Forensic Investigations of Dam Failures

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Case Histories

• A few introductory notes:
  – All major litigation on each project is completed
  – All information reported here is in the public domain

• Dam Failures discussed today
  – The “Classics” plus
  – Taum Sauk
  – Silver Lake
  – Saluda Dam
  – Swinging Bridge

  – Will not talk about Tampa Bay, Lake Dehli, Levee Failures
References

- Dr. A.J. “Skip” Hendron
- Brian Green
- Prof. J. David Rogers
- Euler Cruz & Rafael Cesário
- Dr. David Petley
Definition of Failure

• Failure at a dam is “an uncontrolled release of water”
• Causes of Failure
  – Overtopping – the most common cause
  – Piping thru Embankment – 2\textsuperscript{nd}!!
  – Piping thru Foundation – 3\textsuperscript{rd}!!
  – Foundation Degradation
    • Karst development
    • Liquefaction
    • Loss of fines over time
  – Earthquakes – ground motion and faults
  – Failure of gates, stoplogs, flashboard malfunction, penstocks, tunnels, and reservoir slopes
Some “Classics”
We learn from our mistakes!!
Classic Failures

• Had a major impact on dam or hydro engineering

• Had a major impact on dam safety legislation and dam safety regulations

• Had a major impact on society
Folsom Dam
Folsom, California
July 17, 1995
Folsom Dam – “Before”
Folsom Dam – “After”
Folsom Dam

• Increased profession’s awareness of the need for maintenance and inspection of auxiliary features associated with a dam

• Changed FERC’s Inspection Guides
Shih Kang Dam
Taiwan
September 21, 1999
Shih Kang Dam – Taiwan
Impact of building a dam over a fault
Shih Kang Dam - Taiwan
Shih Kang Dam - Taiwan
Austin (Bayless) Dam
Austin, Pennsylvania
September 30, 1911
Austin Dam – “Before”
Austin Dam – “After”
Austin Dam

- Destroyed the myth that “gravity dams can’t fail”
- Illustrates the need for detailed, comprehensive foundation investigations and foundation preparation
- Illustrates the need for temperature expansion/contraction joints in gravity dams
Vaiont Dam
Italy
October 1963
Vaiont Dam – Double Arch
245m (800) ft high
Village of Longarone “Before” Vaiont Dam Failure
The Vaiont Dam Disaster

- Dam completed and filled
- Reservoir cycled up and down several times over three years
- Left Reservoir Slope Failed catastrophically
- Within 30 – 40 seconds, some 270 million m$^3$ of rock crashed into the reservoir.
- Resulting wave overtopped dam by about 100 – 150 m.
Vaiont Dam – Reservoir Slope Failure
Longarone Village “After” Vaiont Dam Failure
Vaiont Dam at the Top
Teton Dam
Teton, Idaho
June 5, 1976
Teton – “Before”
Start of Piping – June 5 – 7:00 AM
June 5 – 11:50 AM
(Crest still intact)
June 5 – 11:50 AM
(Crest now eroding)
June 5 – 12:00 noon
(Crest lost – maximum flood)
Lessons Learned

• Compaction is extremely important throughout the dam and especially at the abutments
• Grout Curtains are critical to prevent piping
• Keyway design is critical
• Filters are a key feature to resist piping
  (When in doubt, add a filter)
Compaction Against Right Abutment
Compaction Equipment after Change
Sayano-Shushenskaya
Khakassia, Russia
August 17, 2009
Accident at Russia’s Largest Hydroelectric Power Station
The Accident – 2009 Aug 17
Before the Accident
After the Accident

Generator floor
General View
Before the Accident

Generator Rotor – Unit 5

The accident started here
After the Accident
Lower Van Norman Dam
Los Angeles, California
February 9, 1971

A Classic that was not a failure!
Lower Van Norman Dam was built by the City of Los Angeles as part of the Los Angeles Aqueduct in 1916 – 1918, using the hydraulic fill and puddled fill techniques. A rolled fill addition was placed in 1924.

The embankment failed during the February 9, 1971 M. 6.7 San Fernando Earthquake, but no water was released.
Lower Van Norman
Lower Van Norman
Forerunner to Modern Liquefaction Analysis

Susceptibility to Liquefaction

• Careful forensic evaluations by the geotechnical engineering group at U.C. Berkeley unraveled the dam’s failure by liquefaction of a zone of low density sandy hydraulic fill, shown in blue in the above sections.
• The State subsequently slated 30 other hydraulic fill dams for retrofitting between 1973 – 75.
Swinging Bridge Dam
Sullivan County, New York
May 5, 2005
Swinging Bridge Dam
Swinging Bridge Dam

- Over time leaks developed
- Fines transported to penstock during dewatering
- Sinkholes developed on crest
- Reservoir drained
- Penstock & Unit abandoned
- Dam repaired and refilled (3 yr shutdown)
Silver Dam Lake
Upper Peninsula, Michigan
May 2003
Silver Lake Dam
Dead River Hydroelectric Project

- Mountain Top Storage Lake
  - Main Concrete Dam with Spillway & Outlet Pipe/Gate Control
  - Auxiliary Dams and Dikes
  - Emergency Spillway with Erodible Fuse plug

- May, 2003 – snowmelt, Gate Control not Activated
- Fuse Plug Eroded
- Main Dam Overtopped – minimal damage
- Dam No. 2 overtopped & eroded away entirely

- Failure drained approximately 25,000 acre feet of water from Silver Lake Reservoir
- $100 million damage – no fatalities
Silver Lake – Overtopping of Main Dam
Saluda Dam
Columbia, South Carolina
Rehabilitation
Saluda Dam
A Failure that was Prevented!
Aerial View of Saluda Dam

- Intake Towers
- NORTH
- Spillway
- Ash Ponds & Landfill
- McMeekin Station
- Saluda Hydro
- Bush River Rd.
Saluda Dam

Lake Area: 78 square miles
Lake Capacity: 1,600,000 acre feet
Dam Length: 7,800 feet
Max Dam Height: 200 feet
Powerhouse Capacity: 260 MW
Original Construction: Hydraulic Fill
Original Completion: 1930
Original Dam Construction

- Dam was constructed 1927 - 1930
- 11,000,000 cy--semi-hydraulic method
As-Built Dam Configuration

- Semi-Hydraulic Fill
- Most soils “Dumped”
- No compaction
Dynamic Stability Analysis

- Liquefaction Evaluation of Saluda Dam
  - Earthquake record selection
  - Liquefaction methodology

- Post-Seismic Stability Analysis
Liquefaction Analysis

Extensive Liquefaction, Post-Seismic FS < 1
Section AA’ (typ.)

**Lower Bound**

**Best Case**
Remediation Concept

Rockfill Dam
- Length 5,100 feet
- Max. Height 200 feet
RCC Dam

- Length 2,200 feet
- Max. Height 210 feet
Taum Sauk Upper Reservoir
Lesterville, Missouri
December 15, 2005
Taum Sauk on December 14, 2005
Taum Sauk on December 15, 2005
Release of 1.4 Billion Gallons of Water
Original Rockfill Dam X-Section
Original Rockfill Dam X-Section
Panel 72 Erosion
Taum Sauk Forensic Investigation

- Field Investigations
  - Visual Observations
  - Geologic Mapping
    - Breach Area
    - Breach Channel
  - Record Search
  - Test Borings & Sampling
  - Laboratory Testing
  - Instrumentation Investigation
  - Interviews (operators & mgmt)
Forensic Investigation

• Engineering Analyses
  – Hydraulic Analysis (overflow zones, velocity, impingement zone)
  – Rockfill Dike (seepage, piping & stability)
  – Concrete Facing (effect on $\mu$)
  – Liner (effect on $\mu$)
  – Parapet Wall (stability, structural)
  – Asphalt Liner (effect on $\mu$)
  – Grout Curtain (effect on $\mu$)
  – Filters (effect on $\mu$)
Rockfill Dike Stability - Sliding

- Water Pressure
- Resisting
- Normal Force
- Weight of Water
- Estimated Pore Pressure at Overtopping
- Sliding

\[ \text{Water Pressure} \]
Taum Sauk Re-build Data

- Same Footprint
- No change in capacity or generation
- 110 to 140 ft high
- ~ 6800 ft long - 9 monoliths @ ~800 ft
- RCC with processed “old rockfill” dam
- RCC – 2.8 million CY + 0.5 million CVC
- Symmetrical w Concrete Face
- Overflow Release Structure
- Highly redundant Instrumentation
Rock Foundation Preparation
Foundation Preparation
Upstream View of the Fracture Zone
Cleaning and Mapping in Progress
Overflow Release Structure
Taum Sauk on April 1, 2010
Keys to a Forensic Investigation
Keys to a Forensic Investigation

• Investigation Work Plan
  – Plan for Litigation from the beginning
    • Civil or Civil & Criminal
    • Expect Opposing Experts
  – Literature Search
  – Interviews
  – Review of Existing Calculations & Design Basis
  – Field Investigations
  – Laboratory Testing
  – “New” Analysis
  – Report Preparation
Keys to a Forensic Investigation

• Have a well defined engagement letter
• Avoid emails!!
• Avoid derogatory remarks & comments
• Keep consistent & accurate field logs
• Keep confidentiality
• Use NDA’s with Subcontractors
• Treat drafts & preliminary documents consistent with standard corporate policy
• Implement a robust QA/QC Program
• Be open minded!!
Keys to a Forensic Investigation

- Public Domain Literature Search
  - Professional Literature
  - News Accounts & Photos/Videos

- Private File Search
  - STID’s & PFMA’s
  - Permit Applications
  - Inspection Reports
  - Instrumentation Reports
  - Construction Reports & Photos
Keys to a Forensic Investigation

- Field Investigations (drilling, geophysics, etc)
  - Implement a Field Work Plan
  - Implement a HSEP immediately
  - Implement a QA/QC Program
  - Use Calibrated Equipment with traceable records
    - SPT Energy
    - Shelby Tube & Split Barrel Dimensions
    - Pressure gages, flow meters, DRM Systems
  - Use Sample Manifest Protocols
  - Watch the field records carefully!!!!
  - Use NDA’s with subcontractors
Keys to a Forensic Investigation

• **Laboratory Testing**
  – Implement a Laboratory Testing Plan
  – Implement a QA/QC Program
  – Use Calibrated Equipment with traceable records
  – Use defendable Standards (ASTM, C of E, etc)
  – Use Sample Manifest Protocols
  – Watch the lab records carefully!!!!
  – Should Field Logs be adjusted based on lab tests?
Thank you for your time!