The 2017 Oroville Dam Spillway Incident – What Happened and What Should We Learn?

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36th Annual Geotechnical Seminar
GEO-Omaha 2019
ASCE Nebraska Section
8 February 2019

Presentation Content

- Introduction
- Chronology of the incident
- Background information
- Physics of incident – what happened?
- Causes of incident – why did it happen?
- What should we learn?
Team Mission

To complete a thorough review of available information to develop findings and opinions on the chain of conditions, actions, and inactions that caused the damage to the service spillway and emergency spillway, and why opportunities for intervention in the chain of conditions, actions, or inactions may not have been realized. Evaluations of actions, inactions, and decisions for the various stages of the project (pre-design, design, construction, operations, and maintenance) will consider the states of practice applicable to the various time periods involved.

Forensic Team

- John W. France, PE, D.GE, D.WRE – Team Leader and Geotechnical Engineer
- Irfan A. Alvi, PE – Hydraulic Structures Engineer and Human Factors Specialist
- Peter A. Dickson, PhD, PG – Engineering Geologist
- Henry T. Falvey, Dr.-Ing, Hon.D.WRE – Hydraulic Engineer
- Stephen J. Rigbey – Director, Dam Safety at BC Hydro, and Geological Engineer
- John Trojanowski, PE – Hydraulic Structures Engineer
California State Water Project

- Largest state owned and operated water system in the U.S.
- Multiple Purposes and Benefits
- Provides water supply and irrigation
- 32 Storage Facilities
  21 Pumping Plants
  4 Pumping-generating Plants
  8 Hydroelectric Plants
  700 miles of Canals and Pipelines
- Constructed in the 1960s and 1970s

Facility Description

- Embankment dam – 770-ft high, tallest dam in the United States
- Gate-controlled, concrete chute service spillway
- Uncontrolled, overflow emergency spillway
- Powerplant
- Designed and constructed in the 1960s
Oroville Dam

Regulatory Setting

- Both federal and state regulation:
  - California Division of Safety of Dams (DSOD) – State Government
Service Spillway (SS) Description

• Eight top-seal radial gates, each 17 ft 8 in wide x 33 ft 6 in high
• Concrete chute – 179 ft wide, 3,000 ft long, with drop of 500 ft
• Slopes of 5-2/3 % in upper chute and 24.5 % in lower chute
• Four chute clocks at downstream end of the chute
• ~300,000 cfs discharge for PMF
Emergency Spillway (ES) Description

- Uncontrolled overflow structure
- Two sections:
  - 930-foot long concrete gravity weir
  - 800-foot long broad-crested weir
- Maximum weir height of about 50 feet
- ~350,000 cfs discharge for PMF
SS Operation History

Emergency spillway had never operated

Incident Chronology

February 6-10, 12.8 inches of rain, historic flood record.
Spillway Chute Failure

Drain at Station 33+60

10:23 AM

Spillway Chute Failure

10:32 AM
Spillway Chute Failure

Gates Nearly Closed
Incident Chronology

Initial Damage – February 7

- 150 ft. Wide
- 450 ft. Long
- 30 ft. Deep
Initial Damage – February 7

Climb Team Inspection – February 8
Incident Chronology

Balancing Risks

- Additional SS Damage
- Emergency Spillway Operation
- Powerplant Flooding
- Power Transmission Towers
SS Discharge at 55,000 cfs - February 10-12

Flow Begins Over Emergency Spillway
February 11, AM
Incident Chronology

Headcutting Erosion at ES
February 12
Headcutting Erosion at ES
February 12

Evacuation – February 12 – ~ 190,000 People
Increased Flows Thru SS – 100,000 cfs

Erosion Debris in the River
Service Spillway Damage

Background Information

- SS chute design and construction
- SS chute repairs
- SS chute drain flows
SS Chute Design and Construction

- Nominal 15-inch thickness
- No waterstops in joints
- Dowels in joints
- Single layer of reinforcement near top of slab
- Lapped keys in transverse joints
- Keyed longitudinal joints
- VCP drains protruding into the slab
- Foundation anchors at 10-foot spacing, 5 feet into foundation
- 6-inch maximum size aggregate

Drain and Joint Details

- One layer of reinforcing at top
- Protruding drains
- No waterstops in joints
- Dowels
- Lap keyed joint
Herringbone Drains

Chute Slab Anchors

Anchors just below rebar
Comparison to 1960s Practice

• Within the range of other spillways of the time on rock, but generally in mid to low-mid range
• Drains protruding into section were at low end – less than 8 percent had protruding drains and none with as large a percentage of slab thickness
• Did not include typical details for soil foundations
• Not “best practices” of the time

SS Chute Foundations

• Foundation preparation requirements were dramatically relaxed during construction
• Conditions varied
• Areas of “compacted clayey fines”
• Areas of strongly weathered rock
• No adjustments were made in anchors or other chute design details
Foundation Preparation

ES Crest Structure

Foundation Preparation

SS Chute
Foundation Preparation

Photo 39. Chute foundation in vicinity of Sta. 33+60. Tile and gravel underdrains in lanes 2 and 3, rebar in lane 3. View southeast. 11-2-66
Foundation at Initial Chute Failure Location

Approximate outline of initial failure area
History of SS Chute Repairs

• Five documented repair programs
  – 1977
  – 1985
  – 1997
  – 2009
  – 2013

Crack Pattern in SS Chute

12. The concrete along the spillway chute has been repaired. The repaired herringbone crack pattern is said to reflect the underlying drain system.
SS Chute Repairs

- Cracks
- Spalls
- Delaminations
- Ruptured reinforcing bars

Spalls and Failed Prior Repairs
Ruptured Rebar

- Crack
- Ruptured Reinforcing Bars

SS Underdrain Flows

February 3, 2006
SS Underdrain Flows

- Drains flow heavily when SS is discharging
- Flow is from leakage through the slab into the foundation
  - Joints
  - Cracks
- Gates leak when closed

Physics of SS Damage
Contributory Physical Factors

- Foundation conditions (geology)
- Cracks in the slab
- Joints without waterstops
- Slab delaminations and spalling
- Corrosion and failure of reinforcing

Possible Changes Since 2006*

- New chute slab damage and/or deterioration of previous repairs
- Expansion of shallow voids below the slab
- Corrosion and failure of reinforcing or dowels across cracks and joints
- Reduction in anchor capacity

* Most recent previous discharge greater than 54,000 cfs
Factors Unlikely or Not Significant

- Cavitation
- Groundwater flow/pressure
- Seismic damage

What Happened – ES?
Contributory Physical Factors

• Areas of erodible rock (geology)
• Flow concentrations
  – Topography
  – Infrastructure
• Insufficient energy dissipation at crest structure
• No erosion protection downstream of crest structure

Why the Incident Happened

Result of interactions of numerous physical and human factors, beginning with the design of the project and continuing during the half-century until the incident
Why the Incident Happened – SS 1/2

• Incompatibility of as-constructed spillway with foundation and hydraulic conditions
  – Poor communication
  – Lack of adjustments during construction
• Chute slab cracking and drain flows were “normalized”
• Geology was misunderstood

Why the Incident Happened – SS 2/2

• Repairs were not sufficiently robust and durable
• Subsequent inspections and evaluations, including potential failure modes analyses (PFMAs), did not identify the vulnerability
  – No record of comprehensive review of original design, construction, and performance information
Normalization of Cracking and Underdrain Flows

- Cracking observed immediately after concrete placement
- Large drain flows observed during first spillway operation in 1969 – described as “mystifying” and ascribed to leakage through the slab
- Follow-up suggested, but not clear if there was follow-up
- Thereafter, cracking and drain flows were accepted as normal behavior

Durability of Repairs
Inspection and Evaluation History

• Inspections
  – Twice per year DSOD inspections
  – Annual FERC inspections
  – FERC Part 12D five-year inspections
  – California Director’s Dam Safety Reviews

• Potential Failure Modes Analyses (PFMAs)
  – 2004 and 2009 – no significant spillway PFMs
  – 2014 – spillway PFMs were considered

2014 PFMA

• PFMs identified for both SS and ES
• SS spillway PFMs:
  – Category IV, ruled out
  – Focus on release of reservoir water
  – Not whether chute would fail, but rather, if chute failed, would reservoir be released
  – Influenced by misunderstanding of geology
• ES spillway PFMs:
  – Dominated by misunderstanding of geology – discussed later
Why the Incident Happened - ES

• Misunderstanding of geology
  • 2005 memo
    » “Spillway does not empty onto a bare dirt hillside. Instead, it empties onto a hillside composed of solid amphibolite bedrock extending from the spillway crest down to the Feather River”
    » “…Emergency Spillway at Oroville Dam is a safe and stable structure founded on bedrock that will not erode.”
  • 2009 report
    » “The rock between the Feather River and the emergency spillway is very competent and resistant to erosion.”

• Incident management
  – Not trying to second guess; rather review decision process to learn
  – Relative risk of trade-offs may not have been fully informed
  – Dam safety risk of emergency spillway operation may not have been fully recognized
Balancing Risks

Additional SS Damage
Emergency Spillway Operation
Powerplant Flooding
Power Transmission Towers

Why the Incident Happened - ES
Specific decisions were made to limit service spillway flows, when threat from tailwater was actually diminishing
Lessons to be Learned

• General industry lessons
  – Importance of “top-down” dam safety culture and program
  – Limitations of physical inspections
  – Need for comprehensive reviews
  – Need for appropriate attention to appurtenant structures
  – Shortcomings of current PFMA practices
  – Over reliance on regulatory compliance

Dam Safety Culture and Program

• Identified senior executive responsible for dam safety
• Informed by regular communication from dedicated dam safety professionals
Limits of Physical Inspections

- Latent conditions below the surface cannot always be identified by physical inspection
- Knowledge of design, construction, and performance needed
- Additional investigations may be needed

Comprehensive Reviews

- Review of design, construction, and performance against current state of practice and knowledge
- Questions to ask:
  - Consistent with current practice?
  - If not, do differences pose risks?
  - If there is not enough information to know, does possible risk justify further investigation
Attention to Appurtenant Structures

- Sometimes eclipsed by main dam
- Evaluation should be commensurate with risks
- May require specialized qualifications

Potential Shortcomings of PFMAs

- Focus on uncontrolled release of the reservoir
- A PFM categorization can be dominated by a single factor (e.g. geology for Oroville Dam spillways)
- Dependent on team members’ knowledge and experience
Reliance on Regulatory Programs

- Focused on uncontrolled release of reservoir
- May not address risks from component failures short of release
- Compliance may not fulfill owner’s legal responsibilities

Independent Forensic Team Report
Oroville Dam Spillway Incident

- Google “Oroville Dam forensic report”
Thank You!