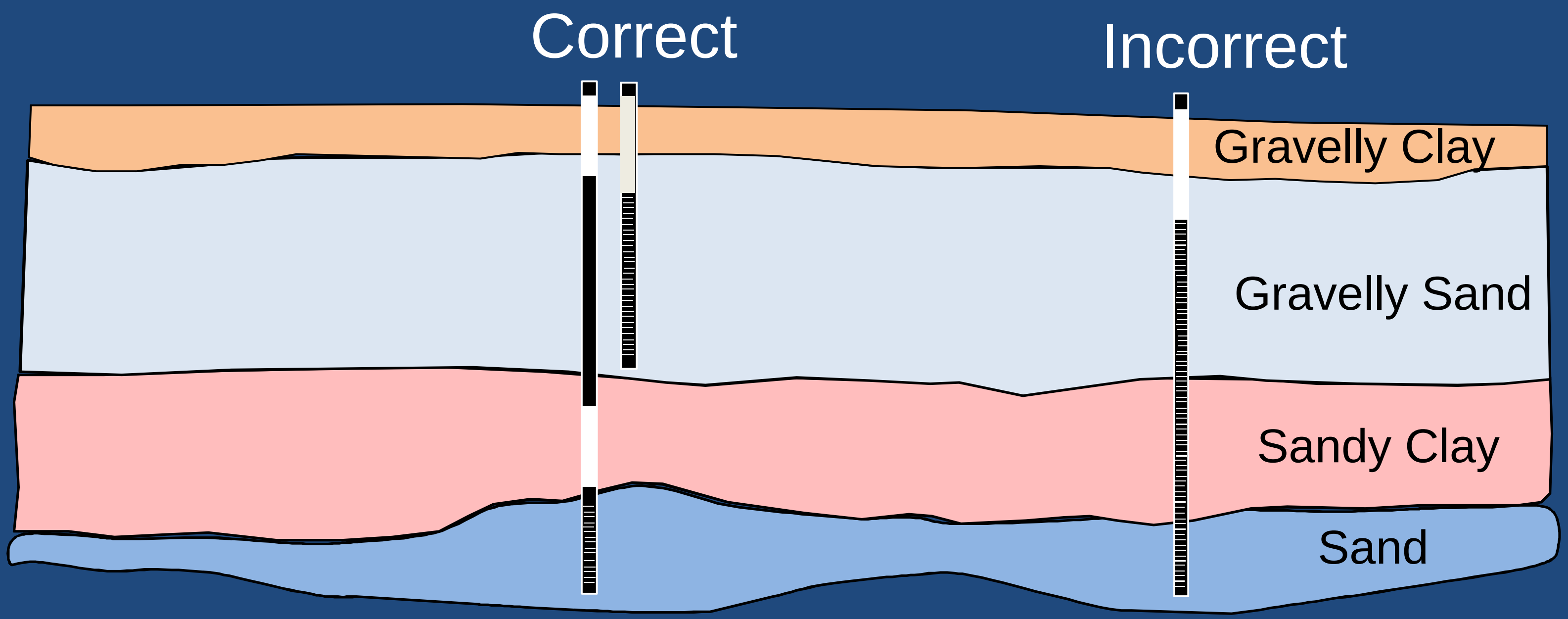
- Types
  - Stand pipes
  - Porous tube
  - Hydraulic (old technology)
  - Pneumatic (old technology)
  - Vibrating wire (including grouted-in piezometers)

Isolated vs. Non-isolated Piezometers



Reference: ASCE, Guidelines for Instrumentation and Measurement for Monitoring Dam Performance, 2000

Isolated vs. Non-isolated Piezometers



These two piezometers measure pressures in two distinct strata.

What pressure does this piezometer measure?

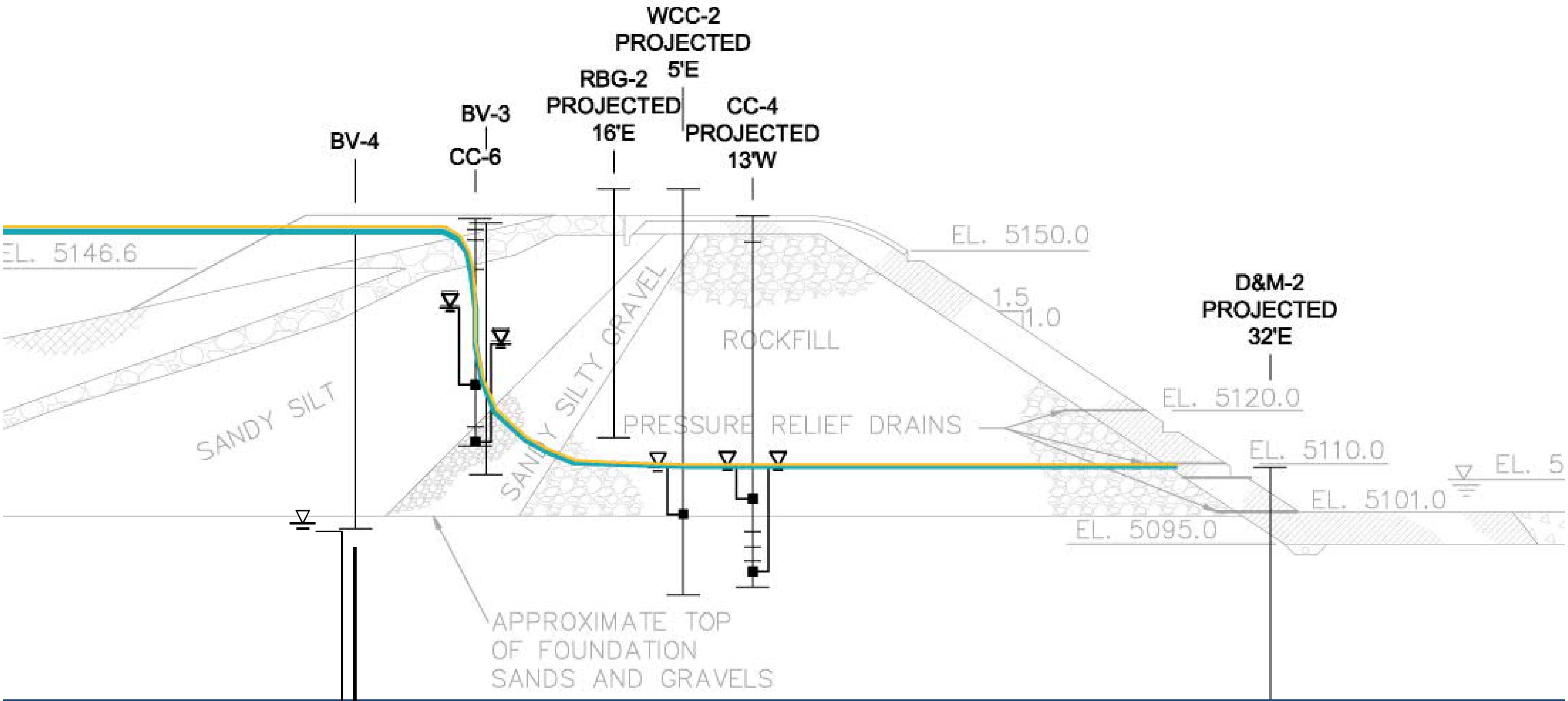
Vibrating Wire Piezometers

- Positives
  - Very responsive
  - Remotely accessible
  - Provide automatic, real-time readings
  - More data at less cost
- Negatives or Cautions
  - Subject to sensor failure, but generally pretty reliable
  - Sensitive to installation technique and calibration
  - Maintenance of transducers and power supply
  - Electromagnetic interference
  - Changes in temperature of both the ambient air and the liquid in the well can affect the accuracy

Grouted VWPs

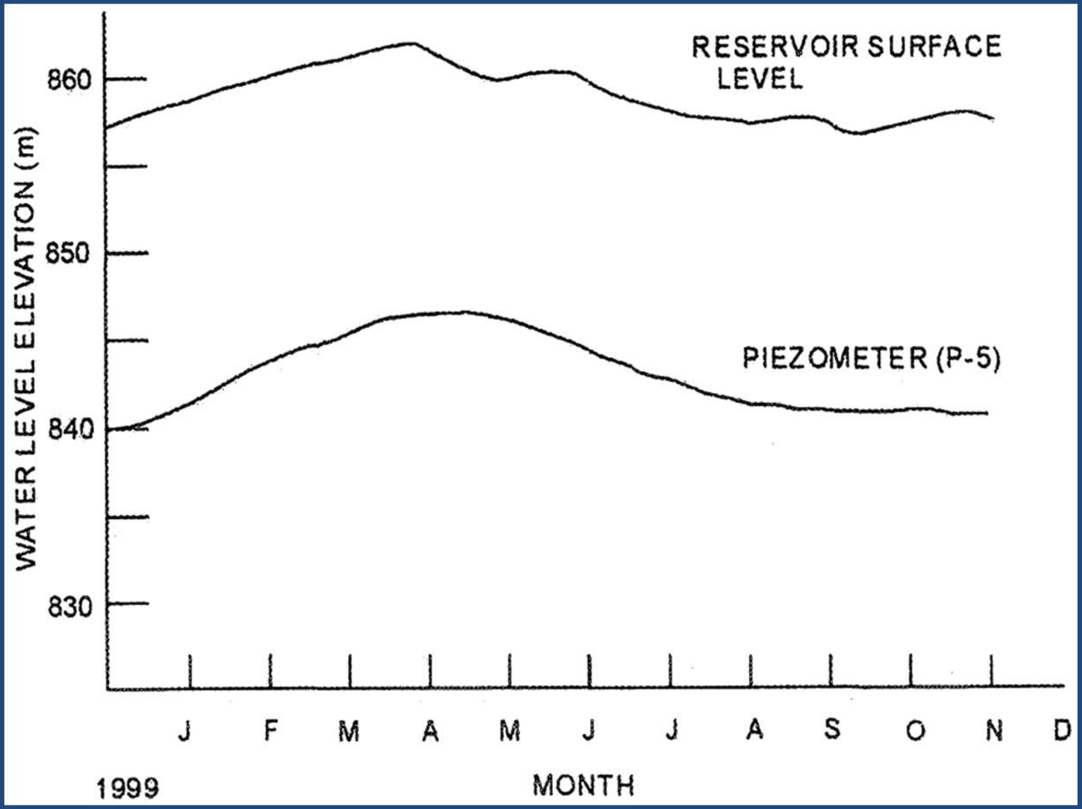
- Positives
  - Less expensive
- Negatives or Cautions
  - Need to use correct grout mix
  - Prevents replacement, recalibration, and manual readings for data verification
  - Can cause initial pressure that may not dissipate (anomalous readings)
  - Careful if transducer is near a material boundary with significant permeability difference

Piezometers



Piezometers

Example data plot



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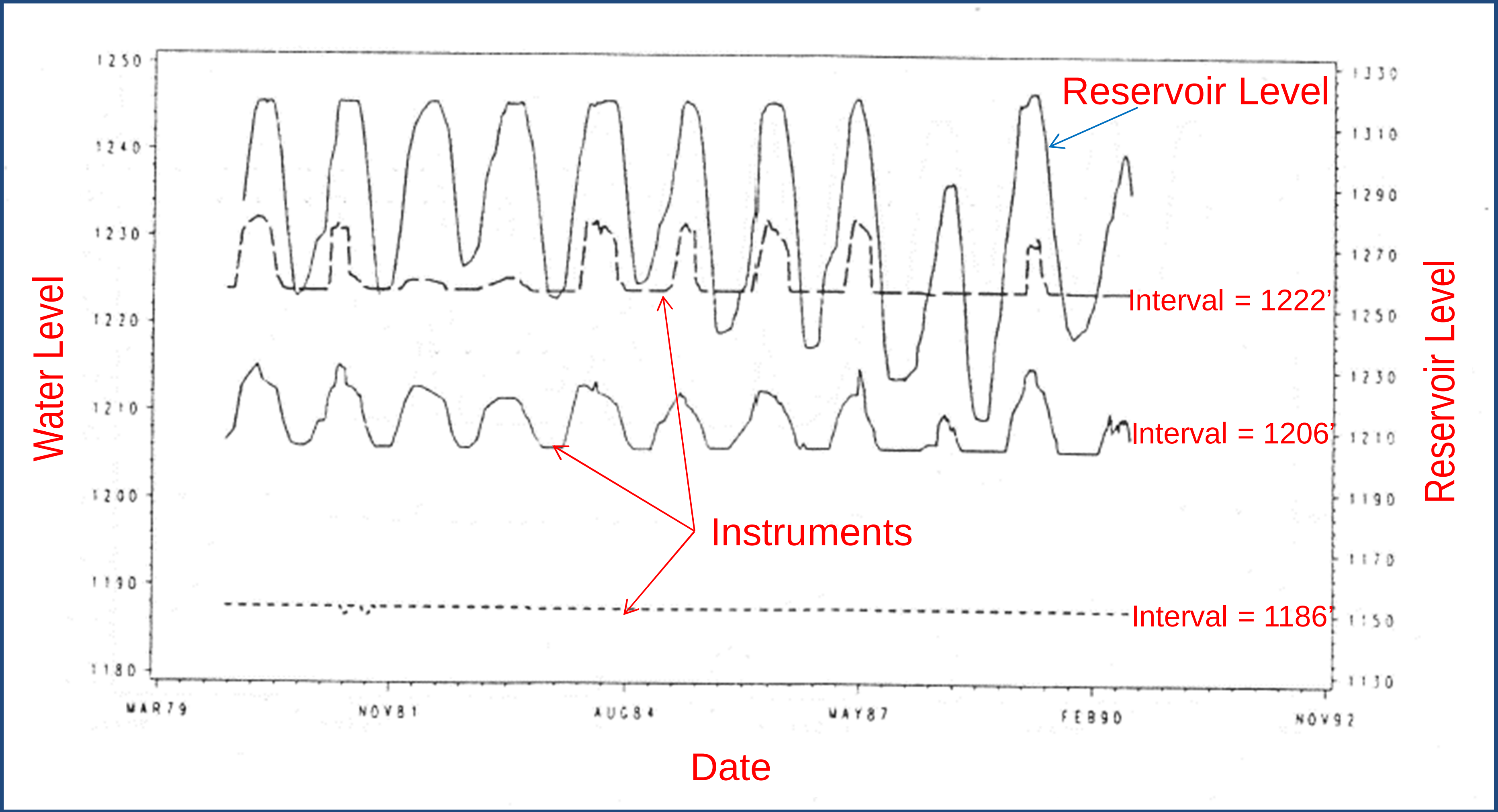
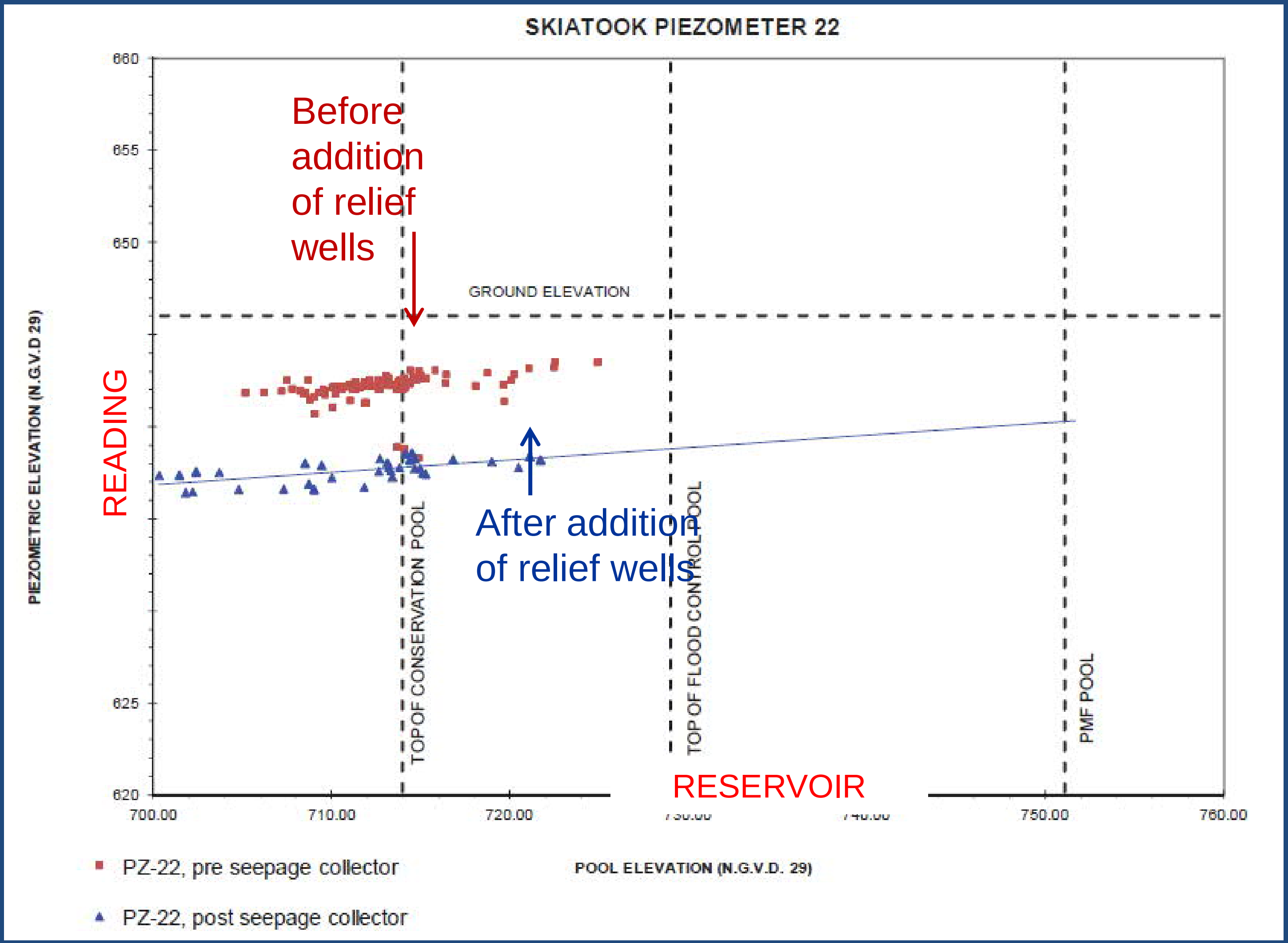
Actual Data Plot: Time vs. Reading

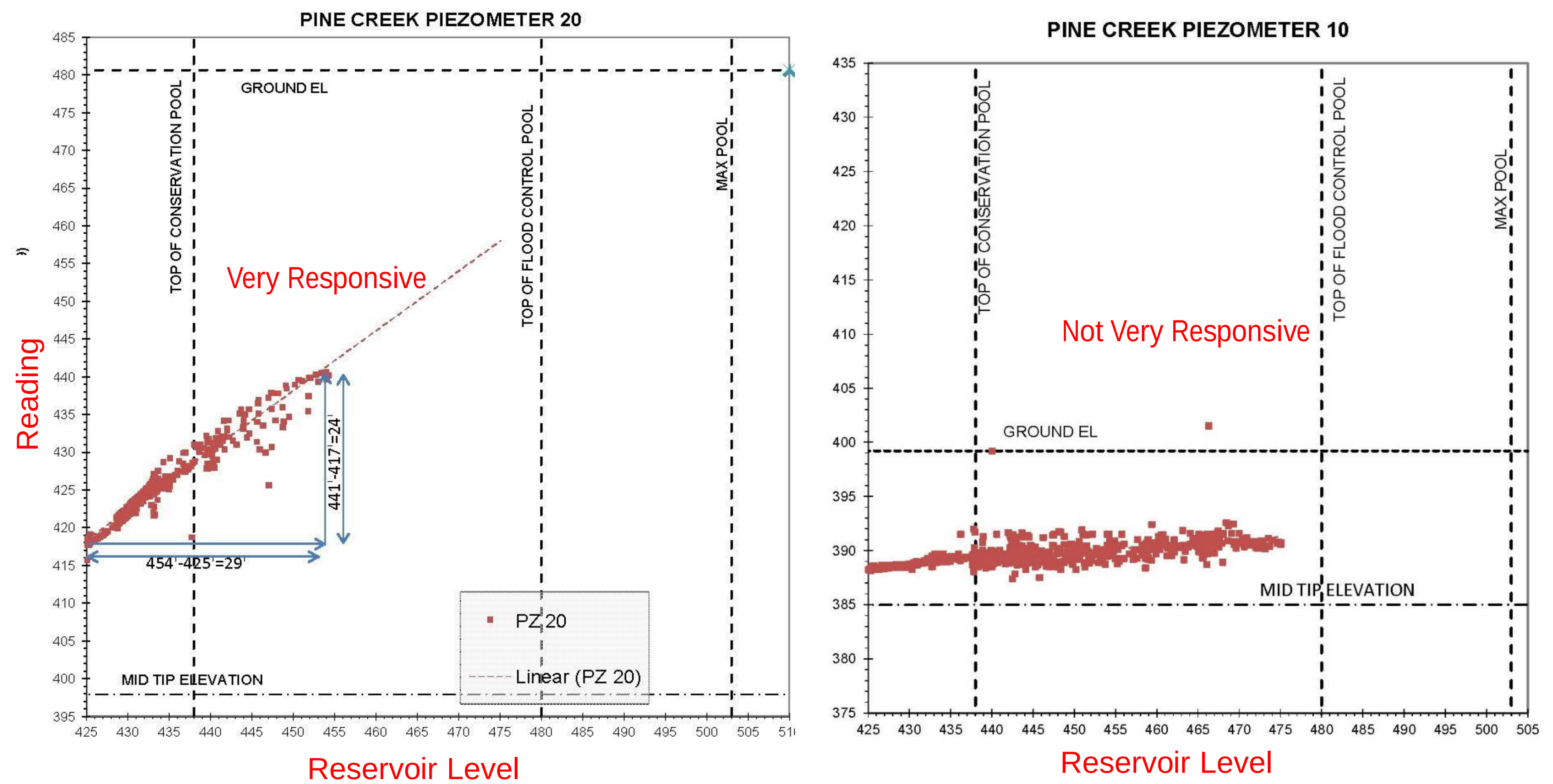
Actual Data Plot: Time vs. Reading



Actual Data Plot: Reservoir Level vs. Reading



Piezometer Response



Piezometer Responsiveness to Pool Changes c/o Kathryn White USACE-SWT

Interpretation of Reservoir Level vs. Reading Plots

- Data are hysteretic?
- How are data extrapolated to reservoir levels not experienced?
  - Caution is appropriate in extrapolation

Water Properties

- Turbidity Monitors
  - Very sensitive devices; careful interpretation needed
- Chemical Properties
  - Can be compared to reservoir or groundwater to determine source
- Temperature
  - Response to changes in reservoir temperatures

Chemistry

- Sample at locations of opportunity
  - Reservoir
  - Piezometers
  - Wells
  - Seepage Locations
  - etc.

- Create Stiff Diagrams

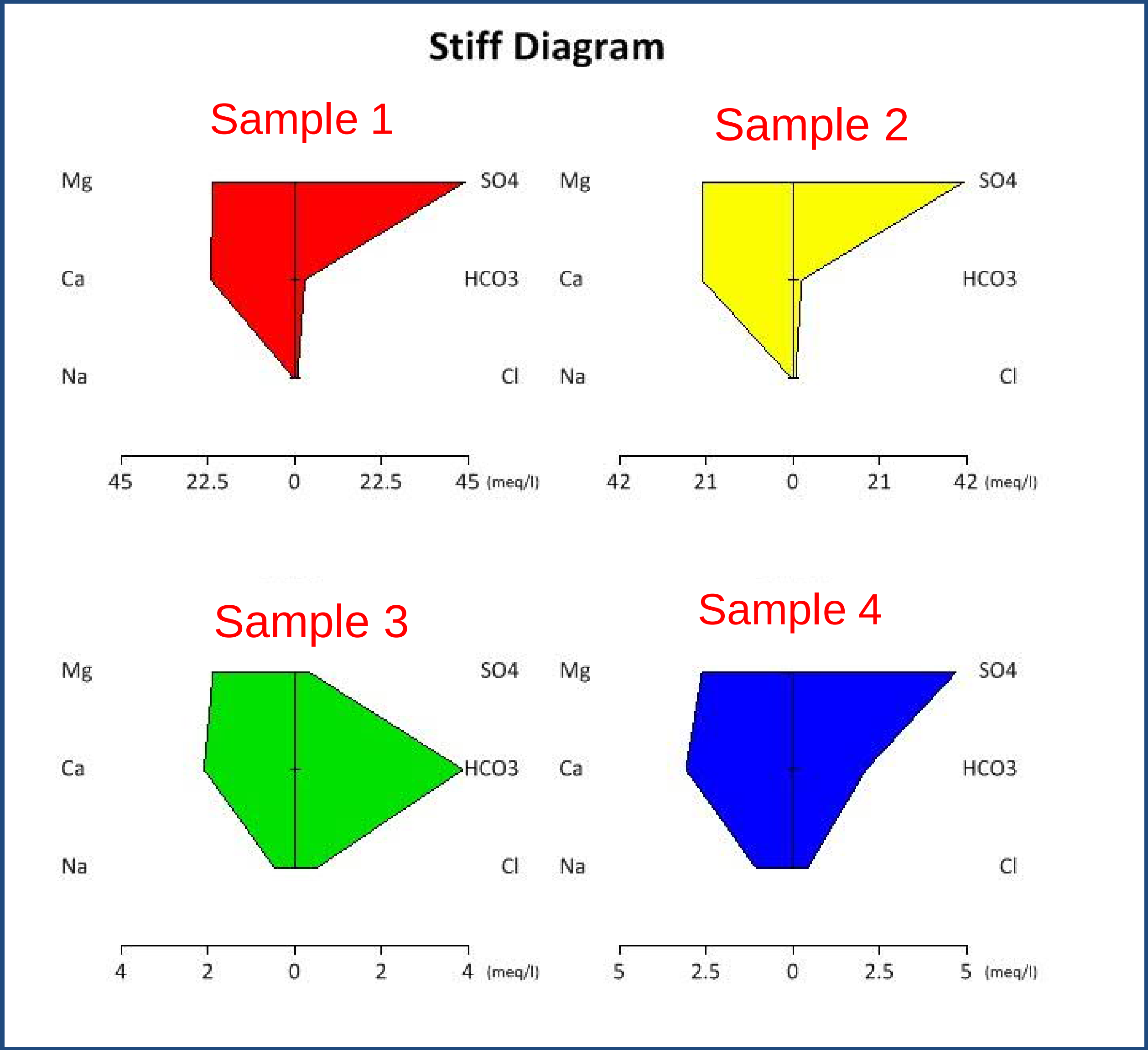
Chemistry

- For each sample, determine the concentration of select cations and anions.

Available from standard water chemistry tests

- Plot the data (Stiff Diagram)

Chemistry



Chemical Signatures

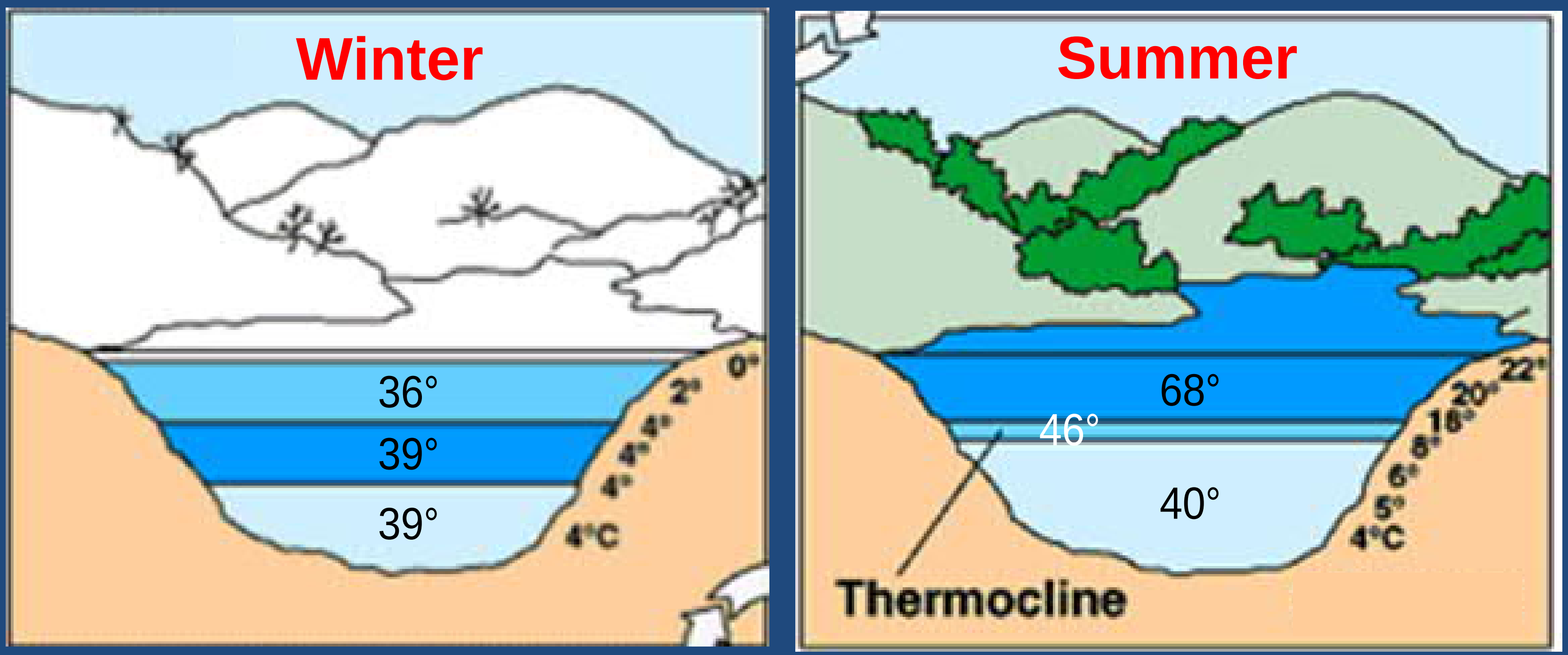
By comparison of water constituents, seepage pathways can be deduced.

Temperature

- Reservoir Temperature Varies
- Groundwater Temperature Varies
- Data is collected from reservoir, ponds, seepage locations, piezometers, inclinometers, etc.
- Temperature variation allows for potential identification of seepage paths

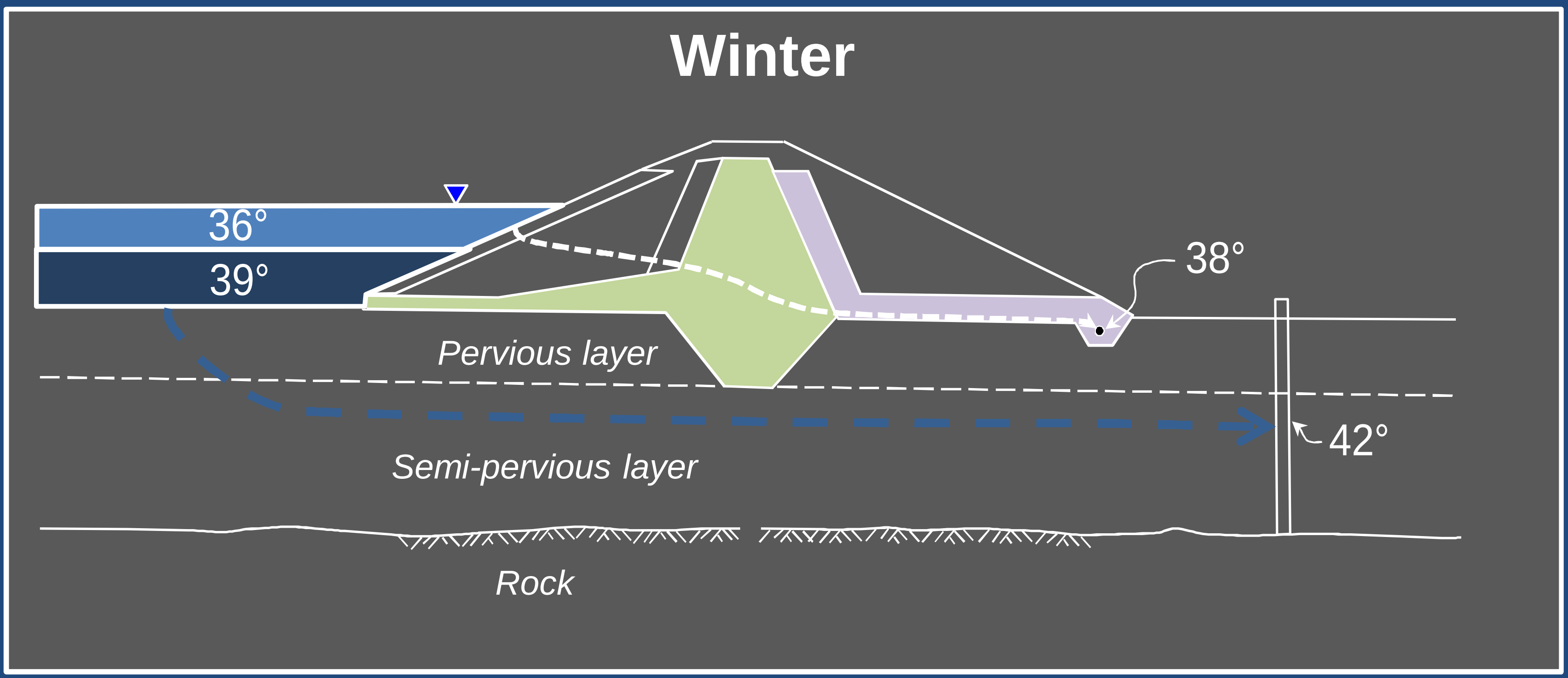
Temperature

Thermal Stratification and Seasonal Variation



Provides a distinct loading signature

Temperature



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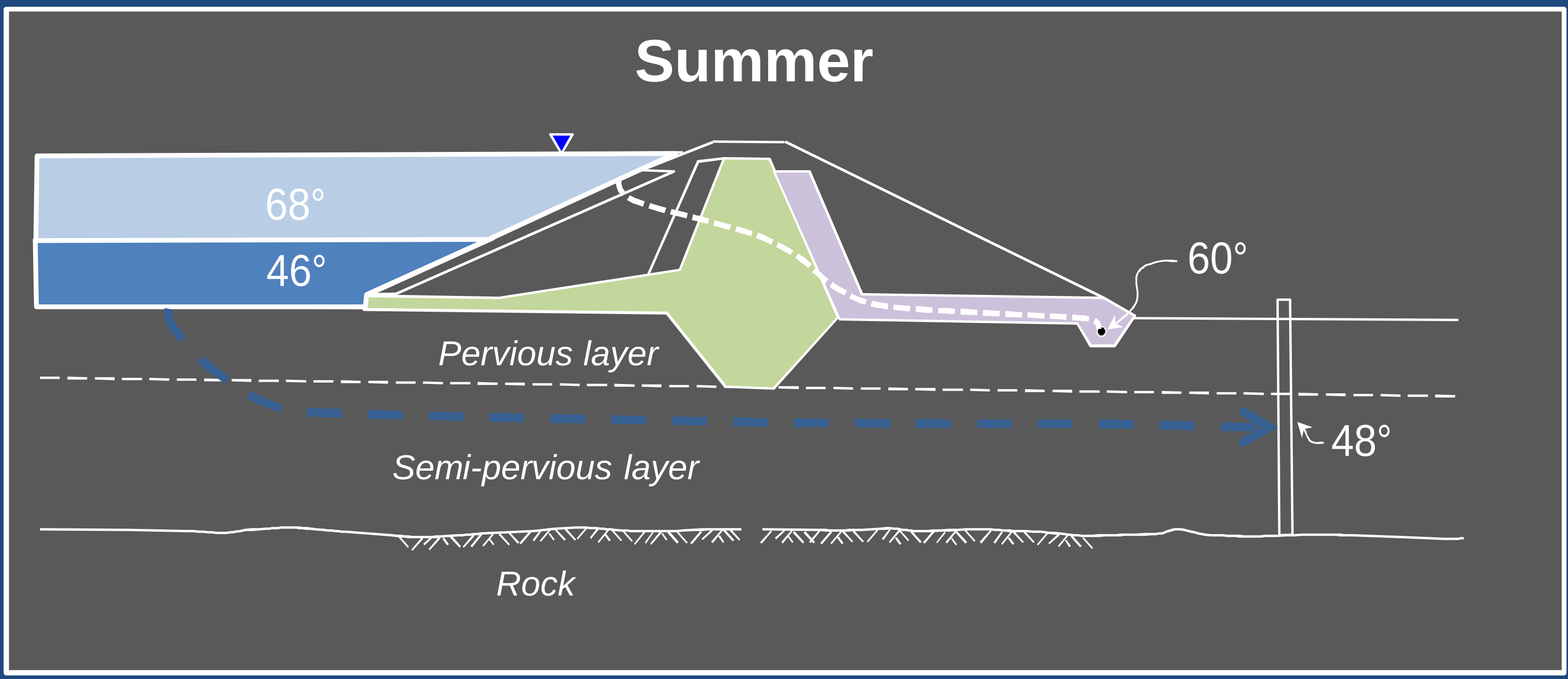
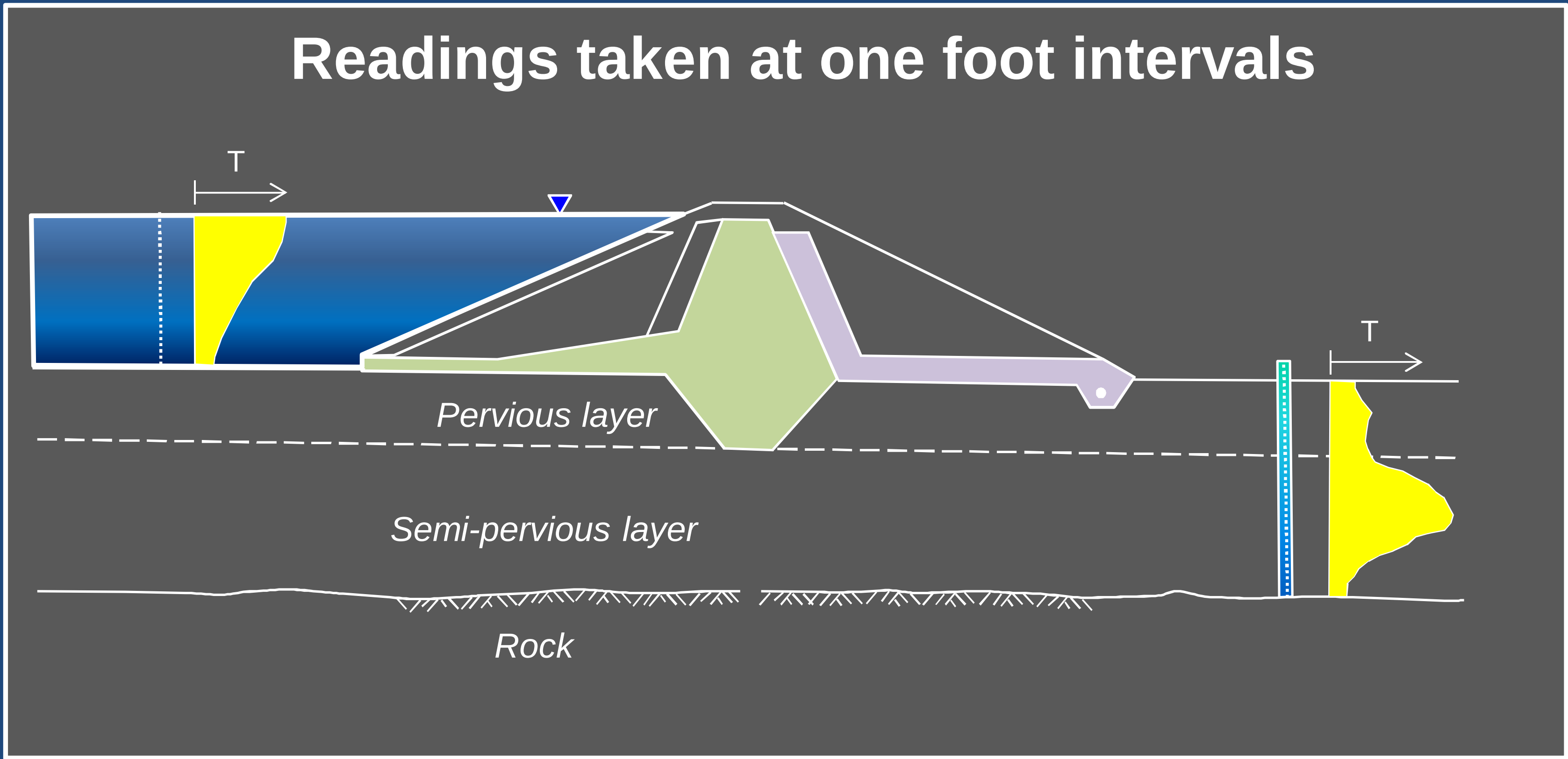


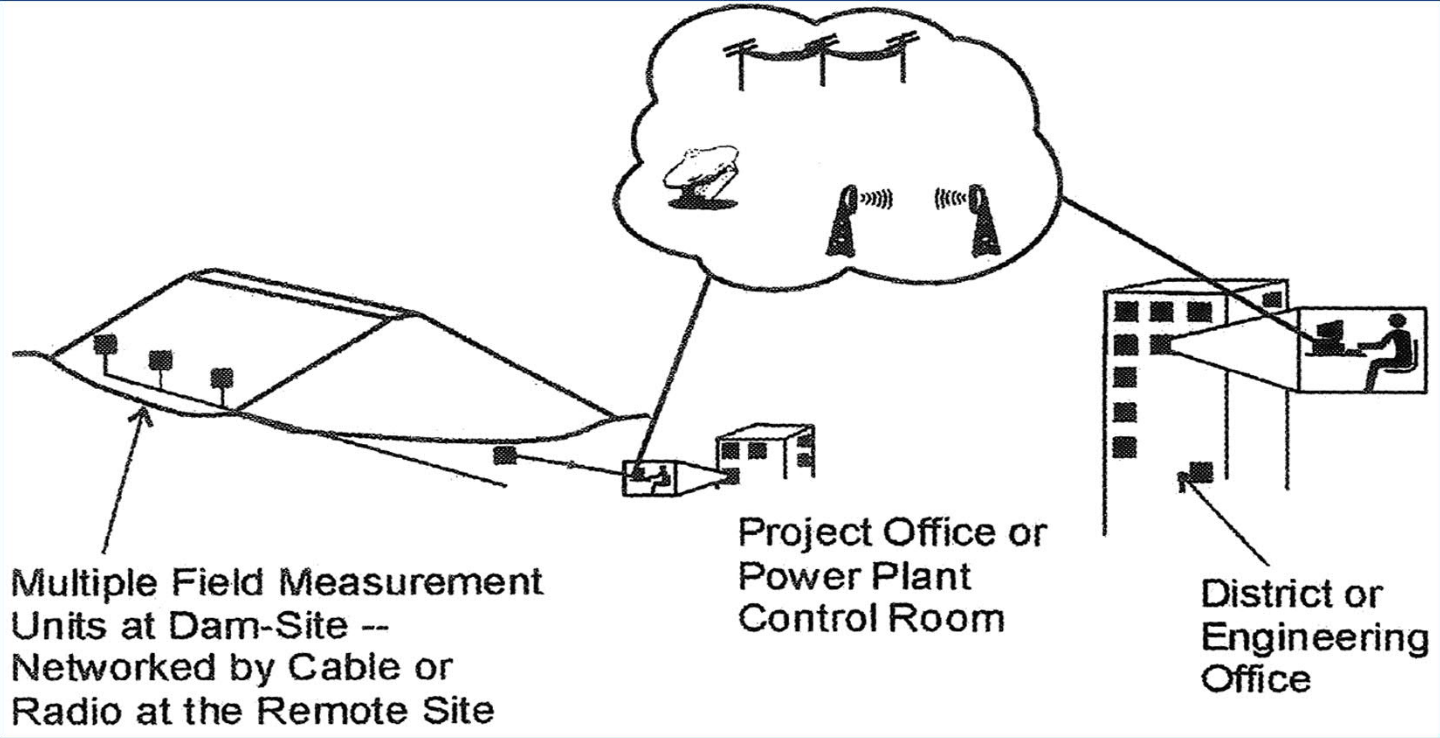
Temperature



Non-Intrusive Methods

- Self-potential
- Resistivity
- Electro magnetic
- Proprietary methods – e.g. Willowstick
- Dye tracing

Automated Data Acquisition Systems (ADAS)



ADAS schematic

Reference: ASCE, Guidelines for Instrumentation and Measurement for Monitoring Dam Performance, 2000

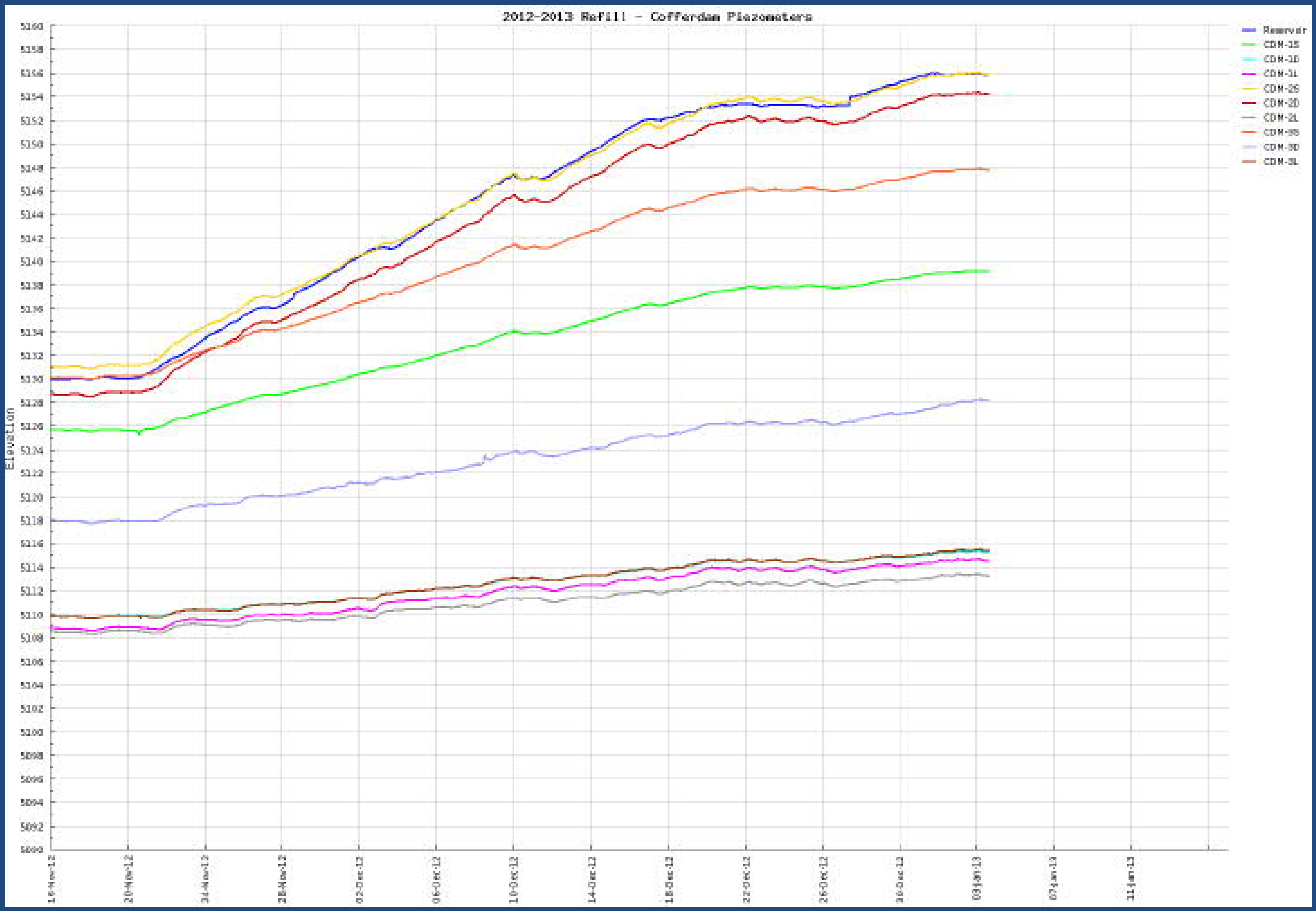
Automated Data Acquisition Systems (ADAS)

Photo c/o Kathryn White USACE SWT

Automated Data Acquisition Systems (ADAS)

Advantages	Disadvantages
• Frequent data collection • Collection and evaluation of data at remote location • “Real time” data evaluation at any time • Efficient data collection	• Maintenance cost • Interruptions due to weather or lost power • Challenges assessing potential false readings • Potential complacency

Automated Data Acquisition Systems (ADAS)



Data Evaluation

- Detecting changes and trends
  - Gradual changes
  - Abrupt changes
  - Trend analysis
- Compare to established “normal” readings and/or design or analysis expectations
- Data validation

Solving the Mystery: Data Gathering

- Original Design
  - Configuration (abutment shape, core width, filters)
  - Foundation treatment/excavation
  - Grouting (Deep enough? Vertical instead of inclined?)
- Construction records/photos
- Modifications
- Past performance records
- Geotechnical studies
- Data gaps? Is investigation warranted? If so - BE CAREFUL!!! DO NO HARM!

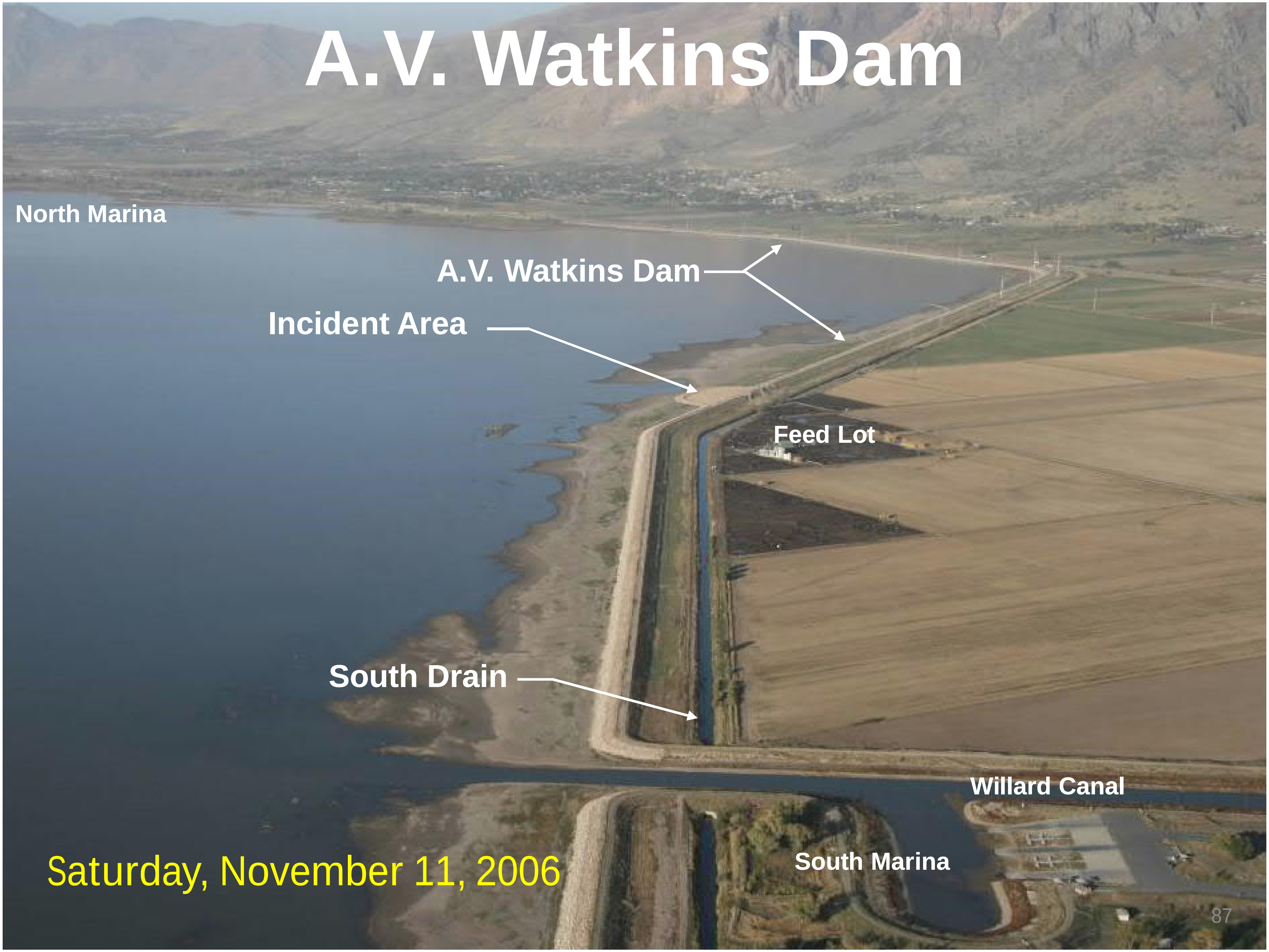
How Big of a Problem is it?

- Review failure modes and then ask questions:
  - What are the potential paths associated with the observed seepage?
    - Along contact? Conduit? Embankment defect?
  - Are there filters? Era of construction
  - Is foundation likely pressurized?
  - Are there likely erodible materials?
  - Does seepage respond to reservoir level? How quickly?
  - How easily monitored? How easy is response?

Case Histories

- Seepage / internal erosion incident with successful intervention:
  - AV Watkins Dam, UT
- Seepage / internal erosion incident with unsuccessful intervention:
  - Big Bay Lake Dam, MS

A.V. Watkins Dam



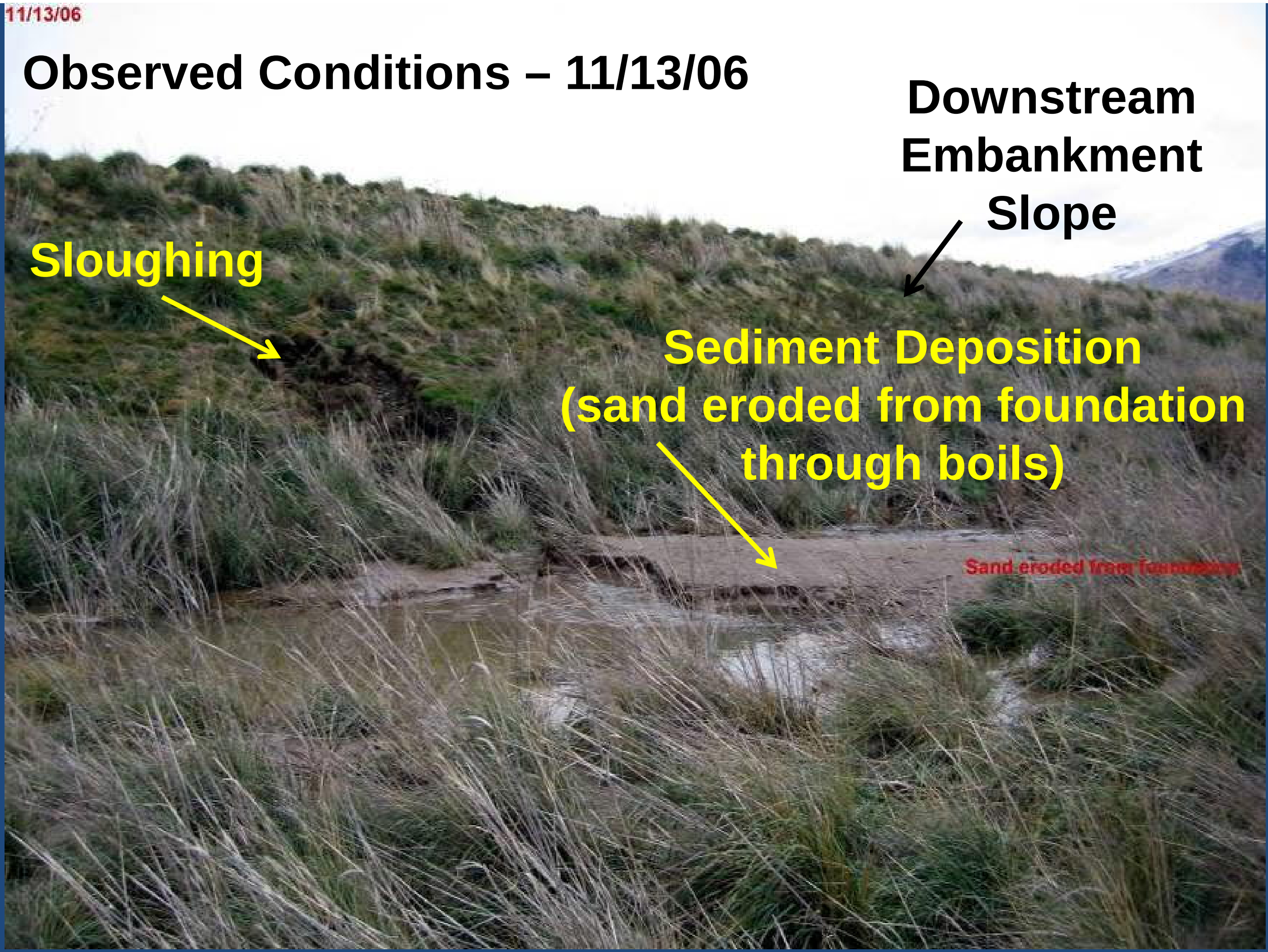
Saturday, November 11, 2006

Detection and Notification

- Monday, November 13, 2006
  – Feedlot operator saw seepage color change and notified district
  – District visited dam
  – About 1:00PM Reclamation staff left for the dam

Sediment Transport

- Significant sediment deposition in South Drain



- Concentrated seepage discharging 500 to 1000 gpm
- Upstream sinkholes
- Downstream sand boils, sinkholes and slope failure


Seven sand boils at the
downstream toe,


Sand accumulated near
sand boils


Numerous sinkholes between
the d/s toe and the south drain

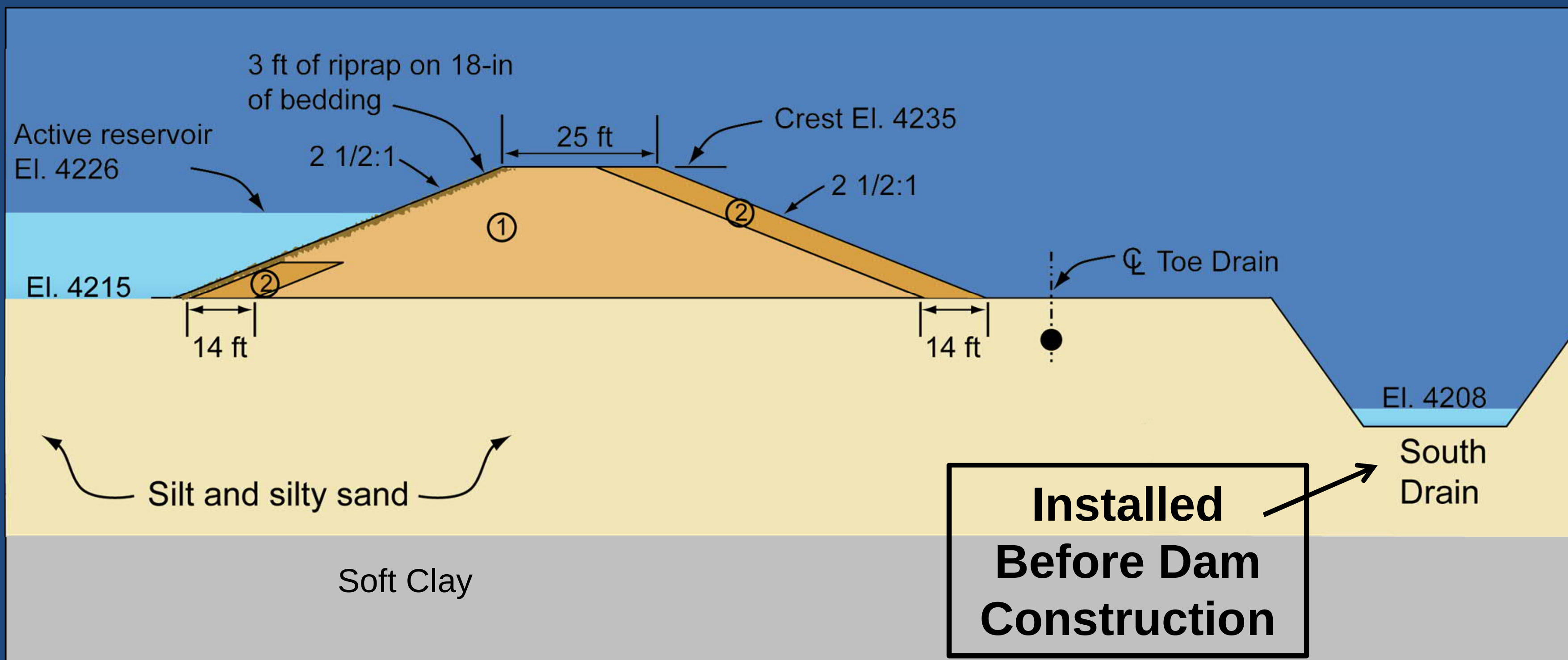
Slope Instability

Piping Channel under Hard Pan

A.V. Watkins Dam-
Emergency Response

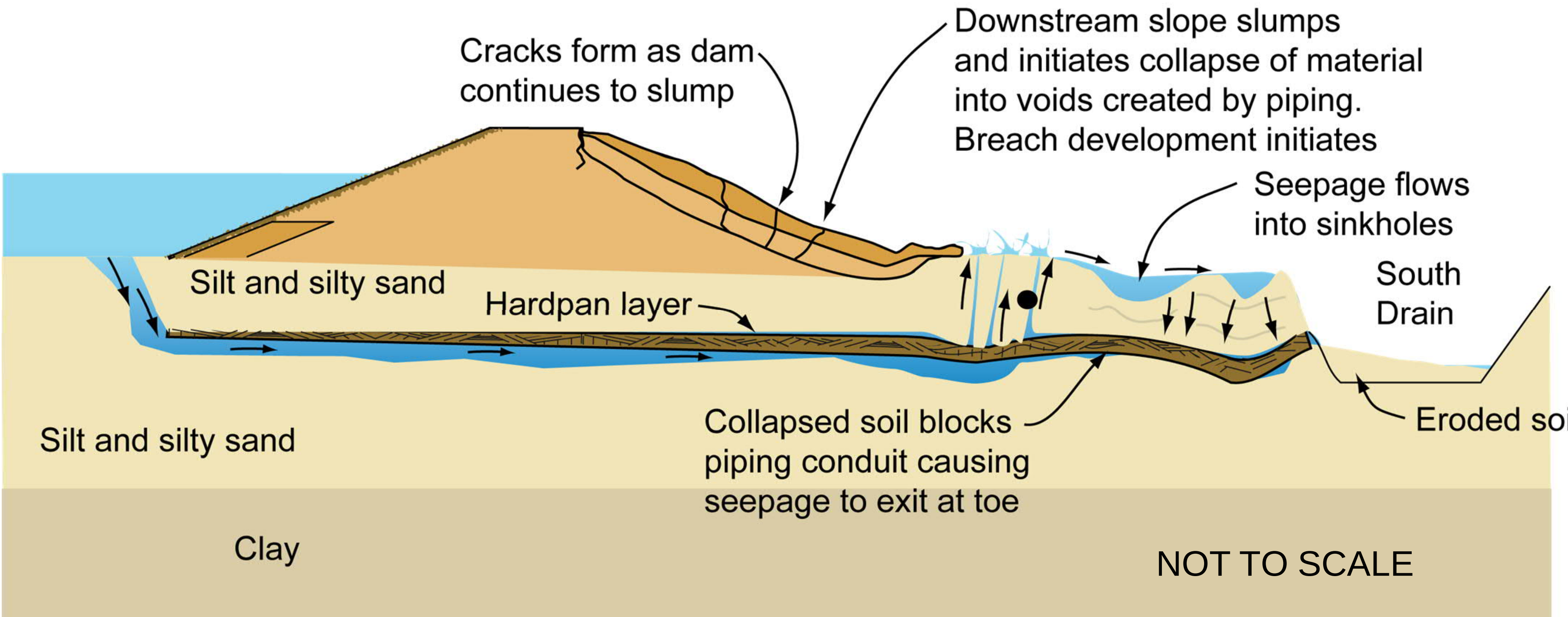
- Declared EAP Response Level 1
- Stationed equipment on west dam (LOW hazard section)
- Filter/drain materials and equipment
- Lighting

Typical Southeast Embankment Cross-Section



- Quick conditions noted during first filling in 1964 at reservoir El. 4221
  - Installed toe drain 15 ft from downstream toe, ~5 ft deep

A.V. Watkins Dam
Failure Mode Illustration



- IE Through Foundation (failure in progress)
  – Horizontal exit

Emergency Response

- Lowered reservoir
- Mobilized sand and gravel materials and equipment to site
- Attempt to place downstream filter blanket using sand fails → sand washes away
- Constructed thick 75 ft by 100 ft downstream filter and stability berm over seeps at embankment toe and up downstream face
  – Still 100 to 200 gpm cloudy seepage discharge

Response Time is Critical –
Work at Night at A.V. Watkins Dam


Filter placement
11/13/06

Downstream Filter and Stability Berm

Mobilize more material for upstream berm

Emergency Response

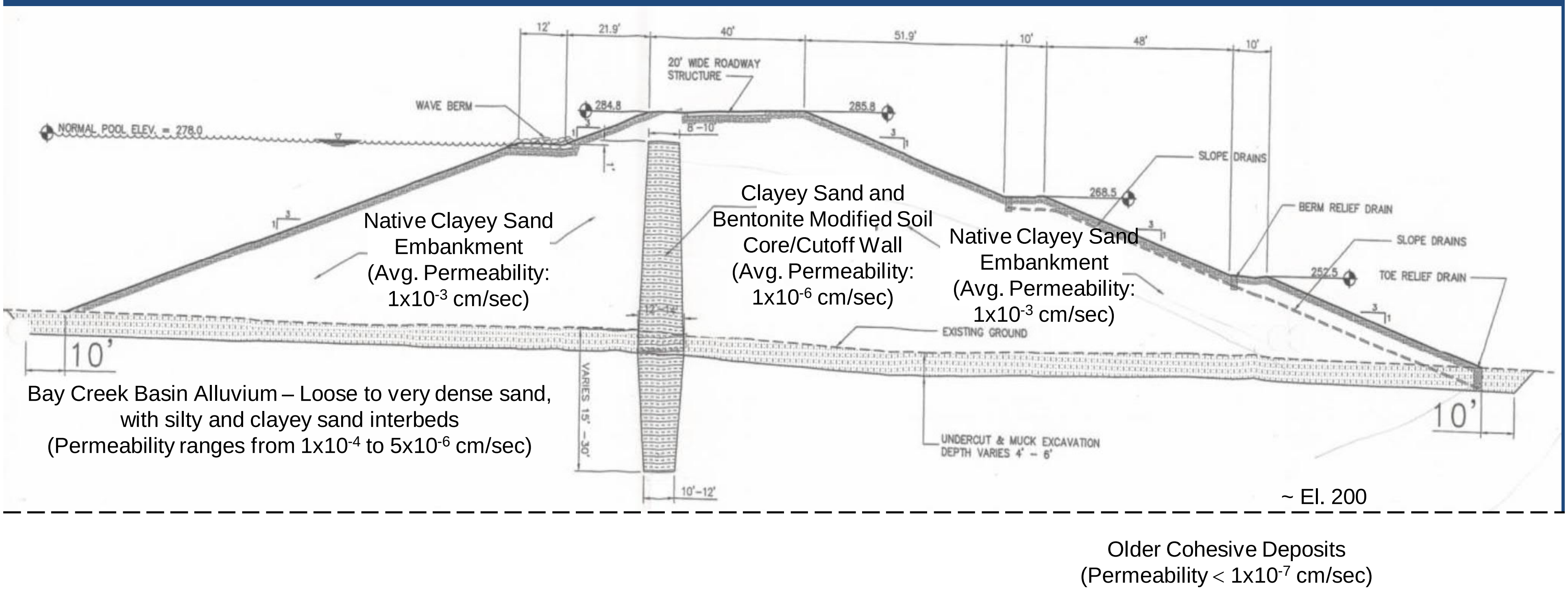
- Constructed large upstream berm ("choke filter") at sinkholes to cutoff seepage entrances
- Dam stabilized November 18, 2006 (5 days after incident)

Big Bay Lake Dam

- Seepage / internal erosion incident resulting in dam breach

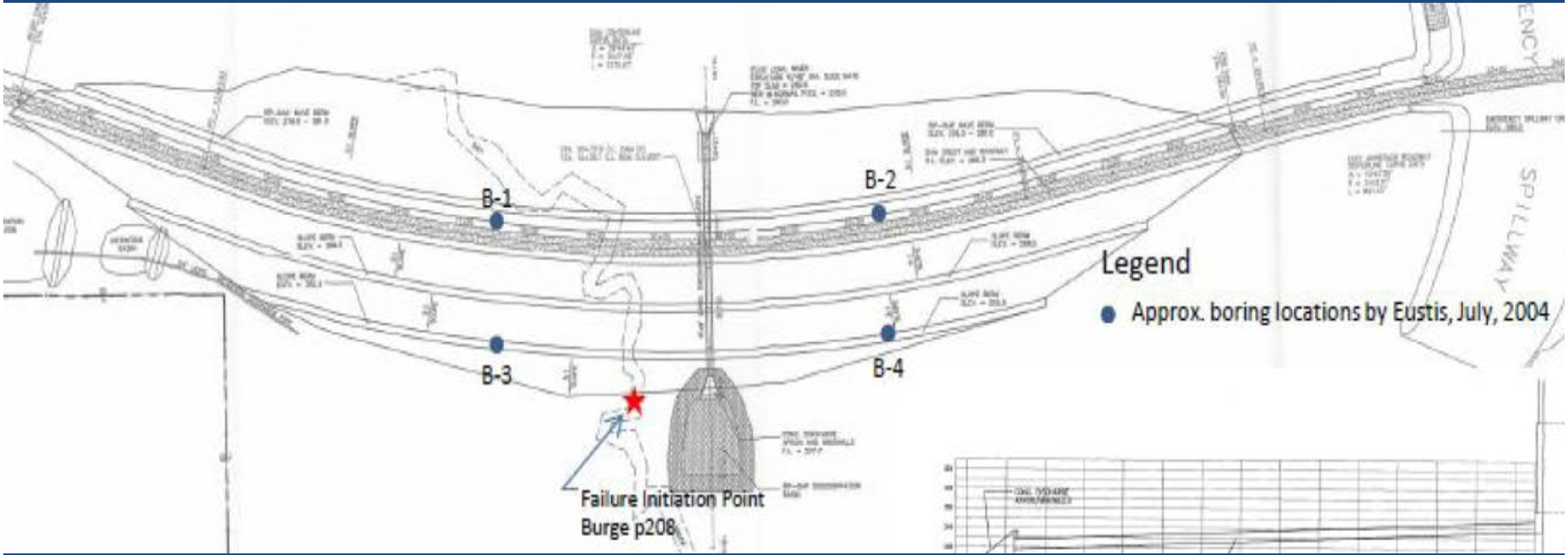
Embankment Cross-Section at Outlet Conduit

- Dam breach centered on outlet conduit



Embankment Plan

- Failure initiation point



Day Before Incident – March 11, 2004

- Local resident sees ‘mud’ flowing from drain pipe in outlet conduit wing wall

- Verified by maintenance person who calls engineer and departs

Day of Incident – March 12, 2004

- 9:30 am → Engineer observes ‘muddy’ pipe flow, ½-inch-diameter seep west of pipe outlet with estimated flow rate of ½ to 1 gpm, and ‘muddy discoloration’ in riprap basin
- 11:00 am → Engineer performs dam inspection and departs
- 11:45 am → Maintenance person observes increase in pipe flow, notifies engineer, and leaves for lunch

Day of Incident – March 12, 2004

- 12:15 pm → Maintenance person returns to site, observes muddy seepage spraying 30 to 40 ft into air from area 20 to 30 ft southwest of pipe outlet, and calls engineer
- 12:20 pm → Engineer returns to site and observes seep spouting 2 to 3 ft into air with flow diameter of 18 in.
- 12:25 pm → Erosion rapidly progresses upstream, resulting in breach

Sinkhole on Upstream Face

Dam Breach

Big Bay Lake Dam
Failure Mode

- Failure mode never conclusively established
- Potential causes of failure:
  - Defects in outlet conduit (IE Into Outlet Conduit)
  - Inadequate core/cutoff
  - Inadequate filter/drain system
  - Highly erodible embankment and foundation soils

Warning Signs

- Seepage on downstream face
- Significant seepage through cracks in conduit
- Seepage around conduit outlet
- Sediment in outlet basin
- Sinkhole on downstream face
- Changes in toe drain seepage flow rates

Sinkhole on downstream face

Lessons Learned

- Human factors (the need to understand and respond to important warning signs) play a key role in dam failure.
- Don’t leave the site unattended if situation has not stabilized – even at night.
- Proper surveillance, monitoring, and maintenance can provide early detection and intervention (emergency response).

Questions?