Monitoring Programs for Dams

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Agenda

- Why Monitor?
- What Should be Monitored?
- How Should it be Monitored and How Often Should it be Monitored?

Why Monitor?

1) Analytical Assessment (Current Condition)

- Is the dam performing well?
- Is the performance changing?
- Is the dam operating within design conditions/assumptions?
- What caused distress/failure?

2) Prediction of Future Performance

- How will the dam perform when certain conditions arise (based on historical data)?

What Should be Monitored?

- **The monitoring program should detect whether a failure condition is developing.**

- **To evaluate what is driving risk at a dam, a risk assessment should be performed.**

- **Risk assessment includes:**
  - **Review of existing project information**
  - **Brainstorming potential failure modes for the dam (Potential Failure Modes Analysis - PFMA)**
  - **Evaluating whether the failure modes can occur and how significant the associated risk is.**

- **One outcome of the risk assessment is to identify what can be monitored to detect whether the high risk failure modes are developing.**

What Should be Monitored?

- ‘Common’ Failure Modes from Past Failures:
  - Embankments

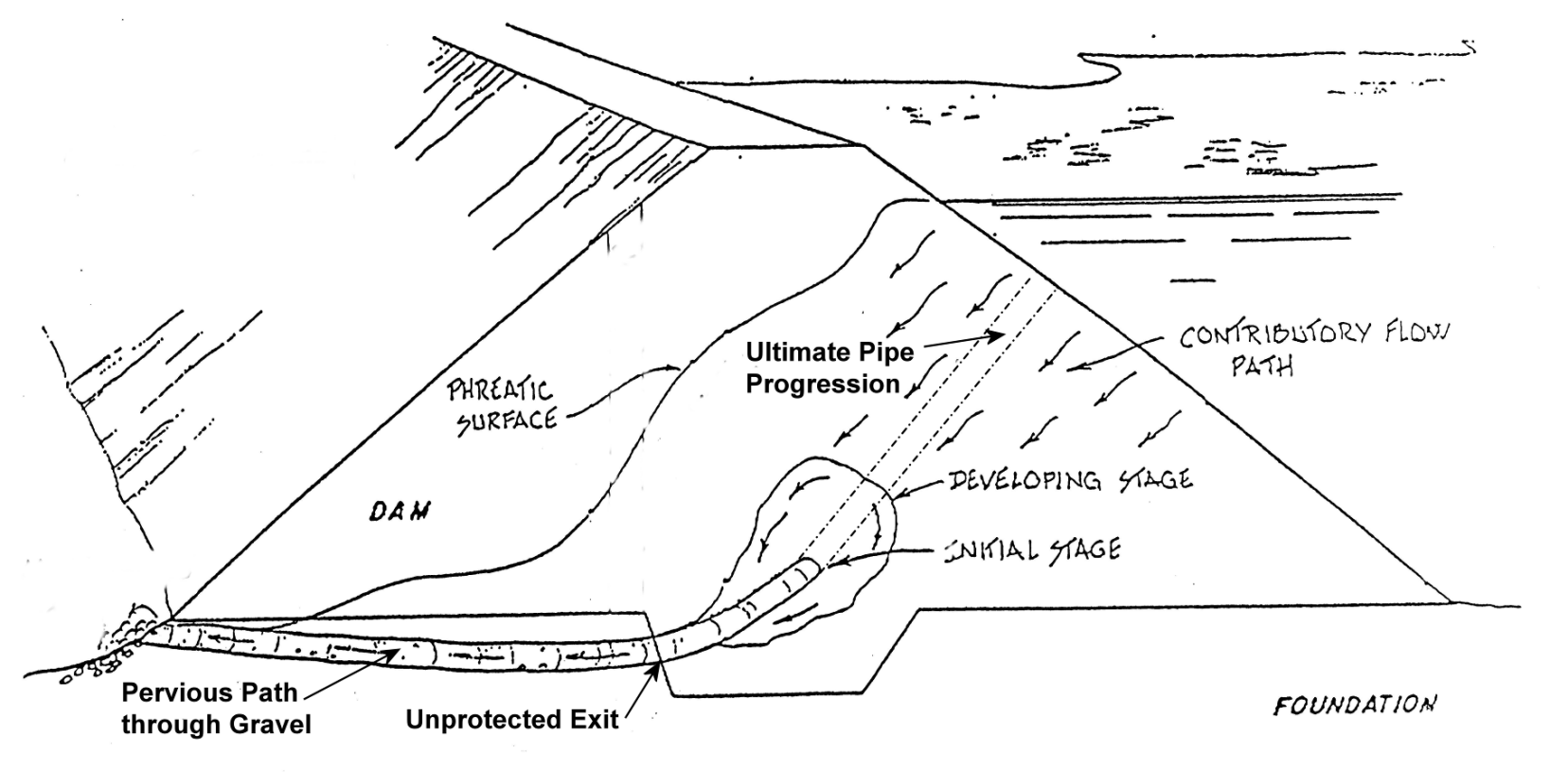
Mode of Failure[1]	% of Total Failures
Piping through Embankment	32
Piping through Foundation	15
Piping – Embankment into Foundation	2
Total Piping	49
Overtopping	34
Spillway	12
Slides	4
Earthquakes	1

- Piping (Internal Erosion) – Monitor Seepage, Piezometric Levels, Ground Movements/Distress
- Overtopping and Erosion – Monitor Reservoir Level and Inflow/Outflow

[1]Reference: Foster, M.A., Spannagle, M. and Fell, R., “Report on the Analysis of Embankment Dam Incidents,” UNICIV Report No. R-374, University of New South Wales, Sydney, Australia, 1998.

Teton Dam, ID – Piping of Embankment Into Foundation

Piping of Embankment Into Foundation



What Should be Monitored?

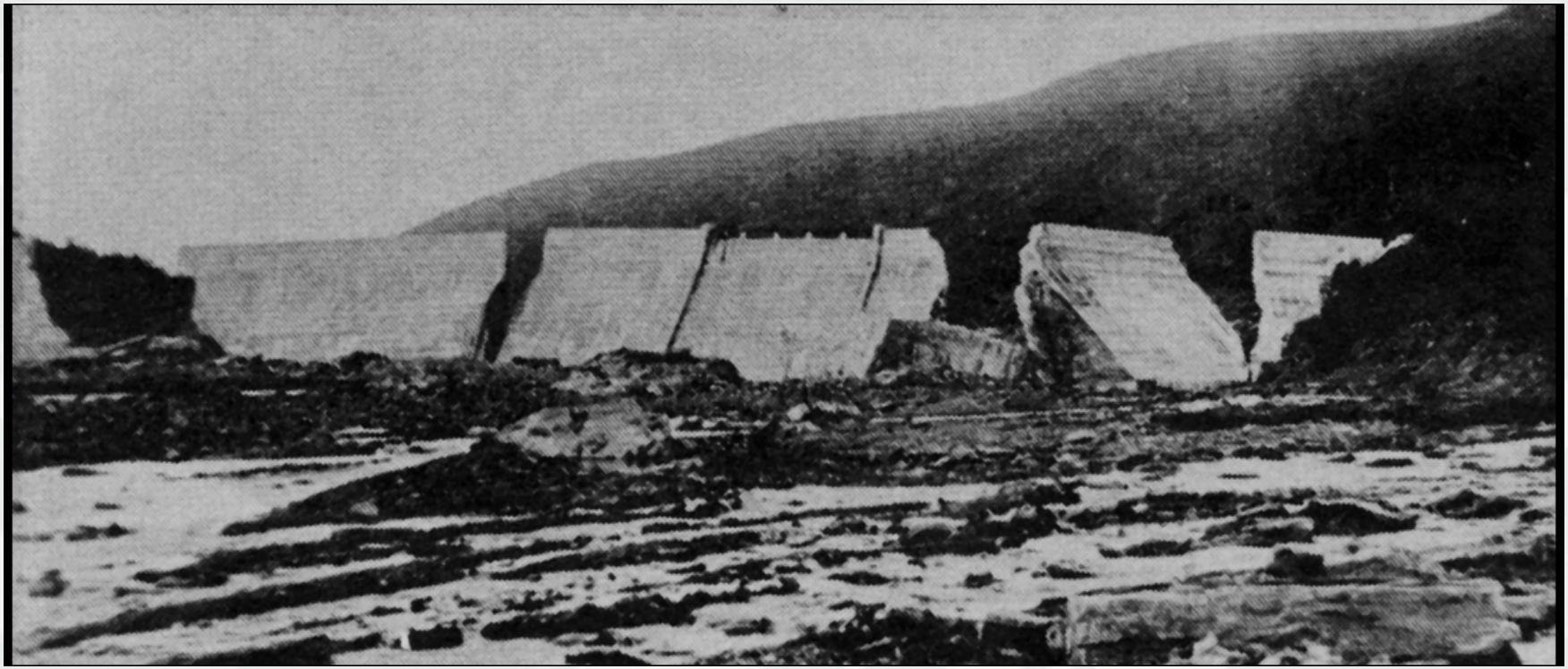
- **'Common' Failure Modes from Past Failures (cont'd):**
  - **Concrete Dams**

Type	Most Common Failure Modes
Gravity on Rock	Sliding on Weak Planes in Foundation
Gravity on Alluvial Soils	Piping (Internal Erosion) in the Foundation
Arch Dams	Sliding on Weak Planes in Foundation
Buttress Dams	Deformation of Supports; Sliding on Weak Planes in Foundation

- **Sliding – Monitor Movements, Uplift Pressure (destabilization)**
- **Foundation Piping – Monitor Seepage, Movements**

- **Reference: (pulled from Bureau of Reclamation and U.S. Army Corps of Engineers references)**

Austin (Bayless) Dam, PA – Sliding Failure of Concrete Dam



Sliding occurred on weak shale layers within the foundation.

How Should it be Monitored?

- **Embankment Monitoring Techniques:**
  - **Piping (Internal Erosion) – monitoring for seepage/ground movements**
    - **Visual Observation**
      - **Reguires training in what to look for**
      - **Seeps**
        - **Observation of known seeps should be treated as an instrument – define a frequency, store the observations for future reference**
        - **Estimate flow rate, clarity (turbidity)**
        - **Take and store photos taken consistently to record appearance at various times of the year**
        - **Record the times it doesn't seep!**
      - **Also look for signs of ground movement/distress regularly (cracks, bulges, offsets)**

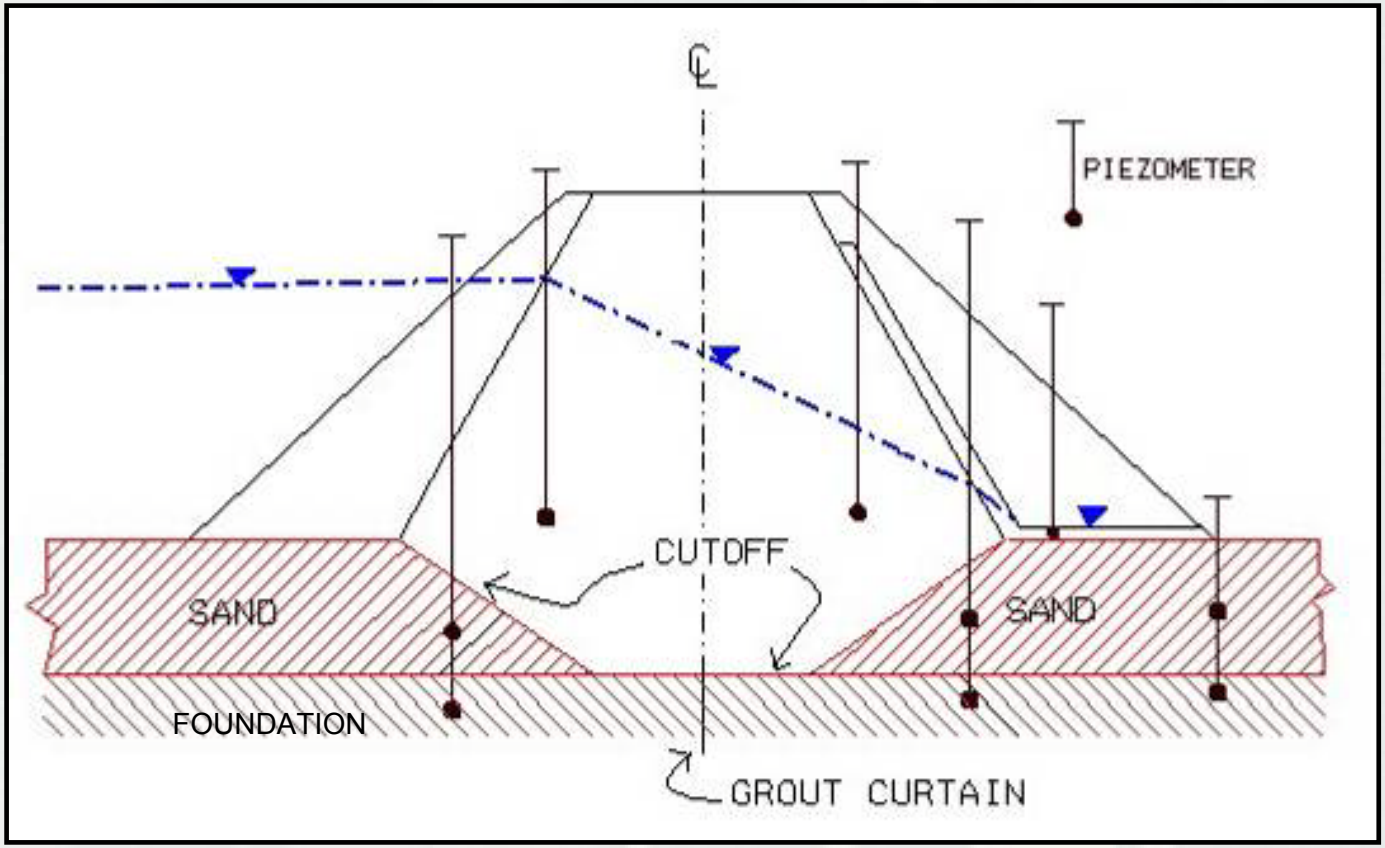
How Should it be Monitored?

- **Embankment Monitoring Techniques:**
  - **Piping (Internal Erosion) – cont'd**
    - **Seepage Collection Weirs/Flumes**
      - **Permits measurement of seepage flow rates**
      - **Toe drains or surface collection**
      - **Wide range of types - need to be designed for expected range of flows**
      - **Flows are often impacted by rain/surface runoff**
      - **Helpful to plot flows with rainfall and pool**
    - **Piezometers**
      - **Permits measurement of location of piezometric water surface in embankment**
      - **Often designed to measure piezometric surface in a zone/layer of interest**
      - **Evaluate whether project has sufficient coverage:**
        - **Plan view (spatially)**
        - **Section view (in all zones/layers)**

How Should it be Monitored?
Visual Observation - Evidence of Distress
Guardrail Movement

How Should it be Monitored?
Visual Observation - Evidence of Distress
New/Changing Seepage

How Should it be Monitored?
Piezometers – Coverage in Cross Section



How Should it be Monitored?

- **Embankment Monitoring Techniques (cont'd):**
  - **Overtopping and Erosion – monitoring reservoir level, inflow/outflow**
    - Visual Observation
    - Reservoir Water Levels (automated for remote sites)
    - Upstream River Gages
    - Rain Gages (manual/automated)

- **Concrete Dam Monitoring Techniques:**
  - **Sliding – monitoring movement, uplift pressure**
    - Visual Observation
    - Survey Monitoring – measure 3D movements
    - Relative Displacements – simple displacement measurements across adjacent monoliths
    - Plumb Bobs/Tiltmeters
    - Uplift Pressure – drainholes in foundation
  - **Piping (Internal Erosion) in Foundation – monitoring seepage, movement of material**
    - Visual Observation
    - Seepage Collection Weirs
    - Piezometers in Foundation

How Should it be Monitored?
Visual Observation - Evidence of Distress
Monolith Movement

How Should it be Monitored?

Data Collection Methods:

- **Visual Observation is a Critical Monitoring Technique**
  - Observers require training
  - Define a frequency of inspection (Monthly, Quarterly, ?)
  - Record observations (even if you don't find anything)
  - Develop a form/inspection checklist
  - Take frequent pictures and store
- **Manual Instrument Data Collection**
  - Trained instrument readers (they should know why they're reading it)
  - Define a frequency of reading
  - Plot the data/review the data
  - Make sure reading equipment/sensors are calibrated
  - Maintain reading equipment/sensors
- **Automated Instrument Data Collection**
  - Does not replace need to visually inspect the project
  - System should be periodically checked for calibration against manual readings
  - Permits high data collection frequency
  - Permits alarm notification
  - Requires maintenance (sensors/hardware/software)

How Often Should it be Monitored?

TYPE OF MEASUREMENT	FREQUENCY OF MEASUREMENTS				
	CONSTRUCTION	FIRST FILLING	FIRST YEAR AFTER FILLING	SECOND AND THIRD YEARS	LONG-TERM OPERATION
VISUAL OBSERVATION	Daily	Daily	Weekly	Monthly	Monthly
RESERVOIR LEVEL	-	Daily to Weekly	Semi-monthly	Monthly	Monthly to quarterly
TAILWATER LEVEL	-	Weekly	Semi-monthly	Monthly	Monthly to quarterly
DRAIN FLOW	-	Daily to Weekly	Weekly to monthly	Monthly	Monthly to quarterly
SEEPAGE/ LEAKAGE FLOW	Monthly	Daily to Weekly	Weekly to monthly	Monthly	Monthly to quarterly
PORE PRESSURE/ UPLIFT	Daily to Weekly	Daily to weekly	Monthly	Monthly	Monthly to quarterly
SURFACE SETTLEMENT	-	Monthly	Quarterly	Semi-annually to annually	Semi-annually to annually
SURFACE ALIGNMENT	-	Daily to monthly	Quarterly	Semi-annually to annually	Semi-annually to annually
INTERNAL MOVEMENT	-	Weekly to Monthly	Monthly to quarterly	Monthly to semi-annually	Monthly to annually
JOINT/CRACK DISPLACEMENT	-	Weekly to Monthly	Monthly to quarterly	Monthly to semi-annually	Monthly to annually
FOUNDATION MOVEMENT	Weekly	Weekly to Monthly	Quarterly	Semi-annually	Semi-annually to annually

Adapted from “Engineering Guidelines for the Evaluation of Hydropower Projects,” FERC, Office of Hydropower Licensing, 1987.

How Should it be Monitored?

Data Review Considerations

- Locate Monitoring/Instruments on a Site Plan
- Data Plots
  - Group the instruments to inform on progression of failure modes
  - Plot instrument data with pool/rainfall to understand behavior
  - Look at time history but also geographical plots (cross-sections, profiles)
  - Define scales carefully – understand the precision of the instrumentation (are the changes significant?)
- Define Thresholds
  - Theoretical based (tied to design/analysis) or historical ranges
  - Often have multiple levels (Low, High)
  - Exceedance of thresholds should trigger a response action

How Should it be Monitored?

Response Actions for Threshold Exceedance:

- **Notify the responsible engineer.**
- **Confirm the reading by retaking it, and where possible, confirm the instrument calibration by the use of redundant readings.**
- **Inspect the dam.**
- **Evaluate the situation and revise the threshold limit (if appropriate).**
- **Increase the frequency of readings to monitor and provide data to further evaluate the situation.**
- **Implement investigative measures such as the installation of additional instruments.**
- **Implement remedial measures such as cleaning foundation drains, repairing damage, or modifying the dam.**
- **Implement emergency measures such as drawing down the reservoir.**

Reference: "Engineering Guidelines for the Evaluation of Hydropower Projects," FERC, Office of Hydropower Licensing, 1987.

Summary

- Monitoring Programs should be able to monitor the develop of potential failure modes.
- A project specific risk assessment should be performed to identify what failure modes present the most risk and therefore what should be monitored.
- The most common failure modes for embankments are piping and overtopping.
- The most common failure mode for concrete dams founded on rock is sliding on weak zones in the foundation; for concrete dams on soil, piping in the foundation.
- Visual observation is the most critical and reliable method for monitoring dams, however instrumentation is also very important.
- Required frequency of monitoring is generally related to how long the project has been in service.
- Thresholds and corresponding response actions should be defined.