How Dams Fail and Proper Dam Maintenance
Meeting Logistics

• All lines are muted
• We will have several Q&A breaks
• Can ask a question at any time using the Question box.
• Meeting is being recorded and can be watched at a later time.
• Meeting slides and other resources are available for download in handout section.
  – Handout with links to other resources
  – When a permit is needed
  – How to apply for a permit
  – Dam Maintenance Manual
  – Copy of today’s PowerPoint slides
Webinar Series

• **May 6: Dams 101 and DNR Dam Safety Program**
  – Learn about how dams work, what are the critical parts and features, and how they are regulated in Iowa.

• **May 13: How Dams Fail and How to Properly Maintain Your Dam.**
  – Learn about common ways that dams fail and how proper maintenance can reduce the risk of failure.

• **May 20: Dam Ownership, When and How to Hire an Engineer**
  – When do you need to call in an expert? We’ll discuss when and how to find and hire qualified engineers to help with repairs and design of dams.

• **May 27: Dam Design and Permitting**
  – This webinar will go into technical engineering design requirements and what’s needed to obtain a permit. We will also discuss upcoming changes to Iowa’s dam safety administrative rules.
Introductions

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Presentation Outline

• Recap of Dams 101
• Primary causes of dam failures
• Examples of dam failures
• Inspection by owners
• Proper dam maintenance
• Required dam repairs
• Dam emergencies
How do dams work?

- Safely Hold Water
  - Clay soil embankments or concrete structures
  - Good foundation and abutment conditions or cutoffs
  - Internal drainage for embankment stability

- Safely Pass Extra Water
  - Spillways
  - Outlet works
Parts of an Embankment Dam

- Groin
- Internal Drains
- Crest
- Upstream Slope
- Outlet Works
- Internal Drain Outfalls
- Reservoir
- Principal Spillway (Inlet Riser)
- Auxiliary (Emergency) Spillway
PARTS OF AN EARTH DAM
(SEE GLOSSARY FOR TERM DEFINITIONS)

LAKE / IMPOUNDMENT

SHORELINE

EMERGENCY SPILLWAY

NATURAL GROUND

LEFT ABUTMENT AREA

WAVE PROTECTION RIPRAP

TOP OF DAM (H.K. & CREST)

EMBANKMENT (FILL)

GROIN AREA & RIPRAP

NORMAL POOL ELEVATION

FREEBOARD

SPILLWAY RISER & TRASHRACK

UPSTREAM SHELL

CORE

DOWNSTREAM SHELL

BLANKET DRAIN AND FILTER

TOE DRAIN AND FILTER

TOE

CUT-OFF (CORE) TRENCH

SPIFFWAY OUTLET STILLING BASIN

RIPRAP

FOUNDATION

IMPERVIOUS STRATUM
How do Dams Fail?

- Inadequate Spillway Capacity/Overtopping
- Spillway scour
- Internal erosion along conduits
- Piping from rodent burrows
- Structural Failure of Inlet or Outlet Works
- Erosion from Uprooting of Trees and Woody Vegetation
- Wave Erosion
- Liquefaction
Why are Dam Failures of Concern?

- Loss of Life
- Property Damage
- Environmental Impact
- Loss of Use
- Repair Costs
Potential Loss of Life
Property Damage
Loss of Reservoir Use
Anatomy of a Dam Failure:
The most common causes of dam failures

**Dam failures are most likely to happen for these reasons:**

**Inadequate maintenance** – Roots from trees can create seepage paths. Bushes harbor rodents, which can damage the dam.

**Seepage path** – Water passes through the dam and can cause damage.

**Overtopping** – Water spilling over the top of a dam can cause damage.

**Structural failure** – Caused by stress or instability from materials used in dam construction.

**Cracking** – Caused by movements such as the natural settling of a dam.

**Transverse cracking** – Caused by shrinkage of embankment materials from severe drying and/or settlement in the embankment or foundation.

**Piping** – When seepage through a dam worsens, forming sinkholes.

**Stability failure** – The foundation or other features that hold the dam in place may collapse.
Causes of Failure

• Dam Overtopping
  – Clogged spillway
  – Inadequate capacity for rainfall event
    • Low hazard dams typically designed for 50 year flood
  – Overtopping causes downstream embankment to erode leading to a potential breach of the dam.
Embankment Failure by Overtopping
Damage Caused by Embankment Overtopping
Overtopping Dam Failure Animation
Causes of Failure

• Seepage through the dam
  – Also called “Piping” or “Internal Erosion”
  – Water finds a weak point, begins to transport soil, flow increases
    • Poor compaction
    • Poor foundation conditions and cutoff
    • Improperly designed penetrations through the dam (conduits or utilities)
Seepage
Internal Erosion

Water from the reservoir penetrates the hydraulic fracture, initiating internal erosion of the side walls of the fracture.

The internal erosion process continues as water flowing in the hydraulic fracture widens the walls of the fracture. Intergranular seepage is not involved in the process, and the soils surrounding the fracture are unsaturated. Intergranular seepage rarely has time to develop, since this type of failure occurs most frequently on first filling of the reservoir.
A vortex may form at the location where water in the reservoir enters the upstream end of the hydraulic fracture.
Internal Erosion along a pipe

Water flowing through the hydraulic fracture can erode the sides, leading to internal erosion and the development of a void along the conduit.

The hydraulic fracture can propagate in a downstream direction and initiate flowing water from the reservoir.
Internal Erosion along a pipe

Water from the reservoir penetrates the hydraulic fracture, initiating internal erosion of the side walls.

Flowing water from the reservoir continues the internal erosion process within the hydraulic fracture. Intergranular seepage is not necessarily involved in this process, and the embankment materials surrounding the void may be unsaturated.
Internal Erosion
Piping Failure Animation
Causes of Failure

• Embankment slides
  – Soils loose strength as they become saturated
    • Saturation of slope due to excessive rainfall
    • Saturation of slope due to excessive seepage
  – Steepness of slope beyond stable design
  – Large trees blowing over opening voids
Embankment Slide
Embankment Slide
Embankment Slide
Causes of Failure

• Structural Failure
  – Spillway deterioration
    • Pipe rusting through
    • Concrete cracking and deterioration
    • Concrete spillway chute undermining
  – Concrete dam deterioration
Spillway Deterioration
Spillway Deterioration
Spillway Deterioration
Question Break
Case Studies

Lake Delhi: 2010
Lake Delhi
Lake Delhi

- Originally constructed in 1927 by Interstate Power Company for Hydroelectric purposes.
- At normal stage the dam held an estimated 3790 acre-feet of water. An estimated 9920 acre-feet of water was stored when the water began to overtop the dam.
- 58 feet high.
- 9 mile long impoundment
- Hydro production ceased in 1973 and dam was sold to Lake Delhi Recreation Association.
Lake Delhi Regulatory History

- Permitted by Iowa Natural Resources Council in 1973
- Required to submit inspection performed by professional engineer every 5 years.
- DNR inspected every 5 years.
2009 Lake Delhi DNR Inspection

- Erosion on upstream water line
  - Being repaired at time of inspection with new riprap
- Left gate could not be opened beyond 8 feet due to concrete deterioration
  - Repair plans were underway
- Trees and brush on downstream slope
  - Never addressed
Upstream Slope
Leak through concrete around gate
Concrete damage
General Timeline of Failure July 23-25, 2010

- Heavy Rains in the watershed causes increase in river flows.
- Thursday night: First flood gate needed to be opened partially.
- Throughout Friday: Gates were increasingly opened to maintain normal pool.
- Friday evening: Gates were raised as far as they could go.
- 08:00pm Mike Ryan receives new notice from the Weather Service 11-14 inches predicted over next 48 hours
- Saturday about 3:00 am: Whirlpool and roadway settlement discovered on south end of dam.
- 5:30 am: 6 foot x 2 foot sinkhole on upstream slope
- Saturday 6:00 am: Boil discovered on downstream side. Piping and internal erosion confirmed.
General Timeline of Failure July 23-25, 2010

• Saturday 8:00 am: Dam evacuated, no further work to open gate or mitigate internal erosion.
• Saturday 10:30 am: Dam begins to overtop.
• Saturday 1:00 pm: Dam fully breached.
Rainfall
Flood peak July 24, 2010, discharge 26,600 cubic feet per second

Flood peak May 23, 2004, discharge 26,000 cubic feet per second

Flood peak June 4, 2002, discharge 10,800 cubic feet per second

November 16, 2010, discharge 173 cubic feet per second

Lake Delhi
Manchester Flooding
Flooding at Lake Delhi
Dam Failure Investigation Setup

• Dam Safety Community reached out to Iowa

• Scope
  – Review the operational characteristics of the project leading up to the breach of the upper reservoir.
  – Perform an evaluation of the breach of the dam to determine the specific failure mode.
  – Submit a final report documenting the results of their findings on the cause of the breach of the upper reservoir and the important lessons learned.
Team

- William Fiedler,  
  - Bureau of Reclamation
- Wayne King,  
  - Federal Energy Regulatory Commission
- Neil Schwanz,  
  - U.S. Army Corps of Engineers
Investigation

- Independent Panel of Engineers
  - Inspected dam and conducted interviews.
  - Established timeline of events
  - Pieced together facts including hydrology, spillway capacity and failure mode.
  - Published report.
Core Wall

- Elevation was 6 feet below top of dam
- Relatively rigid element within the earthen embankment
Estimated 17 hours of time above core wall
Photo IV-12
Approximate whirlpool/vortex locations by Mr David Fink. Approximate developing sinkhole location from post breach inspection shown by red star.
Photo IV-8
Overtopping flow and discolored discharge from beneath geotextile (still photo captured from amateur video).
Photo IV-9
Discolored discharge emerging near toe (DesMoinesregister.com).
Investigation Conclusion

Cause of Dam Breach

From the eyewitness descriptions, photographic and video evidence and limited excavation investigation, the cause of the dam breach was internal erosion in the embankment coupled with overtopping flow. The internal erosion was most likely caused by a seepage path initiated along differential settlement of the embankment material adjacent to the core wall. The failure mode was triggered by reservoir levels that exceeded the top elevation of the concrete core wall which was exacerbated by the inability to open the third gate beyond the 4.25 ft measured in the post breach investigation.

Internal erosion likely caused by seepage path along core wall
Lessons Learned

• Association of State Dam Safety Officials formed a dam failure investigation committee.
  – Developed guidelines for dam failure investigations.
• Record water levels on any dam should put owner on alert.
  – Many dams have not been fully tested.
• Trees and brush on dams impede inspection and inhibit early detection.
• Be diligent about reviewing existing dams for lack of compliance with existing design best practices.
Case Studies

Oroville Dam: 2017
Oroville Dam

- 770 feet high zoned earth fill dam (tallest dam in US)
- Owned and Operated by California Department of Water Resources
- Serves mainly for water supply, hydroelectricity generation and flood control
- Drainage area: 3907 mi²
Oroville Timeline (2017)

• Tuesday, Feb 7, releases of 50,000 cfs, spillway slab starts to break up.
• Can’t stop release of water, but reduced flows through spillway to try to minimize spillway damages.
• Friday, Feb 10, begin prepping for use of auxiliary spillway
• Saturday, Feb 11, 8:00am water begins flowing over auxiliary spillway
• Sunday, Feb 12, evacuation order due to dangerous erosion progressing to base of auxiliary spillway.
• Increased flow over primary spillway to 100,000 cfs
• Sunday, Feb 12, 8:00pm flows ceased over auxiliary spillway.
The erosion that could lead to a collapse at Lake Oroville

Water pours over a concrete wall that forms an emergency spillway when the lake overflows.

The water erodes the earth, forming a hole.

If the hole grows and reaches the lake, the wall could collapse.

Source: DWR

Graphic: Los Angeles Times/TNS
Independent Investigation

- Association of State Dam Safety Officials and United States Society on Dams was requested to create joint volunteer task force (forensic team):
  - Selected dam engineering experts
  - Independent from dam owner and state and federal regulators
  - Determine cause of failure
  - Look at human factors as well
    - The “why did this happen” and “how was this missed” factors
September Interim Memo: Physical Factors Determined

- Failure initiated by uplift and removal of section of slab downstream of station 33+50.
  - Timeline of events from maintenance workers on site.
- Allowed underlying moderately to highly weathered rock beneath the slab to erode with high velocity flows.
- Uplift caused by flow into cracks exceeding capacity of underlying drains.
Contributing Factors

- Underdrains intruded into the chute slab, reduced thickness from 7” from design of 15” causing cracks.
- Absence of waterstops at construction joints
- Relaxed foundation treatment during construction
- Shallow rock anchorage of 5 foot embedment, in placed into weather rock
- Drainage system deficiencies (no filtering, broken pipes, inadequate capacity)
- Single top layer of nominal reinforcement bars
- Large concrete aggregate size, resulting in propensity for cracking and spalling.
Polyethylene Sheet

thinning of slab + no bottom reinforcement rebar

rebar

slab

cement

void (gravel)

6"

4" perf. V.C.P lateral with select gravel backfill

#5 2'-4' @ 18 Wrap this end only to prevent bond


40% thinning with 6" drain pipe intrusion

Bond Break

Joint Sealer

Oroville Slab design

2'-0"

1'-0"

1'-0"

1'-6"

2'-0"
cracks

plastic sheeting

Shifted Gravel "hump" from pour

Irregular gravel shape caused by concrete pressure

Perforated Drain Pipe
2017 First Construction Season Repairs
Oroville Dam 2018
Case Studies

Spencer Dam: 2019
Spencer Dam
Spencer Dam

- Located on Niabrara River near Spencer, NE
- Hydroelectric dam
Spencer Dam

- Built in 1927
- Consists of a powerhouse, 400 foot long concrete spillway and a long earth embankment.
- Failed on March 14, 2019.
- 1 fatality
Timeline of events

• Wet autumn and colder than normal winter produced frozen ground and substantial thickness of river ice and snowpack
• Winter storm (bomb cyclone) beginning on March 12 produced heavy rain on the frozen watershed.
• Major ice run began on the Niabrara River.
• Ice jam temporary clogged on upstream bridge, then let loose.
• Ice clogged the spillway gates and water overtopped and washed out the dam.
• One home and occupant washed away.
• Findings concluded that is dam had not been there flooding alone would have caused damaged the home as well.
Spencer Dam
Spencer Dam
Spencer Dam
Investigation

- Association of State Dam Safety Officials setup a team
- Published report in April of 2020
- Available at [https://www.damsafety.org/](https://www.damsafety.org/)

- Flooding and Ice overwhelmed capacity of the spillway system
- Downstream flooding would have been severe even without the dam failure.
Case Study

Bedford Reservoir: 2018
Bedford Dam

- Built in 1969
- Located in Bedford, IA
- Original use was water supply
- October 2018, spillway pipe failure
Bedford Dam
Bedford Dam
Bedford Dam
Bedford Dam
Bedford Dam
Case Study

Waterford: 2019
Waterford Dam

- Located in Johnston, IA
- Originally built in 1969
- Recreational lake
- Pipe Failure in May, 2019
Waterford Dam
Waterford Dam
Waterford Dam
Waterford Dam

- Spillway pipe reached it’s useful life of about 50 years
- Pipe collapsed leading to large sinkhole as embankment fell into pipe and was carried into the downstream channel.
- Failure was isolated and rest of embankment remained stable.
- Pipe replaced in December of 2019.
Questions on case studies?
The responsibility for proper operation, maintenance, and inspection of dams falls upon dam owners.
Liability

- **Common law holds that the storage of water is a hazardous activity.**
- Dams are owned and operated by individuals, private and public organizations, and the government. The responsibility for maintaining a safe dam rests with the owner.
- Safely maintaining a dam is a key element in preventing a failure and limiting the liability that an owner could face.

- "In today’s litigious society it is safe to assume that in the case of catastrophic dam failure, extensive litigation will ensue. Any competent lawyer, representing the victims, will sue all possible wrong doers in seeking redress...including...the owners and operators of the facility, and...architects, engineers, contractors, subcontractors, and consultants involved in the original construction and any subsequent modifications..."
  
  – Denis Binder, Professor of Law, Chapman University
O&M Pays Off

• Proper operation, maintenance, and inspection of a dam is like that of an older vehicle in need of extensive repair:
  – If left un-maintained, repair is expensive.
  – If maintenance and repair are performed as needed, costs are minimized.
Proper Dam Operations
Dam Operations

- Follow formal O&M manual, if available
- Recordkeeping
  - Design plans and calculations
  - Inspection reports
  - Documentation of repairs
  - Monitoring of seepage and structural cracks
- Periodic Inspection
- Emergency action plan (EAP)
  - EAP must be updated on an annual basis
  - Downstream development is typically a potential concern that can drastically affect EAP contents
- Operation of bottom drain, siphon systems, and gates/flashboards
  - Bottom drains, siphon systems, pool control gates, flashboards, and other outlet control works must be operated at least annually.
  - If systems are deteriorated and have not been operated in many years, they must be inspected by a qualified engineer.
Dam Operations (cont.)

- Monitoring fluctuation of pool elevation
- Removal of floating debris
- Monitoring instrumentation systems
- Monitoring alarm/warning systems
Inspections

• When:
  – Periodically, generally weekly if no issues
    • High hazard dams with permanent pools, daily visit, weekly full walk through.
  – After large rainfall events
  – Especially during “first filling” and high water levels
• Purpose:
  – Identify early warning signs of potential problems or failure
  – Identify O & M needs
  – Monitor instrumentation
Inspections: What to Look For

• Stability of Embankment & Structures
• Erosion - Embankment Upstream & Downstream Slopes, Abutment Juncture, Spillways & Outlets
• Seepage - Through Dam, Abutment, Foundation, Around Structures
• Vegetal Cover - Type & Condition
• Wildlife Damage
• Deterioration/Cracking of Concrete Surfaces & Structures
Additional Resource: Dam Inspections

https://www.youtube.com/watch?v=xCz58JFeqpg&t=1s
Dam Maintenance
MID-LIFE CRISIS OF A DAM

PLANT (TREE) AND ANIMAL PENETRATION PROBLEMS
Dam Maintenance Activities: Embankment

- Nurturing and mowing/burning grassed areas
- Removal of trees and brush
- Removal of floating debris from outlet works
- Repair of eroded/scoured areas
- Maintain upstream slope wave protection
- Control and repair of damage caused by wildlife
Why no trees and brush?

- Tall grass and brush make inspections more difficult
- Tall grass provides a haven for borrowing animals
- Trees can blow over in high winds and severely damage the embankment.
- Tree roots penetrate the embankment and alter its structural integrity.
- Tree roots can become pathways for seepage.
Nurturing and Mowing Grass Areas
Removal of Trees and Woody Vegetation
Repair Embankment Surface Erosion
Maintenance of Upstream Slope Wave Erosion Protection
Identify Wildlife Activity
Control and Repair of Damage Caused by Wildlife

Technical Manual for Dam Owners

Impacts of Animals on Earthen Dams

FEMA 473 / September 2005
Dam Maintenance Activities: Spillways

- Keep spillway free of debris to ensure full capacity
- Opening and closing of outlet & spillway gates to ensure operability
- Painting and repair of metal components
- Grouting and sealing concrete joints/cracks
- Removal and protection of spalling concrete
Debris at Inlet
Opening and Closing of Lake Drains to Ensure Operability
Grouting/Sealing of Concrete Joints/Cracks
Repair Spalling Concrete
Replace or line CMP spillways
Dam Maintenance Activities: Other

- Maintenance and stabilization of outlet channels
- Maintenance or repair and replacement of warning signs
- Maintenance of instrumentation/monitoring systems
- Maintenance of upstream slope wave erosion protection
Public Safety at Dams

- Public safety
  - Public access should be controlled
  - Includes proper warning signs, fencing, etc.

(Photo source: Mary Chind, The Des Moines Register)
Control access where possible
Public Safety: Signage for boats

**SCENARIOS POSSIBLE FOR RIVER USERS TO AVOID A DROWNING ZONE AND DAM**

1. **EARLY WARNING SIGN**
   - To alert river users to the upcoming dam and cue them to watch for instructions about exiting safely. Required only if landing or ingress is located 500 feet or less upstream of a dam, although it may be used optionally to be conservative.
   - PI Part Number: FDNR032EA
   - Water Trail Includes:
     - Portage Around Dam
     - Warning
     - Dam Ahead 1,500 Feet

2. **LAST LANDING ABOVE SIGN**
   - To alert river users at the last landing above the dam.
   - PI Part Number: FDNR105EA
   - Water Trail Launch Available Upstream of Dam to Exit River
   - Warning
   - Dam Ahead 1,500 Feet

3. **LAND-BASED LAST LANDING ABOVE SIGN**
   - To alert those staging watercraft or putting in at the launch.
   - PI Part Number: FDNR117EA
   - Water Trail Launch Available Upstream of Dam to Exit River
   - Warning
   - Dam Ahead 1,500 Feet

4. **MOVE LEFT OR RIGHT SIGN**
   - To cue river users to move left or right for last safe exit and/or portage (20/20 vision).
   - PI Part Number: FDNR117EA
   - Water Trail Launch Available Upstream of Dam to Exit River
   - Warning
   - Dam Ahead 1,500 Feet
   - Move Left For Portage

5. **LAST SAFE EXIT SIGN**
   - To mark the last safe exit and/or portage (20/20 vision).
   - PI Part Number: FDNR117EA
   - Water Trail Launch Available Upstream of Dam to Exit River
   - Warning
   - Dam Ahead 1,500 Feet
   - Move Left For Portage

6. **DROWNING ZONE, UP/DOWNSTREAM LIMITS SIGN**
   - To mark the area beyond which no one should enter because of dangerous currents. Exact placement based on field conditions (20/20 Vision).
   - PI Part Number: FDNR123EA
   - Danger
   - Dam Ahead
   - Exit Now!

7. **PEDESTRIAN DROWNING ZONE WARNING SIGN**
   - Placed at pedestrian approaches to drowning zone areas.
   - Exact placement based on field conditions.
   - PI Part Number: FDNR40218024EA
   - Pedestrian Danger
   - Pedestrian Dam Ahead
   - Pedestrian Exit Now!

8. **OTHER HAZARDS SIGN**
   - Placed on land or on water to alert river users to an upcoming non-dam hazards.
   - PI Part Number:
   - Warning
   - Rapid Ahead
Summary – Take Aways

• Dams of all sizes can and do fail.
• Proper Inspection and O&M can help prevent failure
• Resources are available
Additional Resources

• Association of State Dam Safety Officials
  – Membership open to all dam owners, consultants, and dam safety officials
  – Many available resources both for members and general public
    • http://damowner.org/
    • http://damfailures.org/
    • http://damsafety.org/

• Low Head Dam Safety
  – Concrete or rock dams across a river or stream channel.
  – DNR Water Trails staff works with low head dam owners to improve safety
    around dams.
  – https://www.iowadnr.gov/Things-to-Do/Canoeing-Kayaking/Low-Head-Dams

• Iowa Ponds Website
  – DNR fisheries biologist recommendations
  – https://www.iowadnr.gov/Fishing/About-Fishing-in-Iowa/Iowa-Ponds
Questions
Upcoming Webinars

• **May 20: Dam Ownership, When and How to Hire an Engineer**
  – When do you need to call in an expert? We’ll discuss when and how to find and hire qualified engineers to help with repairs and design of dams.

• **May 27: Dam Design and Permitting**
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https://www.iowadnr.gov/dams