Teton Dam Failure
A Review of the Technical Factors Contributing to the Failure
Outline of Presentation

- Location, Background and Project Statistics
- Technical Causes of Failure to be Discussed
- Geology
- Embankment Design and Materials
- Test Grout Program and the Abutment Cutoff Trench Design Decision
- Foundation Design and Construction
- Embankment Construction
- First filling
- Initial signs of seepage
Outline of Presentation

• Failure Mode
  – description of each step with photos, sketches,
  – detailed interpretation of what is going on inside using the new 3D model
  – forensic investigations / construction photos / analysis to describe the failure mode

• Review of Technical Causes of Failure

• Lessons Learned
Location Map

Teton Dam

Thursday, May 16, 13
Background

- Studies for a water storage site in the area date back to the 1930s
- Site clearing began in 1972; the embankment was completed by
- First filling was spring of 1976
- Dam failed catastrophically on June 5, 1976
Project Statistics

- Height 305 feet (above river bed)
- Structural height over 400 ft (above foundation rock)
- Crest length 3,100 feet
- Base width 1,700 feet
- Zoned earthfill with about 10 million cubic yards
- Gated chute spillway on right abutment with 3 gates
- Outlet works through tunnel in left abutment
- Reservoir volume at failure 250,000 ac-ft at El. 5301.7
- Reservoir length ~ 20 miles
Technical Causes of Failure Discussed in this Presentation

• Role of geologic formations – erodible soil and open jointed rock
• Steep core trench and stress arching
• Hydraulic fracture potential
• Rapid filling
• Design basis
  – Reliance on grouting and special compaction in key trench
  – Lack of foundation surface treatment in key trench
  – Lack of defensive seepage control measures

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Contributors to the failure – *not* discussed in this Presentation

- Lessons *not* learned from the near-failure of Reclamation’s Fontenelle Dam in 1965
- Lack of external design review (CRB)
- Organizational structure (design/construction) and conflicts between offices
- Lack of communication between Design and Construction parts of the organization
- Cost pressures (cost cutting culture; cost/benefit pressures)
- Lack of interaction between geologists and design engineers
- Role of “wet seam” in the failure (from forensics)
Aeolian sediments on plateau are about 30 ft. thick. Alluvium deposited in channel – about 100 ft. thick.
Site Geology

STA 30+00
Crest of Dam
STA 20+00
Spillway
STA 10+00
ORIGINAL GROUND
STA 2+00
GROUT CAP

EL 5300
GROUT CAP
EL 5200
WELDED ASH-FLOW TUFF (RHYOLITE)
EL 5100
RIVER OUTLET WORKS TUNNEL
EL 5000
ALLUVIAL MATERIAL
EL 4900
BASALT
EL 4800
LAKE AND STREAM DEPOSITS
EL 4700

WELDED ASH-FLOW TUFF (RHYOLITE)
AUXILIARY OUTLET WORKS TUNNEL

LAKE AND STREAM DEPOSITS

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Site Geology
Site Geology

- **Welded Ash-Flow Tuff (Rhyolite)**
- **Original Ground**
- **Teton River**
- **Grout Cap**
- **Alluvial Material**
- **Basalt**
- **Lake and Stream Deposits**

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Site Geology

- Terms “welded ash flow tuff” and “rhyolite” are used interchangeably in Teton reports
Site Geology

- Terms “welded ash flow tuff” and “rhyolite” are used interchangeably in Teton reports.
Current Site Geology

Huckleberry Ridge Tuff
“welded rhyolitic ash flow tuff”
erupted from the Henry’s Fork caldera of the Yellowstone plateau

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Current Site Geology
Geologic Investigations

- Foundation exploration drilling program (many phases and drill holes ~ 20,000 ft.)
- Geologic mapping
- Pumping tests
- Groundwater observations
- Pilot grout program and follow up pressure testing
Geologic Investigations

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- Pilot grout program and follow up pressure testing
Geologic Investigations

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Welded ash-flow tuff

• Unit 1 - uppermost – lenticular and tabular plates or slabs, mostly 2 to 6 inches
  – Openings between plates are \( \frac{1}{4} \) to 2 inches, some filled with caliche and silt
Welded ash-flow tuff

- Unit 2 – intermediate layer,
  - high angle joints at 10 to 20 ft. intervals dominate
  - Most joints open 1/8 to 1 inches and coated or filled with calcium carbonate
Welded ash-flow tuff

- Unit 3 – lower layer
  - Contact marked by breccia zone, 6 inches to 2 ft. thick
  - Near vertical joints prominent, can be traced over 100 ft.
  - Spacing 5 to 10 ft., with openings $\frac{1}{4}$ inch to 3 inches
Basalt

- Encountered beneath alluvium on the left side of the channel, but not the right.
- Exposed in foundation for power plant and other various outcrops
- Source of the basalt flow believed to be at the mouth of the Teton Canyon (d/s), and flowed up-canyon over a thin layer of alluvium covering the floor of the gorge to about elevation 5005 ft.
- River subsequently eroded the basalt from the right side, but it remained on the left side

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Project Design

- Project designed by the Division of Design in the Engineering and Research Center of the Bureau of Reclamation located in Denver
Embankment Design Considerations

• What materials are available at the site?

• What type of embankment dam would be best suited for the site? (e.g. homogeneous, zoned earth, central core rockfill, etc.)

• How should the design address the problematic foundation geology that had been identified in the extensive site explorations?
Embankment Design

- **What materials were available at the site?**
  - **ML** eolian silts covering the uplands (millions of cubic yards available nearby)
  - **GP and GW** river deposits in the bottom of the Teton River canyon (quantities almost unlimited at the damsite)
  - **Basalt** could be quarried from exposed remnants of the intraflow (large quantities, but requiring a 4-mile haul)
Embarkment Design

- What type of embankment would be best suited for the site?
  - Homogeneous ML embankment was considered; had the benefit of being an economical choice
  - A zoned earthfill embankment was selected due to concerns about cracking:
    - ML soils contained a high percentage of caliche
    - Earthquake crack protection – seismic zone 3
Embarkment Design

- How should the design address the problematic foundation geology?
1969 Pilot Grouting Program

- Program consisted of drilling and grouting 23 holes
- There were significant takes in several holes
- Grout takes in 2 holes exceeded the amount estimated for the entire project – over 15,000 sacks of cement and over 17,000 cu.ft. of sand.
- High takes at depths less than 70 feet
- Grouting the upper 30 feet of curtain holes was abandoned since the cutoff was expected to go at least that deep

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Critical Design Decision:

- From review of drill logs and pilot grouting program, designers concluded it would be more economical to remove the upper 70 feet of the foundation than to conduct the grouting necessary to seal this rock.

- A foundation key trench 70 ft. deep was provided above El 5100 in both abutments, to remove the more open jointed rock, and reach a groutable, more sound rock.
Critical Design Decision:

There was no precedent for this design at Reclamation.
Foundation Design

- By 1971 the foundation design philosophy was established
- The seepage barrier on the abutments was to consist of:
  1. a 70 ft. deep key trench through the highly jointed rock on the abutments, and
  2. a three-row grout curtain
Foundation Design

- To address cost concerns that the outer two rows of grout holes would accept extremely large quantities, and grout would travel large distances – the grout quantities in the outer two rows were limited.

- This resulted in a single row curtain installed through a central grout cap.

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Foundation Design

- Right key trench
Foundation Design

- In the main channel, 100 feet of alluvial materials were excavated to rock
- Cofferdams and extensive dewatering used to protect the foundation work area

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Embankment Design

• Zoned earthfill embankment with a thick central core
• Maximum height of 305 feet above the valley floor
• 405 feet above the lowest point excavated in the foundation
Embankment Design

- Key defensive design measures that were not included in the design:
  - No transition zone between Zone 1 and the alluvium in the valley bottom
  - No transition zone between Zone 1 and the fractured rock in the key trench, downstream of the grout cap
  - No provisions for surface treatment (dental concrete or slush grouting)
  - No drainage system was provided in either abutment
  - No downstream piezometers or similar instruments were installed
Foundation Construction

- Curtain grouting – two outer “barrier” rows and center grout cap row
  - Special emphasis placed during construction on grouting
  - 118,000 l.f. of grout holes
  - Over 600,000 cf of cement, sand

- The design required blanket grouting only “if required” to treat specific defects
  - Limited blanket grouting was done

- 1971 Design Considerations called for open joints and cracks to be treated by cleaning with air, sealing the surface, and low pressure grouting
  - Drawings and specs did not include this requirement
  - Little of this type of treatment was actually done
  - Instead – slurry concrete or slush grouting was performed
Why not shotcrete the cutoff trench?

- After a site visit – designers considered shotcreting the downstream face of the cutoff trench
- Construction office subsequently developed the “bucket (slush) grouting” procedure
- The construction office also agreed to put extra effort into “special compaction” in the cutoff trench
- No official documentation of these decisions
- Post-failure documentation in the IRG failure report
Slush Grouting

• Design specs did not include “slush grouting” or any other way to treat the Zone 1 / bedrock interface when open joints were exposed

• The construction office directed the placement of over 1800 cy. of slush grout

• Accomplished by simply pouring slurry into open joints by gravity flow

• Slush grouting discontinued above elevation 5205 because the joint size became too small to grout by Thursday, May 16, 13
What is “special compaction”?

• Compaction of materials using special techniques, typically in thinner lifts with smaller hand operated equipment.
Fall of 1972 – work began on the key trench mostly to the right of the spillway

Some grout cap excavation completed

Diversion tunnel construction

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Spring / summer – right abutment key trench excavation continued – starting to take shape

Continued excavation of 100 feet of alluvium in the main channel between the cofferdams

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Construction - 1973

Thursday, May 16, 13
In the channel, difficult rock conditions were encountered, including vertical faces and overhangs.

Drilling and blasting was required to shape the rock.
Construction - 1973

These photos show how the rock was shaped at 0.5:1 slopes with drilling and blasting.

Foundation rock was cleaned.

Also, the grout cap was installed – using steps in some places.

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Excavation through 100 feet of alluvium in the main channel also presented dewatering challenges to the construction.
Throughout 1974, it became more apparent in the photo record that open joints, fissures, void were prevalent.....
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<tr>
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<td>Downstream Curtain</td>
<td>30,537</td>
<td>1,420.64</td>
<td>21.50</td>
<td>214,660 cem.</td>
<td>8.20</td>
<td>4,833.98</td>
<td>51.80</td>
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<td></td>
<td>35,756 sand</td>
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<td>Upstream Curtain</td>
<td>18,289</td>
<td>601.19</td>
<td>30.42</td>
<td>38,838 cem.</td>
<td>2.22</td>
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<td>1,734 sand</td>
<td>30° Angle</td>
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<td>Centerline Curtain</td>
<td>46,434</td>
<td>1,993.87</td>
<td>23.29</td>
<td>51,862 cem.</td>
<td>1.14</td>
<td>1,960.14</td>
<td>27.01</td>
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<td></td>
<td>1,091 sand</td>
<td>30° Angle</td>
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<td>Blanket Holes</td>
<td>1,555</td>
<td>103.11</td>
<td>15.08</td>
<td>52,296 cem.</td>
<td>56.51</td>
<td>811.28</td>
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<td></td>
<td></td>
<td>8,207 sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auxiliary Outlet Works Shaft</td>
<td>6,596</td>
<td>239.36</td>
<td>27.56</td>
<td>10,196 cem.</td>
<td>1.55</td>
<td>756.72</td>
<td>13.47</td>
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<td>Auxiliary Outlet Works Intake Shaft</td>
<td>732</td>
<td>47.91</td>
<td>11.78</td>
<td>10,009 cem.</td>
<td>1.54</td>
<td>663.05</td>
<td>15.10</td>
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<tr>
<td>River Outlet Works Gate Chamber Shaft</td>
<td>2,598</td>
<td>102.38</td>
<td>25.38</td>
<td>13,223 cem.</td>
<td>5.09</td>
<td>585.60</td>
<td>22.58</td>
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<tr>
<td>Total</td>
<td>118,197</td>
<td>5,312.82</td>
<td>22.25</td>
<td>496,515 cem.</td>
<td>4.90</td>
<td>13,502.02</td>
<td>42.87</td>
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<td></td>
<td>82,364 sand</td>
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<td></td>
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</tr>
</tbody>
</table>

Note: 1 cubic foot of cement = 1 bag = 94 pounds = 42.63 kilograms
1 lineal foot = 0.305 meter
1 cubic feet of sand = 80 pounds = 36.29 kilograms

Figure No. 11 - Summary of Drilling and Grouting of Teton Dam
Construction ~ 1975

Thursday, May 16, 13
Reservoir Filling – Plan

• Flow through the river outlet works diversion tunnel (~2400 cfs capacity) would stop on October 1 of the last construction season

• Winter river flows would go through the auxiliary outlet works (~850 cfs capacity)

• “Unless adverse performance develops, unrestricted filling rates will be permitted to elevation 5200. Above elevation 5200 initial filling should not exceed 1 foot per day.”
Reservoir Filling

- October 3, 1975: River outlet works closed
- March 3, 1976: reservoir elevation 5170 (depth of 135 feet); average rate of rise had been approximately 0.2 ft./day
- March 3, 1976: Construction Engineer requested a relaxation of the 1 ft./day filling rate due to heavy snowpack and high expected inflows
- The Denver Office granted this request, allowing 2 ft./day
Reservoir Filling – Actual

- April through May 10, 1976: filling rate was no higher than 2 ft./day
- May 11 through June 5: the 2 ft./day requirement was exceeded - avg. daily rise of 3.0 feet, max. rise of 4.3 feet on May 18 (inflows ~4000 cfs)
- May 12 through June 5: the auxiliary outlet was discharging at a rate higher than its capacity of 850 cfs
Initial Seepage – June 3 and 4

• On June 3, project personnel inspecting the right abutment found two small seeps located 1,300 and 1,500 feet downstream from the toe of the dam.

• On June 4, a small seep was found at the right abutment about 150 to 200 feet downstream from the toe of the dam.
Initial Seepage – June 3 and 4

June 3 seeps

June 4 seep
Failure Mode Description

• Typical internal erosion event tree
  - Reservoir at or above threshold level
    - Initiation – Erosion starts
    - Continuation – Unfiltered or inadequately filtered exit exists
    - Progression – Continuous stable roof and/or sidewalls fails to limit flows
    - Progression – Constriction or upstream zone fails to limit flows
    - Progression – No self-healing by upstream zone
  - Intervention fails
  - Dam breaches

Thursday, May 16, 13
Evidence to support a focused analysis in the vicinity of Sta 14+00

• During construction:
  – Numerous open joints visible in the key trench
  – Large quantities of surface slush grout placed in open joints

• During failure:
  – Location of sinkhole that formed briefly in advance of the erosion was at about Sta 14+00
  – Upstream whirlpool was in the vicinity of Sta 14+00
Evidence to support a focused analysis in the vicinity of Sta 14+00

- Key trench walls completed washed away in this area
- Grout cap missing between Sta 13+96 and Sta 14+26
- Water testing of the grout curtain indicated shallow windows beneath the curtain
- Series of 3 open, transverse, vertical joints evident beneath the key trench
- Low stress zones in the Zone 1 embankment materials
- Stress analysis indicated that as early as May 25 (reservoir El. 5275), the hydrostatic pressure would have exceeded the total stress at the base of the key trench at Sta 14+00
Evidence to support a focused analysis in the vicinity of Sta 14+00

• Post-Failure Forensics:
  – Key trench walls completed washed away in this area
  – Grout cap missing between Sta 13+96 and Sta 14+26
  – Water testing of the grout curtain indicated shallow windows beneath the curtain
  – Series of 3 open, transverse, vertical joints evident beneath the key trench
  – Low stress zones in the Zone 1 embankment materials
  – Stress analysis indicated that as early as May 25 (reservoir El. 5275), the hydrostatic pressure would have exceeded the total stress at the base of the key trench at Sta 14+00
Failure Mode Description

- Reservoir in first filling – untested at all levels
  - Reservoir at or above threshold level
    - Initiation – Erosion starts
    - Continuation – Unfiltered or inadequately filtered exit exists
    - Progression – Continuous stable roof
    - Progression – Constriction or upstream zone fails to limit flows
    - Progression – No self-healing by upstream zone
  - Intervention fails

- Dam breaches
Reservoir at threshold level

- Approximate theoretical gradient at 14+00 – by date

<table>
<thead>
<tr>
<th>Date</th>
<th>Estimated Gradient (30 ft width)</th>
<th>Estimated Gradient (6 ft width)</th>
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<tr>
<td>Feb 1976 - first wetting</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>March 31</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>May 1</td>
<td>1.7</td>
<td>8</td>
</tr>
<tr>
<td>May 15</td>
<td>2.5</td>
<td>12</td>
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<tr>
<td>June 1</td>
<td>4.3</td>
<td>22</td>
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Thursday, May 16, 13
Reservoir at threshold level

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<td>4.3</td>
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Failure Mode Description

- Initiation
  - Reservoir at or above threshold level
    - Initiation – Erosion starts in right abutment key trench
    - Continuation – Open / unfiltered exit exists
    - Progression – Continuous stable roof
      - Progression – Constriction or upstream zone fails to limit flows
        - Progression – No self-healing by upstream zone
      - Intervention fails

- Dam breaches
Initiation Starts in the Right Abutment Key Trench

- Garner and Fannin Venn Diagram illustrates that internal erosion initiates due to an unfavorable combination of:
  - Material properties (easily erodible)
  - Hydraulic conditions (leading to scour at the fnd contact)
  - Stress conditions (leading to hydraulic fracture and scour above the contact)
Initiation Starts in the Right Abutment Key Trench

- Material properties
  - Loess soils – uniformly graded and erodible
  - Low Plasticity Index (single digits)
  - Achieving high density everywhere using special compaction methods is unlikely
Initiation Starts in the Right Abutment Key Trench

• Hydraulic conditions
  – Locally high gradients existed (early May - estimated 1.5 to over 4)
  – Full reservoir head in open joint system
  – Flow velocity through joints not sealed with slush grout and open windows in grout curtain – allows scour at the Zone 1 / rock contact

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Initiation Starts in the Right Abutment Key Trench

- Significant water passing through rock just beneath the grout cap, and possibly through the grout curtain at greater depth
- Concentration of through-going joints beneath and alongside the key trench
- Erodible fill within the key trench and in contact with the jointed rock downstream from the key trench
Initiation Starts in the Right Abutment Key Trench

- Larger cavities likely connected due to the high gradients to form a single erosion tunnel

Thursday, May 16, 13
Initiation Starts in the Right Abutment Key Trench

- Forensic evidence: Grout cap missing 13+96 to 14+26
Initiation Starts in the Right Abutment Key Trench

- Forensic evidence: Grout cap missing 13+96 to 14+26

Thursday, May 16, 13
Initiation Starts in the Right Abutment Key Trench

- Three prominent nearly vertical continuous joints crossing between Sta 13+96 and 14+26 (grout cap missing)
Initiation Starts in the Right Abutment Key Trench

- Three prominent nearly vertical continuous joints crossing between Sta 13+96 and 14+26 (grout cap missing)
Initiation Starts in the Right Abutment Key Trench

- 2-inch open fracture crossing the grout cap near Sta 13+90
- Erosion may have initiated at this set of open joints, or at other similar ones no longer there
Initiation Starts in the Right Abutment Key Trench

• Stress conditions
  – Geometry of key trench favorable to arching – multiple directions

• Static stress analysis performed by J.M. Duncan included in IP report as supporting evidence that low stresses existed and hydraulic fracturing may have occurred
Initiation Starts in the Right Abutment Key Trench

- First, second and third order arching
- Stress analyses modeled first order only with 2-D models
Initiation Starts in the Right Abutment Key Trench

- As early as May 20, the stress conditions could have allowed water to move both longitudinally and transversely in the vicinity of Sta 15+00.
Initiation Starts in the Right Abutment Key Trench

- By June 5, the low stress area is over 200 ft in length (along profile)
- Low stress zone is above the bottom of open jointed rock
Initiation Starts in the Right Abutment Key Trench

• Role of grout curtain, grout cap, and open joints in the narrow key trench
  – Direct scour of Zone 1 by flow through open joints

• Role of arching and low stress zones
  – All three orders of arching were evident at Sta 14+00 (cross sections, profiles, photographs)
  – High degree of arching, combined with presence in this area of open transverse joints capable of delivering and carrying away large quantities of water, make cracking a highly probable potential cause of breaching the key trench fill
Initiation Starts in the Right Abutment Key Trench

• Physical conditions conducive to both possibilities

• There is strong evidence for both initiators:
  – Scour along the base of the key trench
  – Arching leading to low stress zones

• If the grout curtain was determined to be not effective, failure was most likely due to scour from underseepage

• If the grout curtain was determined to be fully effective, failure was most likely a result of hydraulic fracturing
Failure Mode Description

• Continuation – open / unfiltered exit

- Reservoir at or above threshold level
- Initiation – Erosion starts in right abutment key trench
- Continuation – Open / unfiltered exit exists
- Progression – Continuous stable roof
- Progression – Constriction or upstream zone fails to limit flows
- Progression – No self-healing by upstream zone
- Intervention fails
- Dam breaches
Continuation – no filtered exit

• With no filter on the downstream slope of the key trench, Zone 1 materials were easily moved into the foundation rock joints

• The joint system downstream of the key trench likely served as the repository for eroded materials as flows found their way through the right abutment (continued for days or weeks)

• One breach, or multiple breaches across the key trench, occurred in the vicinity of Sta 14+00

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Evidence of a Joint System Repository

- Slush grout surface treatment
- El 5200 contour
- Sta 14+00

LEGEND
- 0 - 5 cubic yards
- 6 - 10 cubic yards
- 11 - 20 cubic yards
- 21 - 30 cubic yards
- 31 - 40 cubic yards
- 41 - 50 cubic yards
- Greater than 50 cubic yards

Thursday, May 16, 13
Continuation – no filtered exit

- In the upstream right abutment, the reservoir continued to rise and find more available pathways.
- Eventually, as inflows continued to increase, and the downstream joint system was being infilled with Zone 1, the capacity of the downstream open joint system was exceeded by the flows.
- With flow quantities increasing, and the flow capacity of the downstream rock mass being limited (joint size and infilling), the water needed another way out.
- This was the beginning of a turning point in the failure mode.
Erosion Pathways along Joints

- Upstream Right
- Key Trench CL
- Dam Axis
- Downstream Right

Thursday, May 16, 13
Erosion Pathways along Joints

- Upstream Right
- Key Trench CL
- Dam Axis
- Downstream Right

Thursday, May 16, 13
Erosion Pathways along Joints

- Upstream Right
- Key Trench CL
- Dam Axis
- Downstream Right

Thursday, May 16, 13
Erosion Pathways along Joints

Thursday, May 16, 13
Continuation – no filtered exit
• The large repository volume (open joints) in the vicinity of Sta 15+00 to 17+00 could have provided sufficient void space for seepage and eroded materials to go unnoticed for days
• Eyewitness accounts suggest that sometime overnight on June 4, seepage began to daylight, and damp areas were observed at the right groin
• On June 5 the flows increased and exited through talus, first at the groins at El 5045 and 5200.

• How much damage has been done before June 5?
Before June 5, how much damage do you think was done?
Muddy flow from talus / slopewash

- 8:30 am June 5
- Elevation 5045 (toe)
- 20-30 cfs
Muddy flow from talus / slopewash

- 8:30 am June 5
- Elevation 5045 (toe)
- 20-30 cfs
Surface flows increasing

- ~10:15-10:30 am
- 15 cfs flow developed into a backwards progressing tunnel

Thursday, May 16, 13
Surface flows increasing

- ~10:15-10:30 am
- 15 cfs flow developed into a backwards progressing tunnel

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Erosion Pathways along Joints
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Thursday, May 16, 13
Erosion Pathways along Joints

Approx. d/s limit Zone 1
Failure Mode Description

- Progression – roof forms in the key trench
  - Reservoir at or above threshold level
    - Initiation – Erosion starts in right abutment key trench
    - Continuation – Open / unfiltered exit exists
  - Progression – Continuous stable roof
    - Progression – Constriction or upstream zone fails to limit flows
    - Progression – No self-healing by upstream zone
  - Intervention fails
- Dam breaches

Thursday, May 16, 13
Progression – continuous stable roof forms in the key trench

• At first, the roof is across the steep, narrow key trench – arching allows this to occur – possibly days before – and completely through the failure mode progression

• Rock joints also serve as roof
Failure Mode Description

- Progression – flows not limited
  - Reservoir at or above threshold level
  - Initiation – Erosion starts in right abutment key trench
  - Continuation – Open / unfiltered exit exists
  - Progression – Continuous stable roof
  - Progression – Constriction or upstream zone fails to limit flows
  - Progression – No self-healing by upstream zone
  - Intervention fails

- Dam breaches
Progression – flows not limited

• Full reservoir head is provided to the key trench through the extensive system of open joints upstream of the core

• Flow through the embankment is not necessary – therefore the embankment does nothing to limit flows
Failure Mode Description

• Progression – no self healing by upstream zone

- Reservoir at or above threshold level
- Initiation – Erosion starts in right abutment key trench
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- Intervention fails

Dam breaches

Thursday, May 16, 13
Progression – no self healing by upstream zone

• Since most of the flow is from the upstream open jointed rock, there is no opportunity to self heal the damage that is being done in the steep narrow key trench
Progression of erosion

- ~10:30-10:45 am
- Dozers sent to fill eroding hole
Progression of erosion

- ~10:45-11:00 am
- Dozers working downstream – pushing riprap into hole (approx. Sta 15+25)
- Evidence (diesel exhaust) of upstream dozers pushing riprap into developing whirlpool (approx. Sta 14+00)
Progression of erosion

- ~10:45-11:00 am
- Dozers working downstream – pushing riprap into hole (approx. Sta 15+25)
- Evidence (diesel exhaust) of upstream dozers pushing riprap into developing whirlpool (approx. Sta 14+00)

Thursday, May 16, 13
Progression of erosion

Flow from reservoir

Flow eroding downstream

Flow from open joints

Thursday, May 16, 13
Progression of erosion

- ~11:00 am
- Dozers working downstream – one dozer got stuck in the loose dirt and riprap
- Second dozer tried to pull it out

Thursday, May 16, 13
Progression of erosion

- ~11:00 am
- Dozers working downstream – one dozer got stuck in the loose dirt and riprap
- Second dozer tried to pull it out

Thursday, May 16, 13
Progression of erosion

11:20 – 11:35 am

Thursday, May 16, 13
Progression of erosion

- 11:20 – 11:35 am

Thursday, May 16, 13
Progression of erosion

- ~11:30 am

Thursday, May 16, 13
Progression of erosion

- ~11:35 am
- Second hole appears briefly approx. Sta 14+00

Thursday, May 16, 13
Progression of erosion

Thursday, May 16, 13

- ~11:45 am
- Second hole approx. Sta 14+00
- Note dozers leaving upstream side
Failure Mode Description

- Intervention fails
  - Reservoir at or above threshold level
    - Initiation – Erosion starts in right abutment key trench
    - Continuation – Open / unfiltered exit exists
    - Progression – Continuous stable roof
      - Progression – Constriction or upstream zone fails to limit flows
        - Progression – No self-healing by upstream zone
      - Intervention fails
  - Dam breaches

Thursday, May 16, 13
Intervention fails

• River outlet works inoperable due to ongoing coating work – work crews were preparing to move out of the area to use the outlet works
• Auxiliary outlet works (right side) releasing 900 cfs
• Dozers sent around 10:45 to fill downstream hole
• When upstream whirlpool formed, dozers began pushing materials into it (but this was not a prime source of water)
• By the time the seepage was visible, so much damage was done internally there was essentially no way to stop the failure
Failure Mode Description

• Dam breaches

▷ Reservoir at or above threshold level

▷ Initiation – Erosion starts in right abutment key trench

▷ Continuation – Open / unfiltered exit exists

▷ Progression – Continuous stable roof

▷ Progression – Constriction or upstream zone fails to limit flows

▷ Progression – No self-healing by upstream zone

▷ Intervention fails

Thursday, May 16, 13
Breach

- Crest collapse and dam breach
- 11:57 am
Primary Technical Causes of Failure

Thursday, May 16, 13
In discussing the global cause of the failure:

“The failure of Teton Dam resulted from overconfidence in the seepage barrier and from the consequent failure to provide those additional defenses needed to cope with its inevitable imperfections.”

Ralph B. Peck, 1978
Independent Panel Report

• The failure was caused not because some unforeseeable fatal combination existed, but because (1) the many combinations of unfavorable circumstances inherent in the situation were not visualized, and (2) because adequate defenses against these circumstances were not included in the design.
Primary Technical Causes of Failure

- Design Decision: Seepage barrier was to consist of a 70 ft. deep key trench and grout curtain
  - Objective was to remove problematic rock to facilitate grouting
  - Outer 2 rows of the grout curtain were not intended to achieve closure – simply to provide a “barrier” for the center row
  - Allowed full head on the upstream side of the steep, narrow key trench; very high gradients across a short distance
  - Erodible fill placed in the narrow key trench
  - Geometry of key trench allowed arching and low stress zones
  - Rock below the key trench was jointed and permeable
Primary Technical Causes of Failure

• The objective of the design focused on providing a seepage barrier – preventing seepage

• State-of-the-art (late 1960s, early 1970s) design philosophy should have been to assume that a defect (crack or concentrated leak) is going to occur, and subsequently design to control seepage associated with that defect.

• No filter was placed on the downstream side of the narrow key trench
Primary Technical Causes of Failure

- Reclamation designers felt that surface grouting was a field problem to be negotiated with the contractor
- Field procedures used for surface grouting by pouring grout into open fractures
  - This practice didn’t work for fractures less than 0.5 inches wide (also, some were infilled with silt)
  - The practice was discontinued at elevation 5205, with no input from designers
- “Special compaction” of Zone 1 over/around open joints to protect against erosion into the joints
Primary Technical Causes of Failure

- Forensic Investigation Findings: Key Trench Geology
  - Foundation rock below the base of key trench exposed after the dam breach had open joints, some partly filled with grout, both upstream and downstream of the key trench
Primary Technical Causes of Failure

- Forensic Investigation Findings: Key Trench Geology
  - Foundation rock below the base of key trench exposed after the dam breach had open joints, some partly filled with grout, both upstream and downstream of the key trench
Primary Technical Causes of Failure

• Forensic Investigation

Findings: Key Trench Geology

– Joint conditions were evident (open, stepped, near vertical and small overhangs)
– Open transverse joints in bottom of key trench; notably in the vicinity of 14+00, where several sets of major through-going joints were apparent
– No slush grout, no dental concrete; soil placed against joints
Primary Technical Causes of Failure

- Forensic Investigation Findings: Key Trench Geology
  - Water testing investigations indicated zones of leakage beneath the grout cap
  - Included “ponding tests” and drilling, coring and water pressure testing
  - Topography of the bottom of key trench had a concentration of steps and overhangs conducive to arching and poor compaction (making soils more easily erodible)
Lessons Learned

• Design and construction coordination - better overall communication
• Design and construction communication - foundation approval process where every square foot of foundation is approved and documented by designers and geologists
• External review – recognize the importance of having a review outside of the organization
• Designs should include multiple lines of defense against seepage and internal erosion, including filters and drains
• Instrumentation is important for evaluation of dam performance, particularly during first filling
Lessons Learned

• Foundation shaping and treatment is critical. Proper treatment reduces the potential for erosion into and along the rock foundation. Shaping helps allow better compaction and reduces the chance of having continuous, low stress zones with erodible materials.

• First filling rate guideline – 1 ft. / day. Allows embankment strains time to adjust to stresses, minimizes cracking potential.

• Designers should perform regular site visits – are the foundation conditions and treatment consistent with what was expected during design?
Teton damsite today

- The left section was later excavated for additional forensic investigations

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The End
The End

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