Seepage Detection and Monitoring

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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

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>Erosion</th>
<th>Embankment Sliding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode of Failure:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External Erosion</td>
<td>48%</td>
<td></td>
</tr>
<tr>
<td>(Overtopping)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal Erosion</td>
<td>46%</td>
<td></td>
</tr>
<tr>
<td>Static Instability</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Seismic Instability</td>
<td>2%</td>
<td></td>
</tr>
</tbody>
</table>

% Over the World:

- Erosion: Internal Erosion - 46%
- Embankment Sliding: Static Instability - 4%

% Over the World:

- Erosion: External Erosion (Overtopping) - 48%
## ICOLD Statistics

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

| 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

- No warning signs observed: 3%
- Increase in pore pressures: 3%
- Whirlpool in reservoir: Unknown
- Cracking: 7%
- Settlements: 17%
- Sinkholes: 43%
- Muddy leakage: 24%
- Increase in leakage: 24%

- Failures:
  - 51 failure cases
  - 43%

- Accidents:
  - 102 accident cases
  - 41%
  - 47%
Internal Erosion Mechanisms and Pathways

• Best Overview References
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

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

Adapted from slide by Robin Fell, UNSW
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
Internally Unstable Soils
Concentrated Leak Erosion:

IE Through Embankment

BEP:

Contributory flow path
Developing stage
Initial stage
Foundation

Dam
Phreatic surface
Unprotected exit

All zoning not shown
IE Through Foundation

BEP:

Volume increase

σ′ = 0

Heave

Blowout

Rupture

Uplift

Cohesionless foundation

Impervious

Water

Confining layer

Previous layer
IE Through Foundation

BEP (horizontal exit most dangerous):
IE of Embankment Into Foundation

Concentrated Leak Erosion:

BEP:
Water flowing through the hydraulic fracture can erode the sides, leading to internal erosion and the development of a void along the conduit.
IE Into or Out of Outlet Conduit

(a) SEEPAGE INTO CONDUIT
HOLE IN CONDUIT

(a) SEEPAGE ALONG OUTSIDE OF PIPE
HOLE IN PIPE
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

Visual Observations

- New/increasing seepage and sediment deposition
Visually Estimating Seepage Discharge Volumes

- Sink faucet ~ 2-5 gpm
- Garden hose ~ 10-20 gpm
- 4” Pipe ~ 100-200 gpm
- Fire hose/hydrant ~ 500-800 gpm
Visual Observations

- Cloudy discharge
- Pluming
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

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.

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

outlet

weir

47
Seepage Weirs and Flumes
Seepage Weirs and Flumes

- Sediment monitoring
Seepage Weirs and Flumes

Bucket and stopwatch

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

Change in flow rate around reservoir elevation 406 ft
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 appropriate 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

Correct

Incorrect

Gravelly Clay

Gravelly Sand

Sandy Clay

Sand

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

Reference: ASCE, Guidelines for Instrumentation and Measurement for Monitoring Dam Performance, 2000
Actual Data Plot: Time vs. Reading
Actual Data Plot: Time vs. Reading

- Reservoir Level
- Water Level
- Interval = 1222'
- Interval = 1206'
- Interval = 1186'
- Instruments
- Date

March 1987 to November 1992
Actual Data Plot: Reservoir Level vs. Reading

Before addition of relief wells

After addition of relief wells
Piezometer Responsiveness to Pool Changes c/o Kathryn White USACE-SWT

Piezometer Response

Very Responsive

Not Very Responsive

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)
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

Winter

36°
39°
39°

Summer

68°
46°
40°

Provides a distinct loading signature
Temperature

Winter

Pervious layer

36°

39°

Semi-pervious layer

38°

Rock

42°
Temperature

Summer

- Pervious layer
- Semi-pervious layer
- Rock

- Temperature readings:
  - Temperature at the top: 68°
  - Temperature at the middle: 46°
  - Temperature at the bottom: 60°

- Angles:
  - 60°
  - 48°
Temperature

Readings taken at one foot intervals

Pervious layer

Semi-pervious layer

Rock
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)

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Frequent data collection</td>
<td>• Maintenance cost</td>
</tr>
<tr>
<td>• Collection and evaluation of data at remote location</td>
<td>• Interruptions due to weather or lost power</td>
</tr>
<tr>
<td>• “Real time” data evaluation at any time</td>
<td>• Challenges assessing potential false readings</td>
</tr>
<tr>
<td>• Efficient data collection</td>
<td>• Potential complacency</td>
</tr>
</tbody>
</table>
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
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

Actively Piping Sand Boil
Observed Conditions – 11/13/06

- 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
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?