2004 FAILURE OF BIG BAY DAM
Lamar County, Mississippi

Presented By
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Alvi Associates, Inc.
Acknowledgments

- Keith Ferguson – HDR
- Dusty Myers – Mississippi Dam Safety Division
- Mark Baker – National Park Service
- Hal van Aller – Maryland Dam Safety Division
- Colleagues at Alvi Associates
Audience Background Survey
Outline

- Description of Dam
- Failure Description
- Physical Factors
- Human Factors
- Conclusions
Plan View

- Privately owned
- East-west axis, 2000’ long, downstream is to south
- Outlet: concrete riser, 8’x8’ culvert, concrete apron, riprap basin
- Normal pool of 900 acres, over 11,000 acre-feet
Embankment Section

- Over 50’ high, 42’ normal pool
- 360’ wide, 3:1 slopes with berms
- Core/cutoff wall – soil mixed with bentonite clay

Big Bay Dam Failure
Breach in Progress

- Breach centered on outlet works
- Less than 2 hours to empty reservoir
Post-Failure - Breach

Big Bay Dam Failure
Post-Failure - Breach

Big Bay Dam Failure
Post-Failure - Breach
Plan View – Failure Initiation Point
24 Hours Before Failure

March 11, 2004 (afternoon)

- Local resident sees ‘mud’ flowing from drain pipe in culvert outlet wingwall
- Maintenance Person visits site, notes ‘muddy’ pipe flow, calls Engineer and departs
24 Hours Before Failure

March 12, 2004

- 8:30 – Maintenance Person sees ‘a little soil’ in pipe flow, calls Engineer

- 9:00 to 9:30 – Engineer visits site and sees ‘muddy’ pipe flow, ½” seep with ‘soil particles’ west of outlet, and ‘muddy discoloration’ in riprap basin

- 11:00 – Engineer performs overall dam inspection and departs

- 11:30 to 11:45 – Maintenance Person calls Engineer noting pipe flow increase, leaves site for lunch
24 Hours Before Failure

March 12, 2004 – cont’d

- 12:00 to 12:15 – Maintenance Person returns to site, sees muddy water spraying 30’ to 40’ into the air from an area 20’ to 30’ southwest of outlet, calls Engineer

- 12:20 – Engineer returns to site and sees the water spouting about 2’ to 3’ into the air with a flow diameter of about 18”

- 12:25 – Erosion rapidly grows and progresses upstream, resulting in breach
Downstream Damage

Over 100 structures impacted

- Destruction of 48 homes, 1 bridge
- Damage to 53 homes, 2 churches, 3 businesses, 1 fire station

No fatalities (EAP activated)

$1.1 million legal settlement
PhysicalFactors
Physical Factors & Warning Signs

- Inadequate filters/drains
- Inadequate core/cutoff
- Downstream seepage
- Sediment in basin
- Leakage into culvert
- Highly erodible soils
- Sinkholes in embankment
Internal Drains/Filters

- Drains at downstream face and toe
- No chimney or blanket filter/drain
- No filter or anti-seep collars for culvert
Downstream Toe Filters/Drains

Gravel fill and wrinkles – lack of intimate contact between fabric and native soil
“Excavations were made along the fill side of the wingwalls and along the box sidewalls for approximately 50’ into the lower berm back-slope.”

“Upward percolation of ground water was also observed in this area around the headwall and wingwall.”

“We built a very large gathering system at the end of the box and the pipe that you see is draining it. The pipe ran for approx. 2 months after installation, then quit.”

“During this repair (August 1999 leakage around conduit), the rip-rap dissipation pool was observed to have silted in …”
<table>
<thead>
<tr>
<th>Boring No.</th>
<th>Sample No.</th>
<th>Depth (feet) (note 3)</th>
<th>Classification</th>
<th>Est. Initial Void Ratio</th>
<th>Coefficient of Permeability (cm/sec)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>7</td>
<td>11 - 12.5</td>
<td>Clayey sand with trace of gravel (SC)</td>
<td>0.394</td>
<td>3.7 x 10^-6</td>
<td>Test of “Cutoff” material</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>23 - 24.5</td>
<td>Clayey sand with trace of gravel (SC)</td>
<td>0.434</td>
<td>5.8 x 10^-4</td>
<td>Test of “Cutoff” material</td>
</tr>
<tr>
<td>B-1</td>
<td>17</td>
<td>31 - 32.5</td>
<td>Sandy clay with trace of coarse sand (CL)</td>
<td>0.447</td>
<td>1.0 x 10^-5</td>
<td>Test of “Cutoff” material</td>
</tr>
<tr>
<td>23</td>
<td>43 - 44.5</td>
<td>Clayey sand (SC)</td>
<td>0.34</td>
<td>1.5 x 10^-7</td>
<td>See Figure 6 for gradation, test of “Cutoff” material</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>50 - 52</td>
<td>Clayey sand (SC)</td>
<td>0.509</td>
<td>4.3 x 10^-4</td>
<td>See Figure 6 for gradation</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>63 - 64.5</td>
<td>Fine sand with clay, gravel and trace of coarse sand (SP-SC)</td>
<td>0.307</td>
<td>3.0 x 10^-5</td>
<td>Foundation soil below “Cutoff”</td>
<td></td>
</tr>
<tr>
<td>B-2</td>
<td>7</td>
<td>11 - 12.5</td>
<td>Clayey sand with vertical sand layer and gravel (SC)</td>
<td>0.407</td>
<td>2.0 x 10^-4</td>
<td>Test of “Cutoff” Material</td>
</tr>
<tr>
<td>11</td>
<td>19 - 20.5</td>
<td>Clayey sand with gravel (SC)</td>
<td>0.448</td>
<td>3.3 x 10^-6</td>
<td>Test of “Cutoff” Material</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>27 - 28.5</td>
<td>Clayey sand with fine sand layer (SC)</td>
<td>0.398</td>
<td>4.5 x 10^-5</td>
<td>Test of “Cutoff” Material</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>39 - 40.5</td>
<td>Clayey sand with gravel (SC)</td>
<td>0.405</td>
<td>3.3 x 10^-5</td>
<td>Test of “Cutoff” Material</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>49 - 50</td>
<td>Clayey sand with gravel (SC)</td>
<td>0.446</td>
<td>2.2 x 10^-5</td>
<td>See Figure 6 for gradation, test of “Cutoff” material</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>65 - 66.5</td>
<td>Clayey sand with trace of gravel and coarse sand (SC)</td>
<td>0.537</td>
<td>3.2 x 10^-3</td>
<td>See Figure 6 for gradation, foundation soil below “Cutoff”</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>75 - 76</td>
<td>Silty clay with clay layer (CL)</td>
<td>0.628</td>
<td>8.2 x 10^-8</td>
<td>Older cohesive soils</td>
<td></td>
</tr>
<tr>
<td>B-3</td>
<td>13</td>
<td>59 - 60</td>
<td>Clay (CH)</td>
<td>0.682</td>
<td>1.9 x 10^-9</td>
<td>Older cohesive soils</td>
</tr>
</tbody>
</table>

Notes: 1. cm/sec = centimeters per second  
2. (SC) indicates soil classification by the Unified Soil Classification System  
3. Top elevation of boring B-1 was 281.8, and boring B-2 was 282.8 at the time of drilling.  

Big Bay Dam Failure
Face of Breach – Core Wall?

Big Bay Dam Failure
Significant leaks through culvert defects
Highly Erodible Embankment & Foundation Soils

Typical Gradation vs. Critical Velocity (Foundation Soil)

\[ V_c = 0.03 (D_{50})^{-1} \]
\[ V_c = 0.1 (D_{50})^{-0.2} \]
\[ V_c = 0.35 (D_{50})^{0.45} \]

Jean-Louis Briaud, 9th Peck Lecture, 2007

Big Bay Dam Failure
Sinkhole(s) in Downstream Face of Dam

07/23/02 MS03237 FILLED IN AREA IN LINE WITH THE LEAK IN THE CONCRETE BOX CONDUIT
Sinkhole on Upstream Face of Dam

Big Bay Dam Failure
6. Highly erodible soils
7. Inadequate core/cutoff
8. Sediment in basin
Sequential Seepage/Piping Analysis

Big Bay Dam Failure
Seepage Gradients (Piping Potential)

Big Bay Dam Failure
<table>
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<tr>
<th>Year</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>Mid to late 1980s</td>
<td>Design, with lack of adequate seepage/piping controls</td>
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<td>1990 and 1991</td>
<td>Construction, using erodible and permeable soils</td>
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<td>1993</td>
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<td>1999</td>
<td>Seepage around culvert outlet, ‘silt’ in riprap outlet basin</td>
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<td>1999</td>
<td>Remedial excavation/backfilling around culvert outlet</td>
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<td>Pre-2002</td>
<td>Sinkhole in downstream face backfilled</td>
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<td>2002</td>
<td>Engineer authorized to inspect annually and study seepage, maintenance person directed to inspect weekly</td>
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<tr>
<td>2004</td>
<td>Failure 13 years after construction, sinkhole found in upstream face</td>
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</tbody>
</table>
How Failure Generally Unfolds

- Interaction of contributing factors over time
- Series of steps, often small
- Long time span, usually years or decades
- Eventually, contributing factors ‘line up’ and become jointly sufficient to manifest failure

Big Bay Dam Failure
Human Factors
Natural tendency is disorder (entropy) and ‘drift into failure’

Human effort is needed to create/maintain order and achieve success

Human effort sometimes falls short
Why Do We Fall Short?

- Human fallibility and limitations
- Tradeoffs between safety and other goals
- Complexity

Big Bay Dam Failure
Why Do We Fall Short?

- Human fallibility and limitations
  - Misperceptions
  - Incomplete information
  - Limited cognitive ability
  - Inaccurate models
  - Biases
  - Use of heuristic shortcuts
  - Faulty memory
  - Unreliable intuition

Big Bay Dam Failure
Why Do We Fall Short?

- Safety is under pressure from other goals (tradeoffs)
  - Reduce costs and increase profits
  - Meet schedules
  - Build/maintain relationships
  - Competition
  - Political pressures
  - Personal goals

Big Bay Dam Failure
Why Do We Fall Short?

- Grappling with complex systems

**Features**
- Multiple components and interactions
- Physical and human components
- Nonlinear behavior
- Large effects from small causes
- Feedback loops

**Implications**
- Difficult to model
- Uncertainty
- Lack of predictability
- Difficult to maintain control

Big Bay Dam Failure
Centrality of Human Factors

- In engineering, we *always* have interacting physical and human factors.
- Physical systems are deterministic → no physical ‘mistakes’
- So, failure is *fundamentally* due to human factors.

Big Bay Dam Failure
An attitude of being **preoccupied with avoiding failure**

Aware → Alert → **Vigilant** → Worried → Paranoid → Panicking
Why Might Vigilance Be Lacking?

- **Ignorance** – insufficiently aware of risks due to misperception or insufficient knowledge

- **Complacency** – aware of risks, but overly risk tolerant (fatigue, laziness, emotions, indifference, atypical values, etc.)

- **Overconfidence** – aware of risks, but overestimate ability to manage them

Big Bay Dam Failure
Fostering Vigilance

Organizational **safety culture** in which **everyone** places value on safety at **all** organizational levels

Match people with **suitable personalities** to safety roles

- Vigilant, cautious, inquiring, skeptical, meticulous, disciplined, intellectually humble, interpersonally assertive, etc.

- Reviewers, inspectors, regulators, operators, emergency action planners, etc.
Vigilant Attitude → Best Practices

- Vigilant preoccupation with avoiding failure typically leads to implementing best practices (common in dam engineering).
- ‘High-reliability organizations’ (HROs) are exemplars.
- Best practices → success
- Neglect best practices → failure
- Failure results from not doing what’s necessary to succeed, not from doing ‘special’ things to fail.

Big Bay Dam Failure
## Best Practices for Dams

<table>
<thead>
<tr>
<th>General Design Features</th>
<th>Organizational and Professional Practices</th>
<th>Warning Signs</th>
</tr>
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<tbody>
<tr>
<td>• Conservative safety margins</td>
<td>• Safety culture</td>
<td>• Look for them actively</td>
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<td>• Redundancy, robustness, and</td>
<td>• Monitoring and peer review</td>
<td>• Investigate to understand their significance</td>
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<td>resilience</td>
<td>• Information sharing to 'connect the dots'</td>
<td>• Address promptly and properly</td>
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<td>• Progressive failure with</td>
<td>• Diverse teams</td>
<td>• Be suspicious during 'quiet periods'</td>
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<tr>
<td>warning signs</td>
<td>• Recognizing knowledge limitations</td>
<td></td>
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<tr>
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<td>• Use of checklists</td>
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<tr>
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### Big Bay Dam Failure

- **Conservative safety margins**
- **Redundancy, robustness, and resilience**
- **Progressive failure with warning signs**
- **Safety culture**
- **Monitoring and peer review**
- **Information sharing to 'connect the dots'**
- **Diverse teams**
- **Recognizing knowledge limitations**
- **Use of checklists**
- **Appropriate system models and software use**
- **Professional and ethical standards**
Best Practices for Big Bay Dam?

- General design features
  - Conservative safety margins
    - Highly erodible materials used for dam
    - No seepage filter around conduit
    - Core/cutoff wall not impervious enough
    - Cutoff wall not deep enough
Best Practices for Big Bay Dam?

- General design features – cont’d
  - Redundancy, robustness, and resilience
    - Inadequate seepage/piping control
  - Progressive failure with warning signs
    - Piping largely undetected (monitoring systems not used) until hours before failure
Best Practices for Big Bay Dam?

Organizational and professional practices

- Safety culture, including learning from failures
  - Mississippi, local Owner and Engineer, emphasis on personal relationships within local community
- Monitoring and peer review
  - Poor quality of plans suggests lack of review
  - Owner relied almost solely on one Engineer from design to failure investigation, no evidence of peer review
Best Practices for Big Bay Dam?

Organizational and professional practices – cont’d

– Information sharing (and allowing dissent) to ‘connect the dots’

  • Limited communication between Owner/Engineer and Mississippi Dam Safety Division (understaffed)

– Diverse composition of teams

  • Mainly just the perspective of one Engineer
**Best Practices for Big Bay Dam?**

**Organizational and professional practices – cont’d**

- Recognizing knowledge/skill limitations and deferring to expertise
  - Engineer apparently lacked experience, but didn’t seek help
  - Possibly contractor’s first major project
  - Maintenance Person appeared diligent, but lacked training

- Use of checklists
  - No evidence that any checklists were used
Best Practices for Big Bay Dam?

Organizational and professional practices – cont’d

– Appropriate system models and use of software
  
  • No evidence of use of software for seepage or stability analysis
  • No geotechnical design calcs found → cookie-cutter design?

– High professional and ethical standards
  
  • Poor quality of plans
  • No PE seal on plans
Warning signs

- Look for them actively
  - Construction inspection missed defects in culvert
  - Several inspections performed after construction
  - No monitoring systems for piping

- Investigate to understand their significance
  - Missed significance of culvert leakage, sinkholes, discontinuation of drainage, and sediment in basin
  - Test results indicating permeable core/cutoff apparently ignored
Best Practices for Big Bay Dam?

Warning signs – cont’d

- Address them promptly and properly
  - Remedial actions were performed promptly
  - Remedial actions were ineffective and possibly detrimental (e.g., clogging and redirection of seepage)

- Be suspicious during ‘quiet periods’
  - Owner, Engineer, and Maintenance Person did show concern
  - Underwater inspection would have revealed sinkhole(s)
(Unexpanded) Timeline until Failure

- **Mid to late 1980s** – Design, with **lack of adequate seepage/piping controls**
- **1990 and 1991** – Construction, using **erodible and permeable soils**
- **1993** – Normal pool reached
- **1993** – ‘**Wet spots**’ on downstream face
- **1993** – **Remedial** installation of drains at downstream face
- **1993 onward** – **Leakage into culvert** at multiple and changing locations
- **1999** – **Seepage** around culvert outlet, ‘silt’ in riprap outlet basin
- **1999** – **Remedial** excavation/backfilling around culvert outlet
- **Pre-2002** – **Sinkhole** in downstream face backfilled
- **2002** – Engineer authorized to **inspect annually** and study seepage, maintenance person directed to **inspect weekly**
- **2004** – Failure 13 years after construction, **sinkhole** found in upstream face

**Big Bay Dam Failure**
Mid to late 1980s – Design apparently led by a young Engineer with little or no prior dam design experience, with little or no peer review, without geotechnical modeling for seepage and piping, and without using checklists; as a result, design had inadequate and non-redundant seepage/piping controls and lacked monitoring systems found in similar dams; plans of poor quality and no PE seal.

1990 and 1991 – Construction using erodible and permeable soils (missed significance of test results indicating permeability), without extending cutoff to older impermeable layer; apparently first major project of contractor; inadequate construction inspection.
(Expanded) Timeline until Failure

- 1993 – Normal pool reached
- 1993 – ‘Wet spots’ on downstream face
- 1993 onward – Leakage into culvert at multiple and changing locations
- 1993 – Remedial installation of drains at downstream face performed promptly (designed by same Engineer, without peer review), but missed leakage into culvert as piping warning sign
(Expanded) Timeline until Failure

- **1993 to 1999** – Some inspections likely performed by Mississippi Dam Safety Division, but they missed significance of warning signs and not much information sharing with Owner and Engineer.

- **1999** – Seepage around culvert outlet, ‘silt’ in riprap outlet basin.

- **1999** – Remedial excavation/backfilling around culvert outlet to address seepage performed promptly (designed by same Engineer, without peer review), but missed seepage and piping warning signs of leakage into culvert, sediment in basin, and discontinuation of flow in drains (indicating clogging and inadvertently redirecting seepage).
(Expanded) Timeline until Failure

- Pre-2002 – Sinkhole in downstream face backfilled, but significance as piping warning sign missed

- 2002 – Same Engineer authorized to inspect annually and study seepage, and maintenance person directed to inspect weekly, but seepage analysis apparently not performed, and Maintenance Person lacked qualifications

- 2004 – Failure 13 years after construction (failure investigated by the same Engineer); sinkhole found in upstream face which could have been detected by underwater inspection
Conclusions

- Dam failures are fundamentally due to human factors

- Human and physical factors interact, usually for years, until factors become jointly sufficient to produce failure

- The ‘story’ explaining a failure may be complex
Conclusions

Big Bay Dam had *many* areas where best practices not followed, resulting in:

- Many physical deficiencies resulting in inadequate seepage and piping control
- Many missed or neglected warning signs
- Sequential piping leading to catastrophic breach
Conclusions

- Big Bay Dam would likely NOT have failed if best practices had been followed.

- Owner and Engineer weren’t complacent, but the Owner overconfidently relied on an underqualified Engineer who was overconfident, possibly a reflection of the local culture in Mississippi.

- For public safety, effective regulatory framework needed to ensure that owners, engineers, and contractors are sufficiently qualified, vigilant, and implement best practices.
Discussion