2004 FAILURE OF BIG BAY DAM

Lamar County, Mississippi

Presented By

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Alvi Associates, Inc.

Acknowledgments

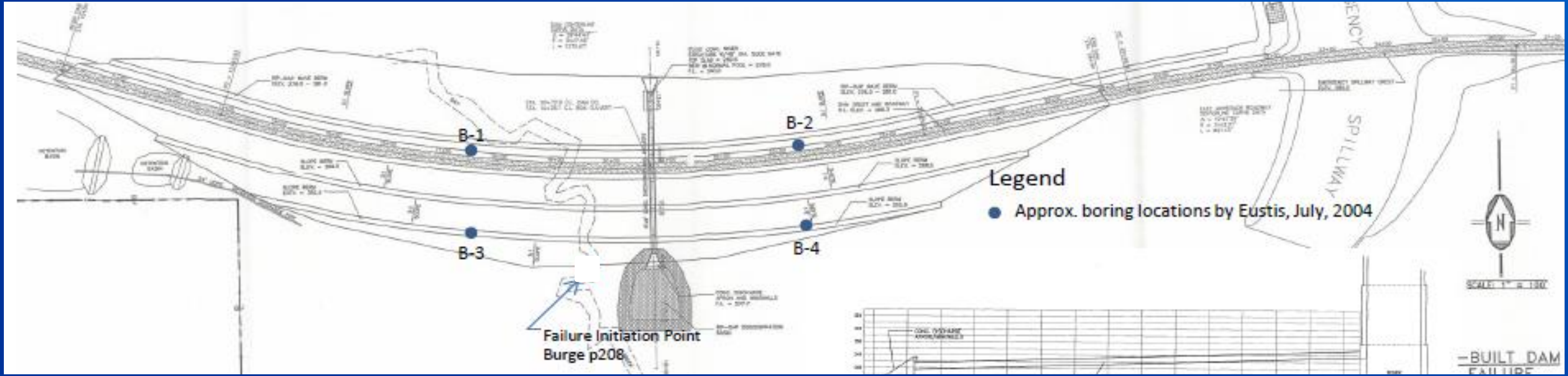
- Keith Ferguson – HDR
- Dusty Myers – Mississippi Dam Safety Division
- Mark Baker – National Park Service
- Hal van Aller – Maryland Dam Safety Division
- Colleagues at Alvi Associates

Audience Background Survey

Outline

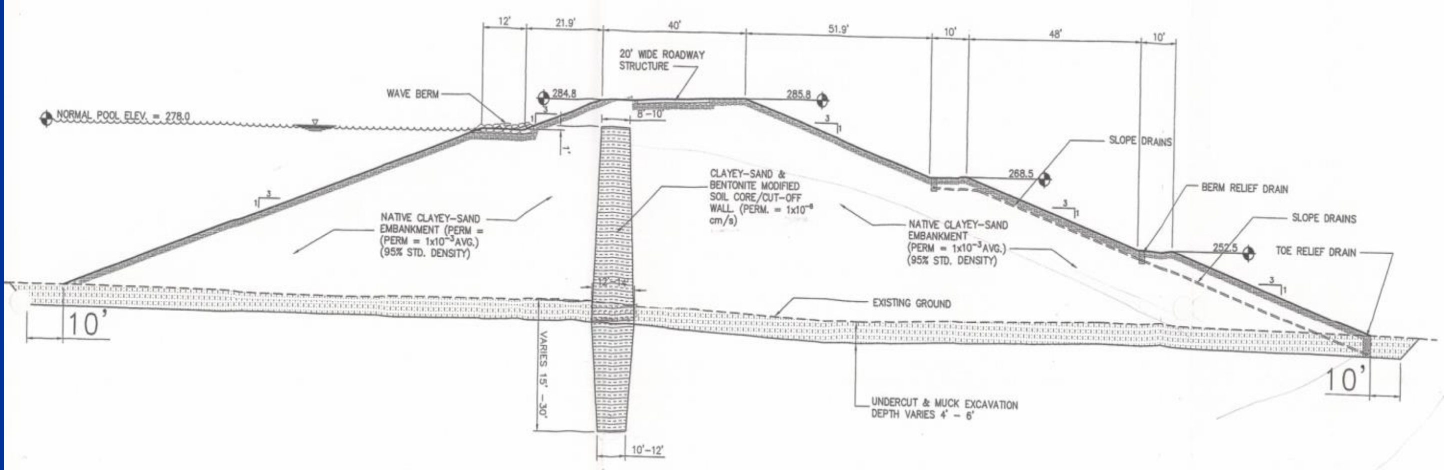
- Description of Dam
- Failure Description
- Physical Factors
- Human Factors
- Conclusions

Plan View



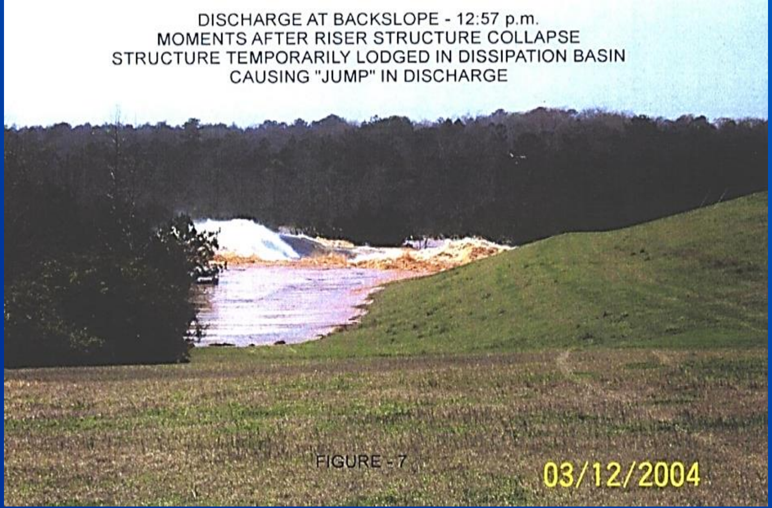
- Privately owned
- East-west axis, 2000’ long, downstream is to south
- Outlet: concrete riser, 8’x8’ culvert, concrete apron, riprap basin
- Normal pool of 900 acres, over 11,000 acre-feet

Embankment Section



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

Breach in Progress



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

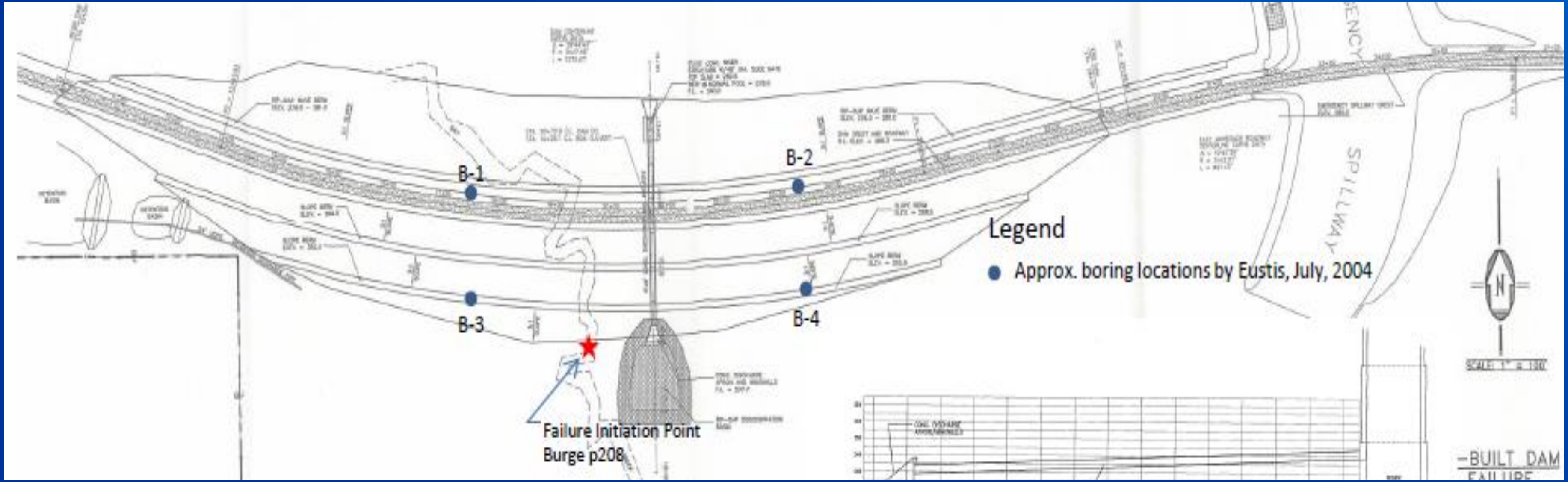
Post-Failure - Breach

Post-Failure - Breach

Post-Failure - Breach

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

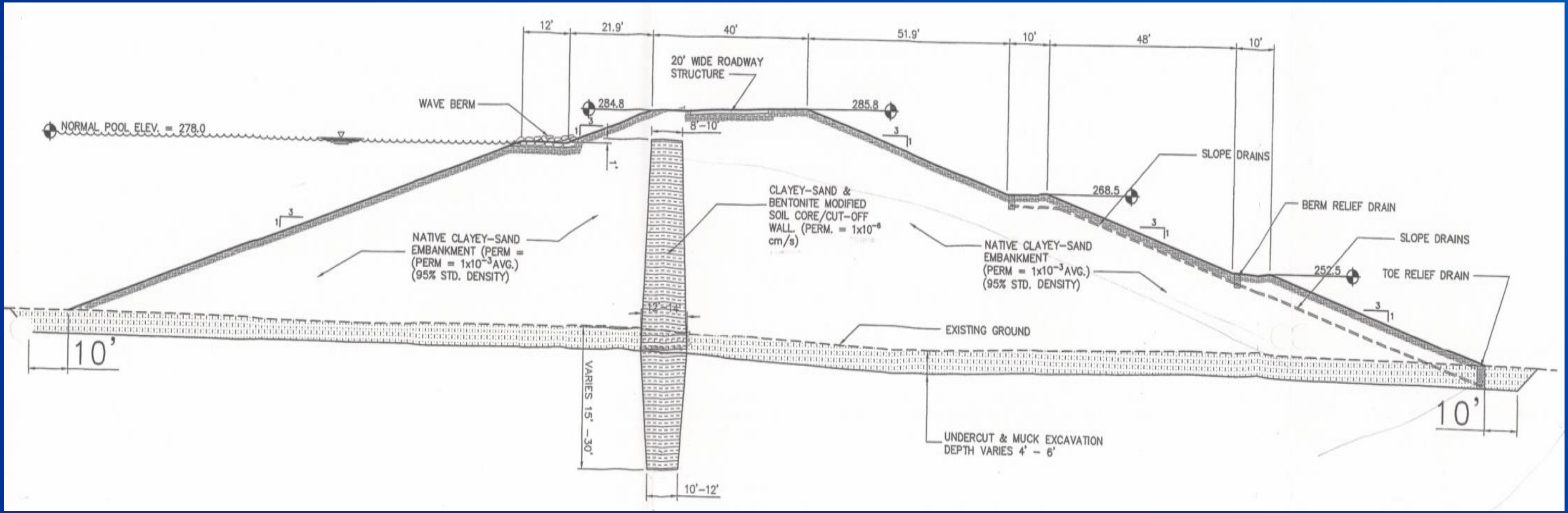
- Over 100 structures impacted
  - Destruction of 48 homes, 1 bridge
  - Damage to 53 homes, 2 churches, 3 businesses, 1 fire station
- No fatalities (EAP activated)
- $1.1 million legal settlement

Physical Factors

Physical Factors & Warning Signs

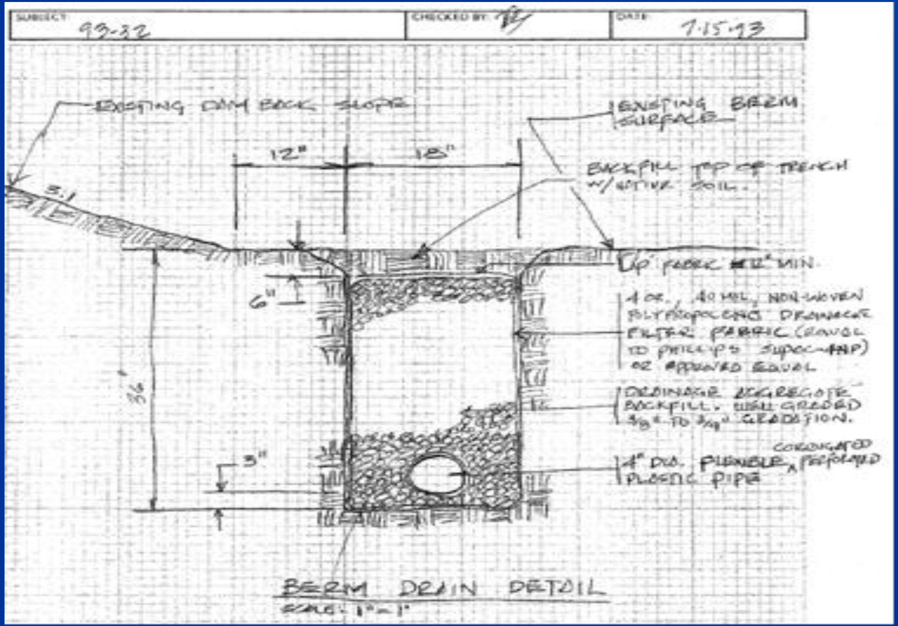
- Inadequate filters/drains
- Inadequate core/cutoff
- Downstream seepage
- Sediment in basin
- Leakage into culvert
- Highly erodible soils
- Sinkholes in embankment

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

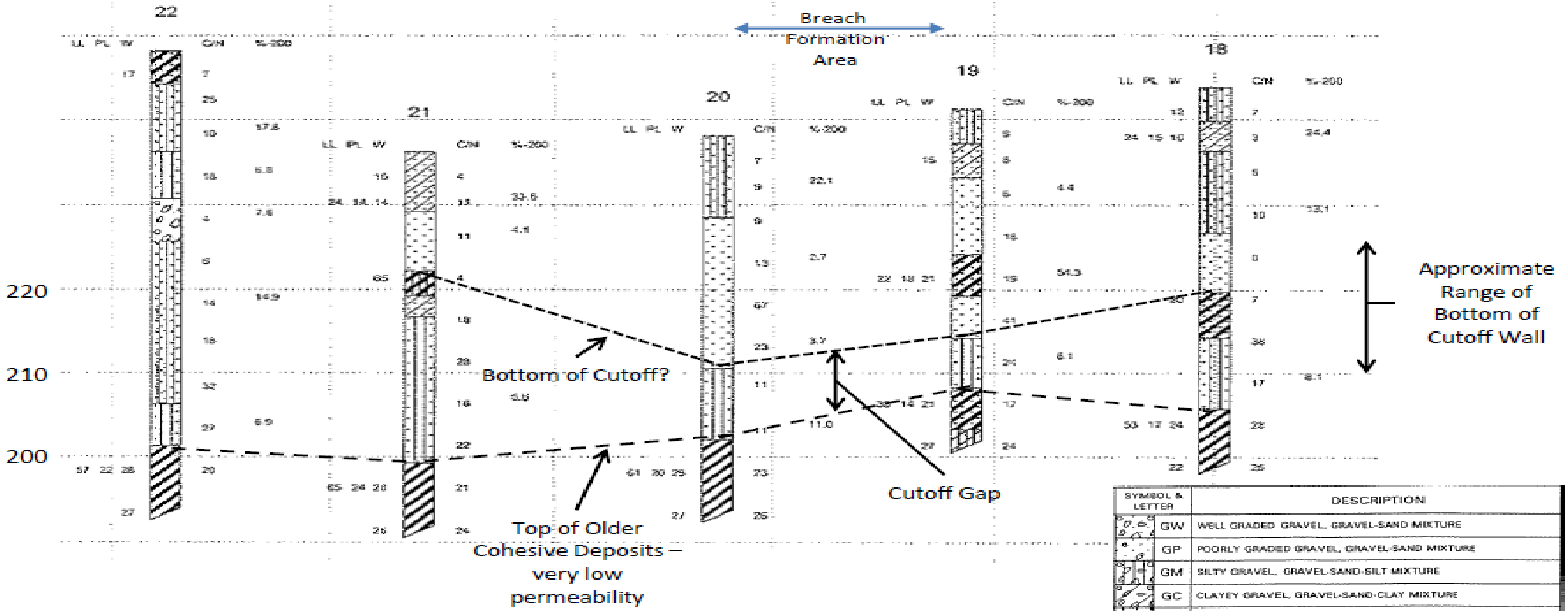
Downstream Filters/Drains, Seepage, and Sediment (1999)

"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 …"



SYMBOL & LETTER	DESCRIPTION
GW	WELL GRADED GRAVEL, GRAVEL-SAND MIXTURE
GP	POORLY GRADED GRAVEL, GRAVEL-SAND MIXTURE
GM	SILTY GRAVEL, GRAVEL-SAND-SILT MIXTURE
GC	CLAYEY GRAVEL, GRAVEL-SAND-CLAY MIXTURE
SW	WELL GRADED SAND, GRAVELLY SAND
SP	POORLY GRADED SAND, GRAVELLY SAND
SM	SILTY SAND, SAND-SILT MIXTURE
SC	CLAYEY SAND, SAND-CLAY MIXTURE
ML	SILT WITH LITTLE OR NO PLASTICITY
ML	CLAYEY SILT, SILT WITH SLIGHT TO MEDIUM PLASTICITY
CL	SILTY CLAY, LOW TO MEDIUM PLASTICITY
CL	SANDY CLAY, LOW TO MEDIUM PLASTICITY (30% TO 50% SAND)
MH	SILT, FINE SANDY OR SILTY SOIL WITH HIGH PLASTICITY
CH	CLAY, HIGH PLASTICITY
OH	ORGANIC CLAY OF MEDIUM TO HIGH PLASTICITY
PT	PEAT, HUMUS, SWAMP SOIL

Foundation Soils

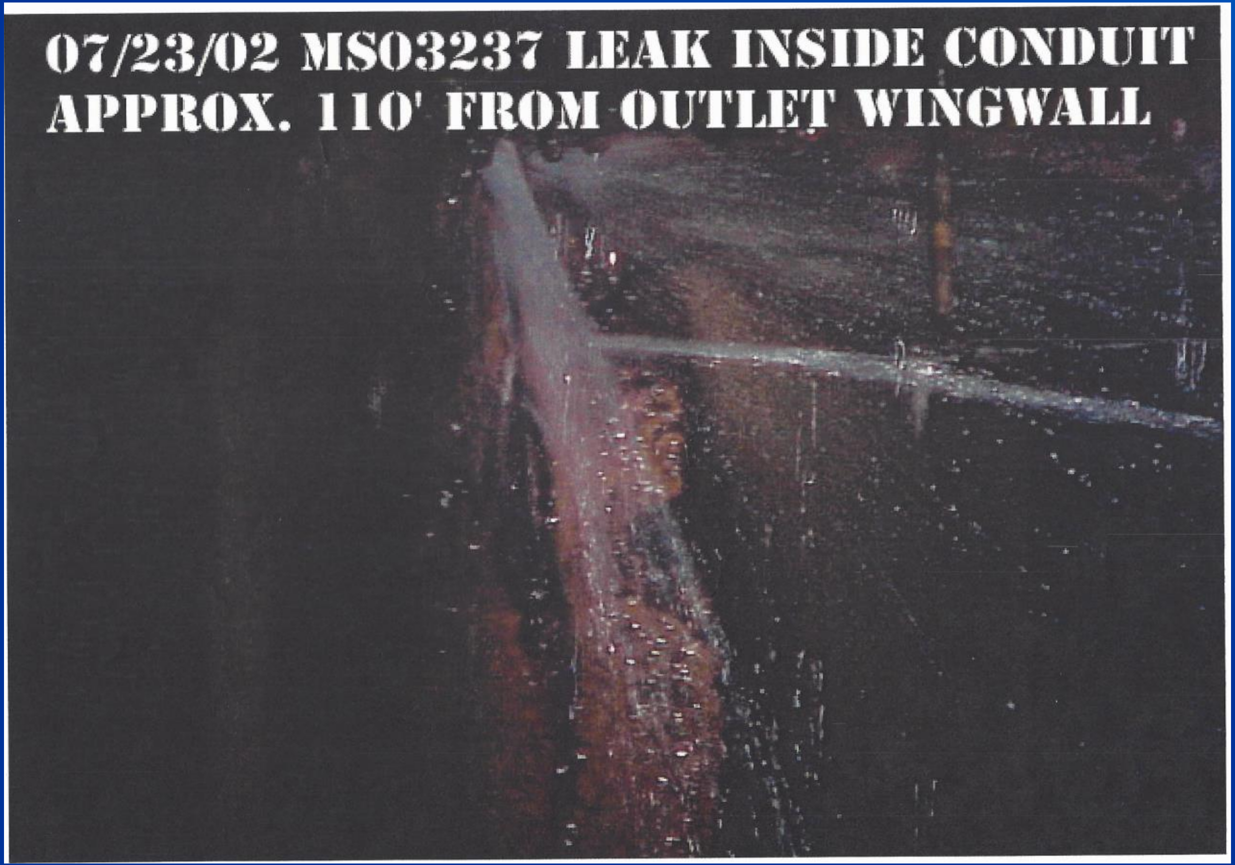
Table 1. Results of Laboratory Testing - Embankment "Cutoff" and Foundation Soils
Eustis Engineering, 2006

Boring No.	Sample No.	Depth (feet) (note 3)	Classification	Est. Initial Void Ratio	Coefficient of Permeability (cm/sec)	Comment
B-1	7	11 - 12.5	Clayey sand with trace of gravel (SC)	0.394	3.7 x 10-6	Test of "Cutoff" material
	13	23 – 24.5	Clayey sand with trace of gravel (SC)	0.434	5.8 x 10-4	Test of "Cutoff" material
	17	31 – 32.5	Sandy clay with trace of coarse sand (CL)	0.447	1.0 x 10-5	Test of "Cutoff" material
	23	43 – 44.5	Clayey sand (SC)	0.34	1.5 x 10-7	See Figure 6 for gradation, test of "Cutoff" material
	27	50 - 52	Clayey sand (SC)	0.509	4.3 x 10-4	See Figure 6 for gradation
	31	63 – 64.5	Fine sand with clay, gravel and trace of coarse sand (SP-SC)	0.307	3.0 x 10-5	Foundation soil below "Cutoff"
B-2	7	11 – 12.5	Clayey sand with vertical sand layer and gravel (SC)	0.407	2.0 x 10-4	Test of "Cutoff" Material
	11	19 - 20.5	Clayey sand with trace of gravel (SC)	0.448	3.3 x 10-6	Test of "Cutoff" Material
	15	27 – 28.5	Clayey sand with fine sand layer (SC	0.398	4.5 x 10-5	Test of "Cutoff" Material
	21	39 – 40.5	Clayey sand with gravel (SC)	0.405	3.3 x 10-5	Test of "Cutoff" Material
	25	49 - 50	Clayey sand with gravel (SC)	0.446	2.2 x 10-5	See Figure 6 for gradation, test of "Cutoff" material
	33	65 – 66.5	Clayey sand with trace of gravel and coarse sand (SC)	0.537	3.2 x 10-3	See Figure 6 for gradation, foundation soil below "Cutoff"
	38	75 - 76	Silty clay with clay layer (CL)	0.628	8.2 x 10-8	Older cohesive soils
B-3	13	59 - 60	Clay (CH)	0.682	1.9 x 10-9	Older cohesive soils

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.

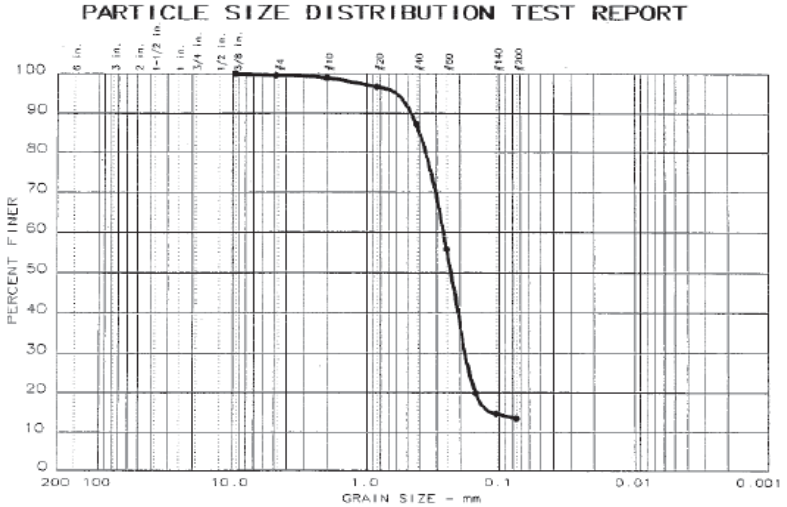
Permeable Foundation Cutoff

Face of Breach – Core Wall?

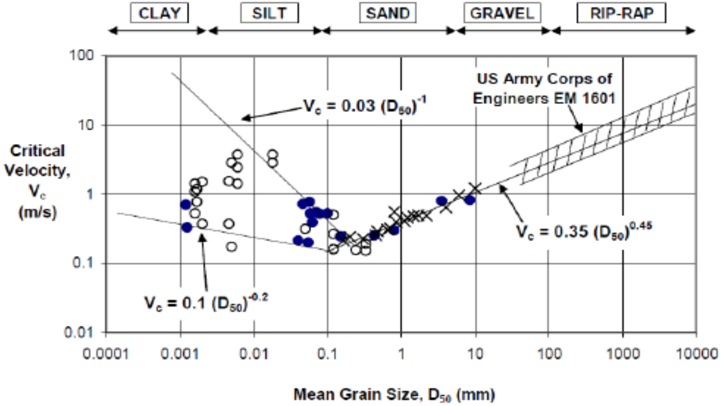


Significant leaks through culvert defects

Highly Erodible Embankment & Foundation Soils

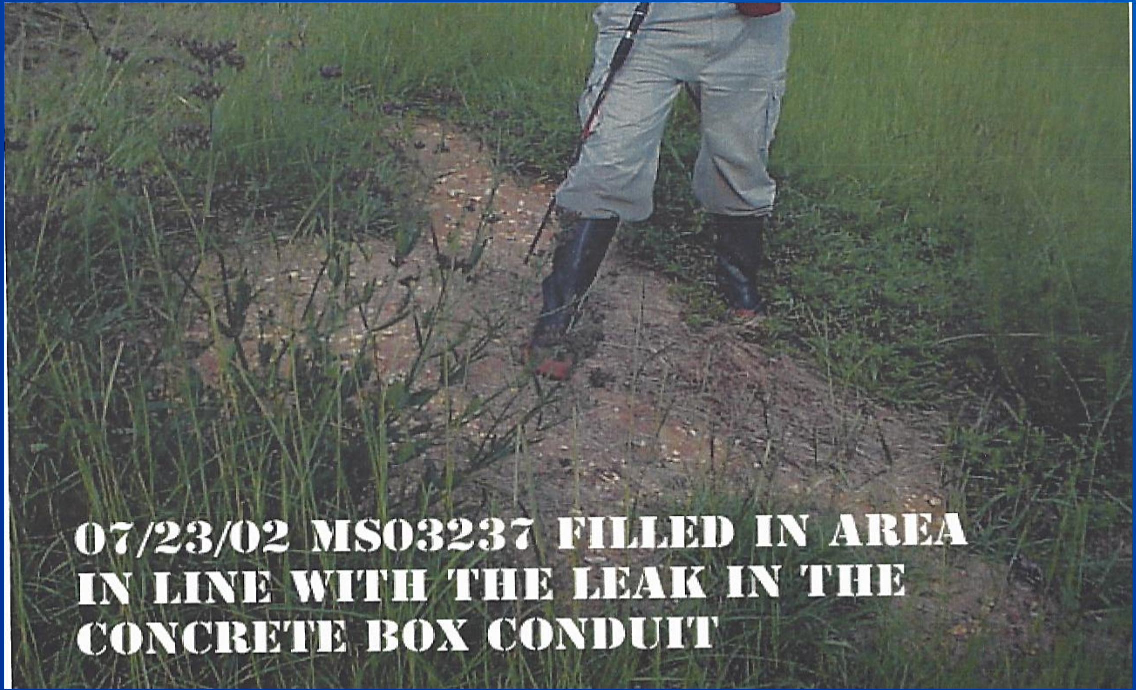


Typical Gradation vs. Critical Velocity (Foundation Soil)

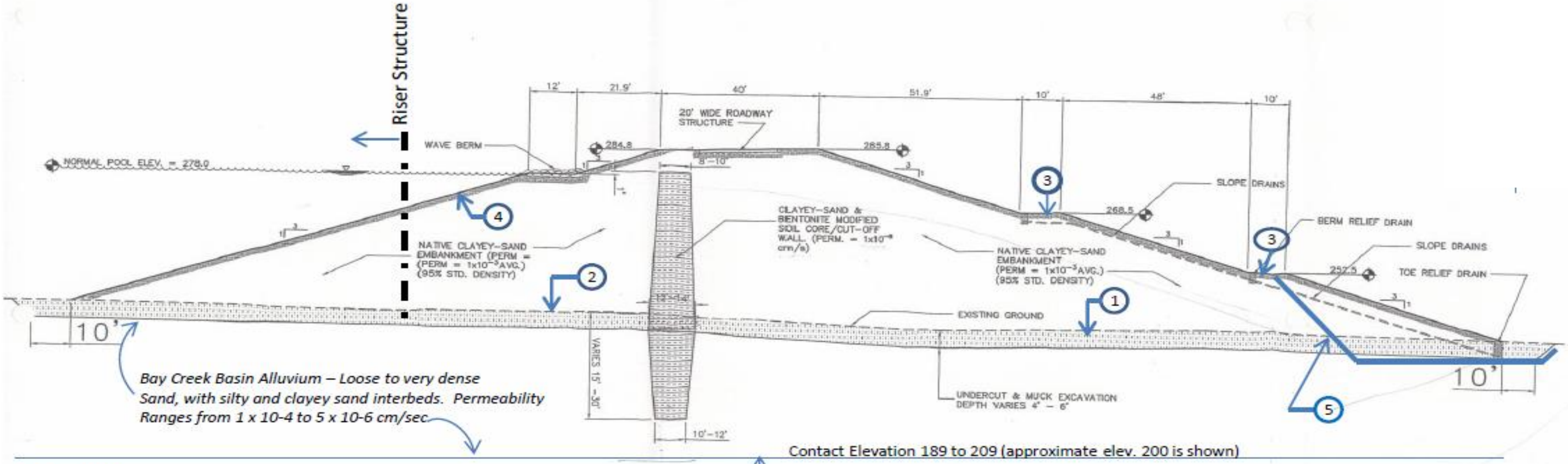


Jean-Louis Briaud, 9th Peck Lecture, 2007

Sinkhole(s) in Downstream Face of Dam



Sinkhole on Upstream Face of Dam



Legend

1. Approximate location of seepage into box culvert conduit. Three 1/8 to ¼ inch discharges from the west upper corner of wall/ceiling interface.
2. Approximate location of 2nd seepage into box culvert conduit. Three discharges beginning about 10 inches above the box floor along west wall. Seeps ranged from a trickle to ¼ to 3/8 inch stream with total flow about 5 to 6 gallons per minute.
3. Approximate location of backfilled sinkhole notes in photo dated 7/23/02. Exact location not well described
4. Possible sinkhole noted along U.S. Slope outside of breach area when reviewing project files for failure review.
5. Approximate extent of the over excavation around the discharge box culvert to repair moist conditions in August 1999. Filter likely clogged due to fabric placement methods

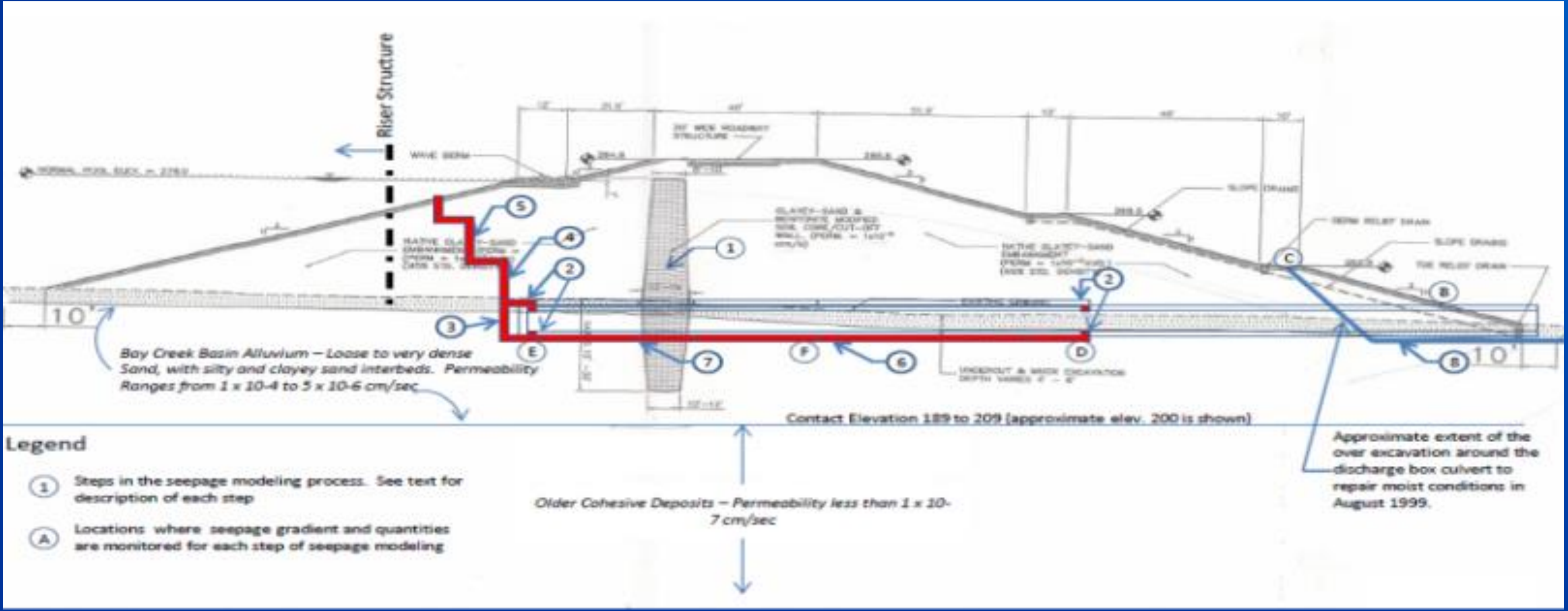
Older Cohesive Deposits – Permeability less than 1 x 10-7 cm/sec

6. Highly erodible soils

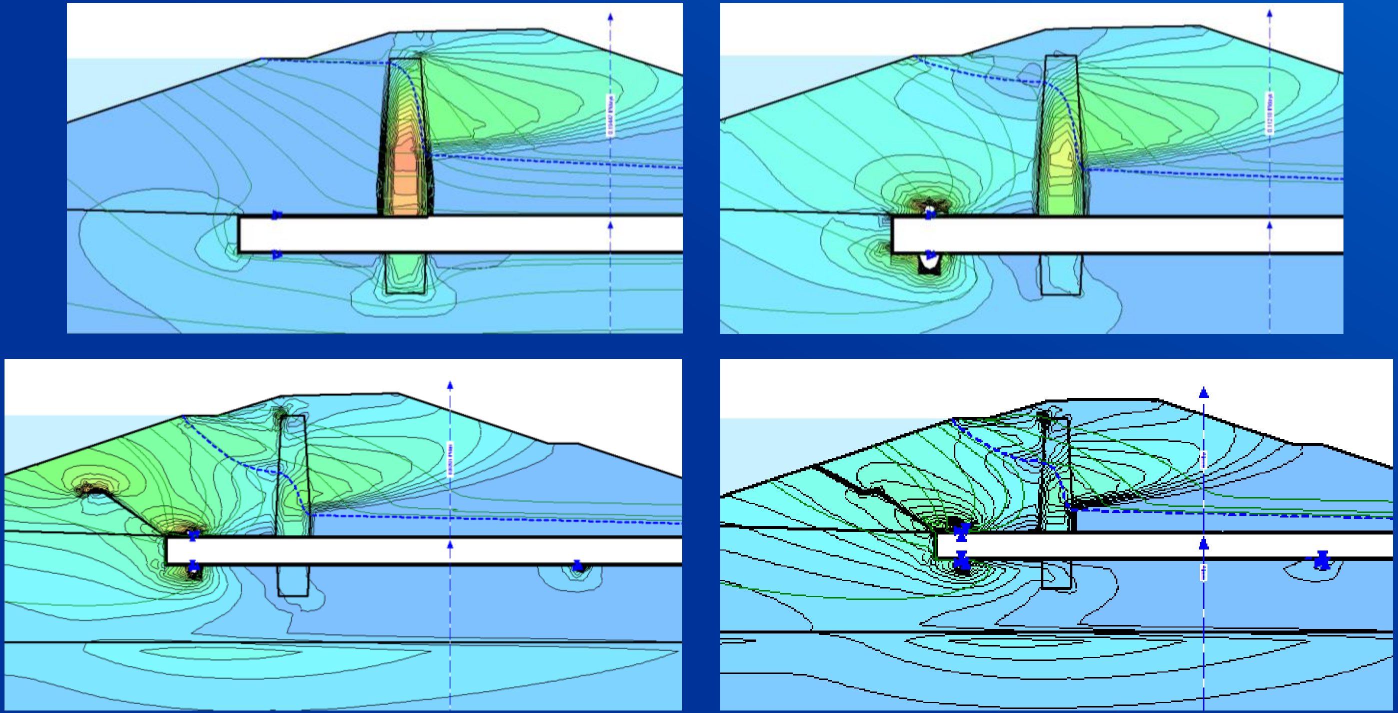
7. Inadequate core/cutoff

8. Sediment in basin

Sequential Seepage/Piping Analysis



Seepage Gradients (Piping Potential)



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

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

Human Factors

Failure vs. Success

- 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

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

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

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

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**

How to Avoid 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

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**

Best Practices for Dams

General Design Features	Organizational and Professional Practices	Warning Signs
• 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	• Look for them actively • Investigate to understand their significance • Address promptly and properly • Be suspicious during ‘quiet periods’

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

Best Practices for Big Bay Dam?

- **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 (eg, 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
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- 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

(Expanded) Timeline until 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