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

John W. France, PE, D.GE, D.WRE
JWF Consulting LLC

Maryland Dam Safety Training
14 November 2018

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

Oroville 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

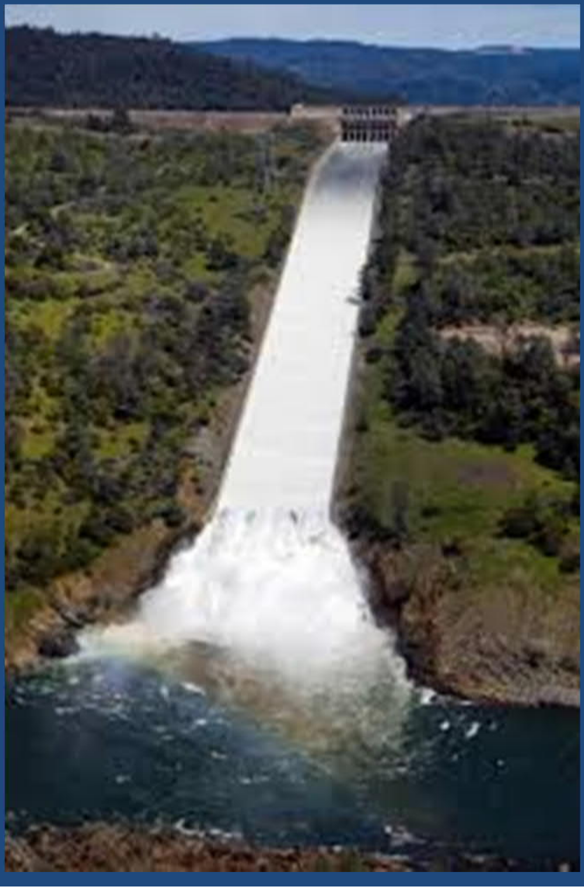
Regulatory Setting

- Both federal and state regulation:
  - Federal Energy Regulatory Commission (FERC) – US Federal Government
  - 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

Service Spillway

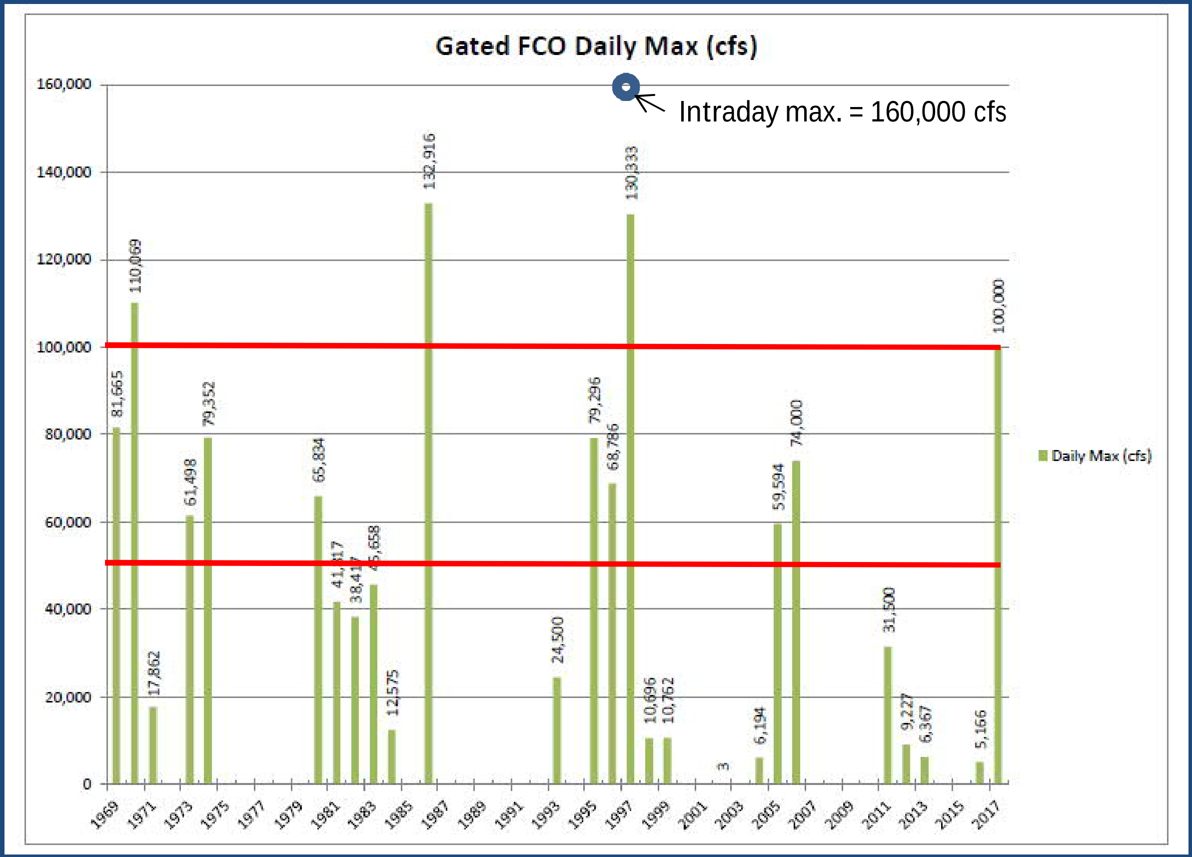


Emergency Spillway (ES) Description

- 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

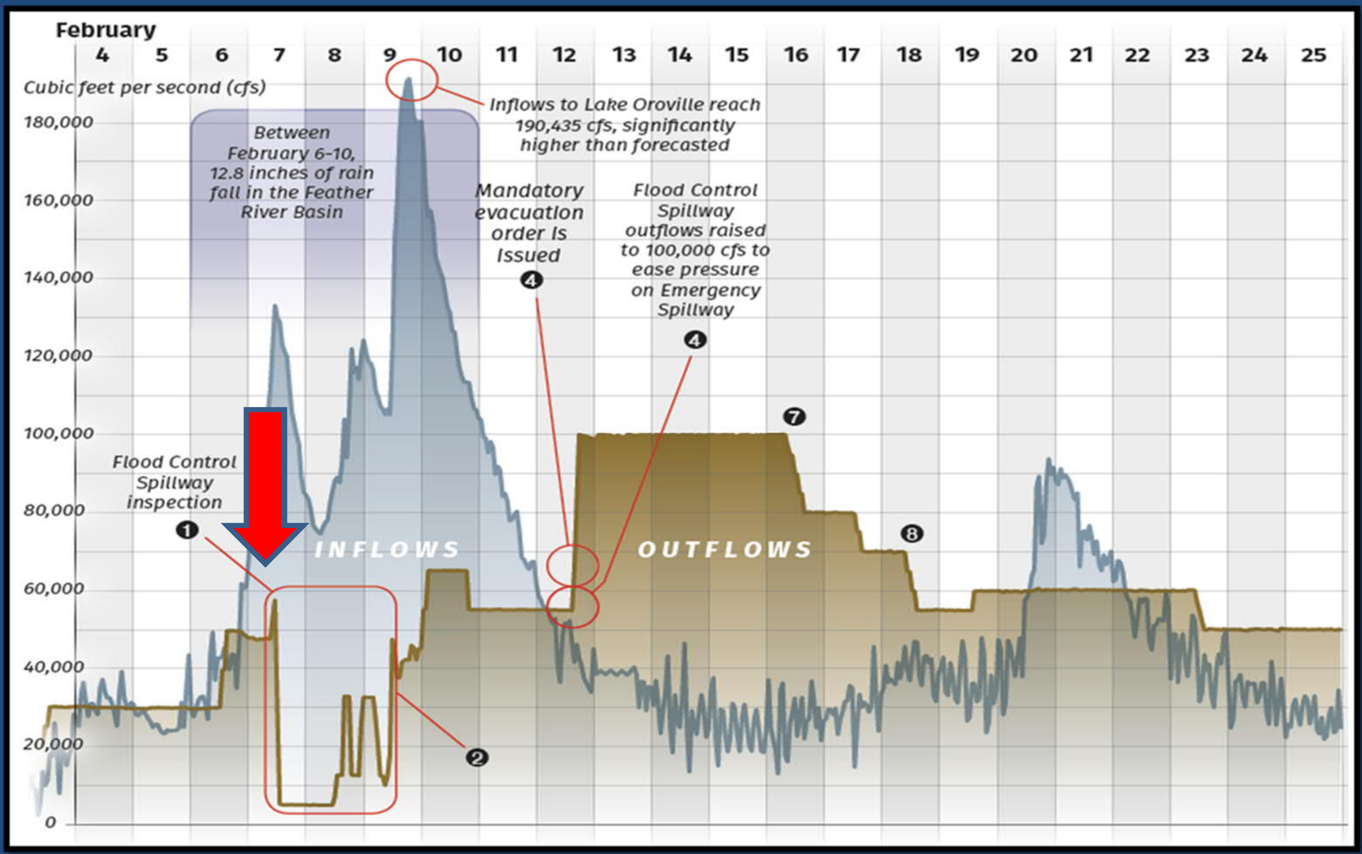
Emergency Spillway

SS Operation History

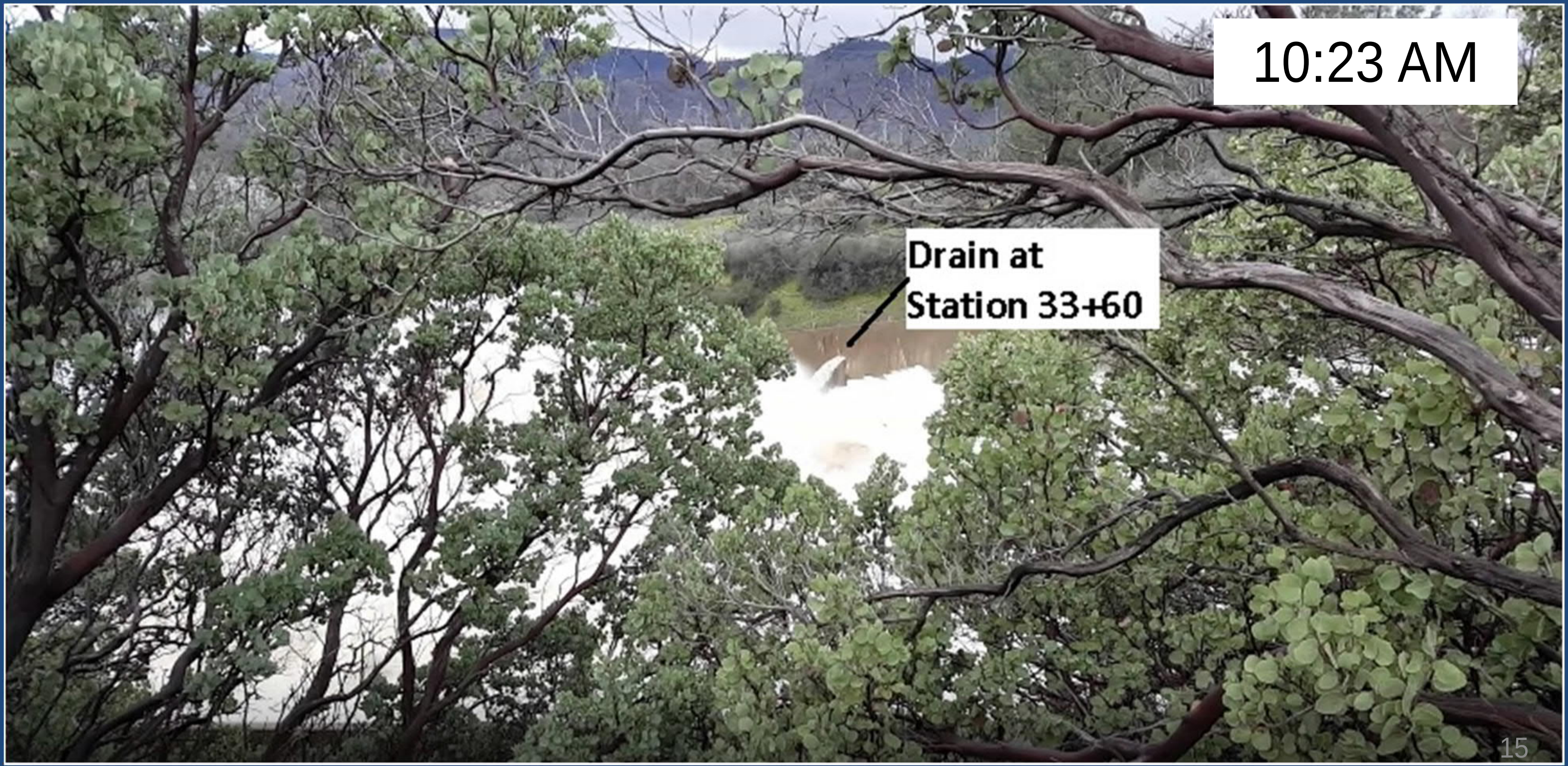


Emergency spillway had never operated

Incident Chronology

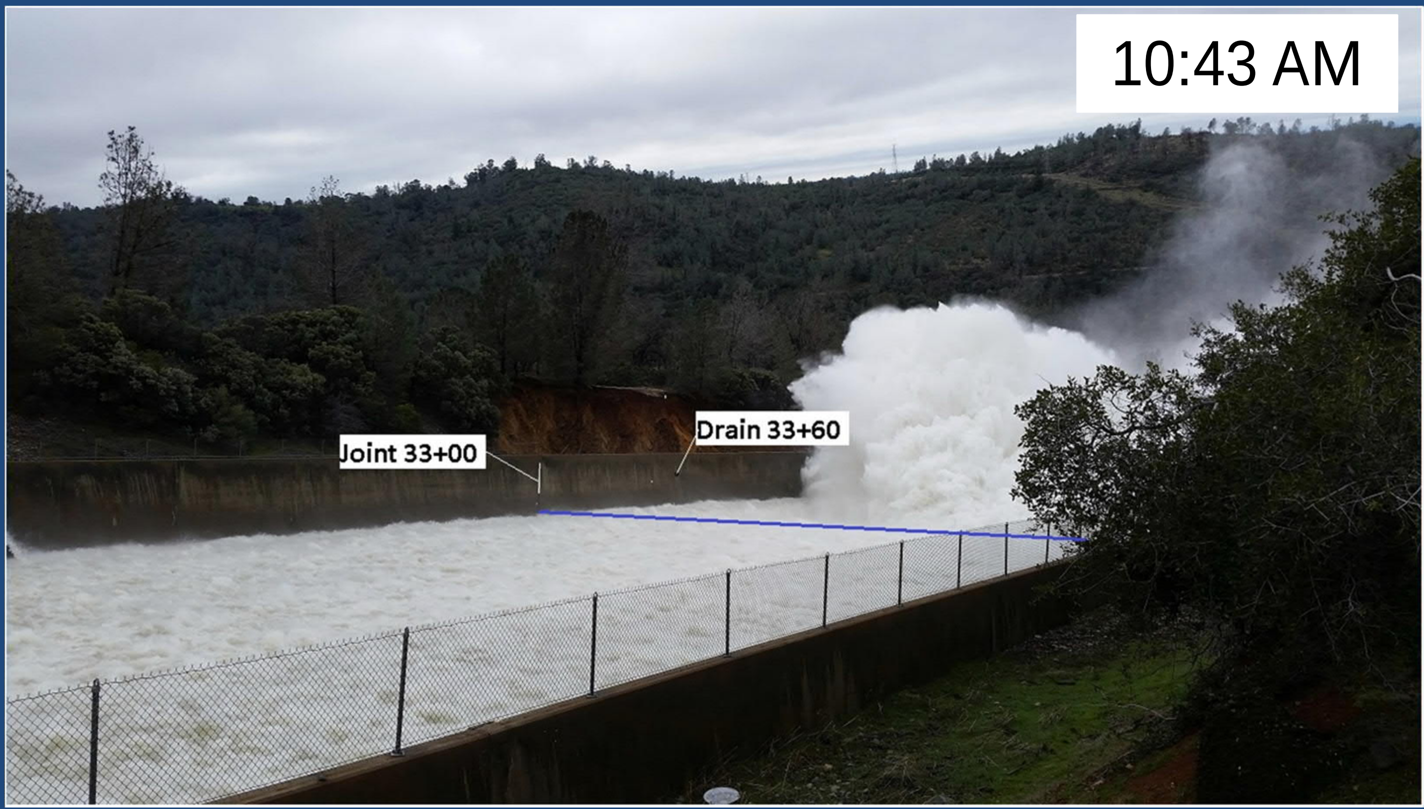


Spillway Chute Failure



Spillway Chute Failure

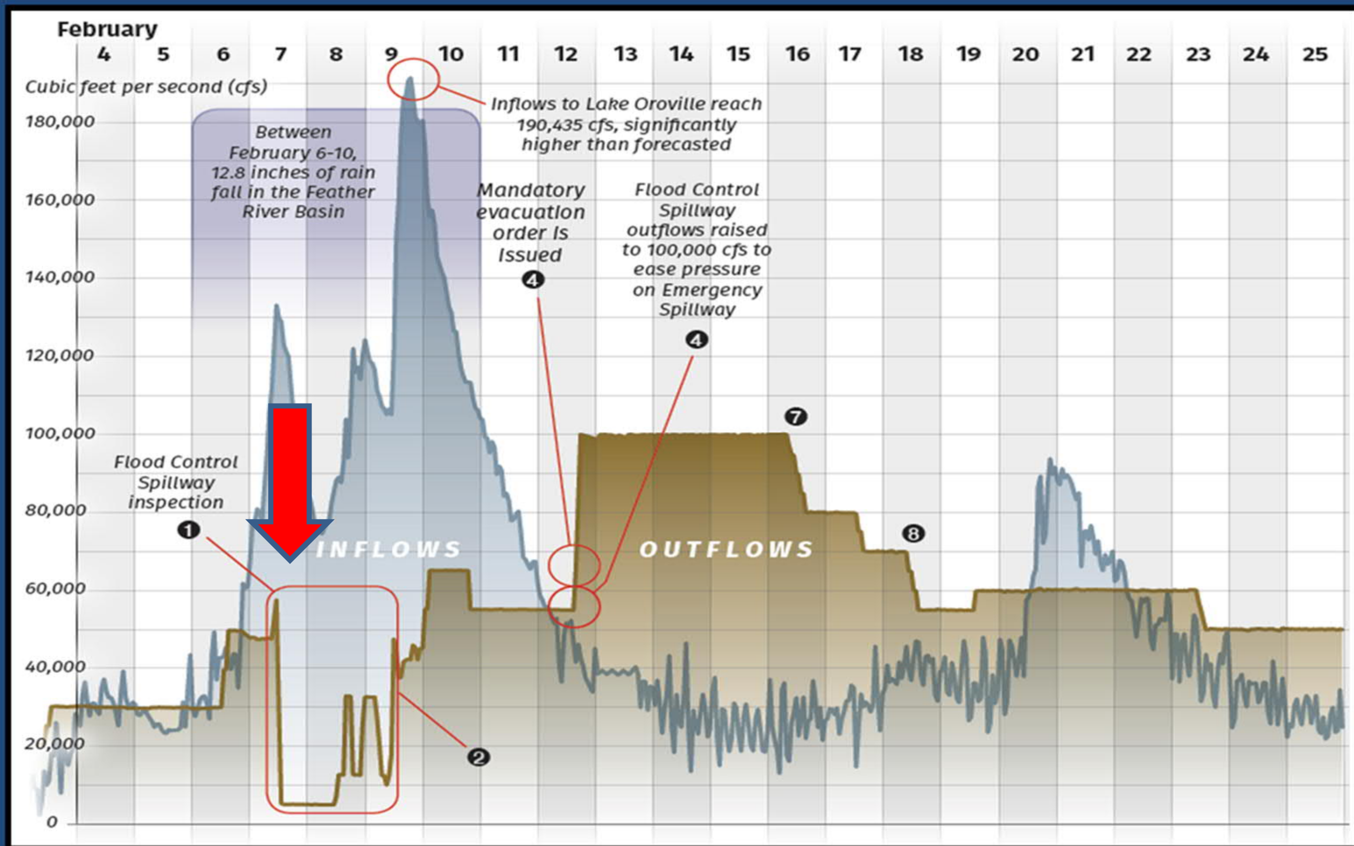
Spillway Chute Failure



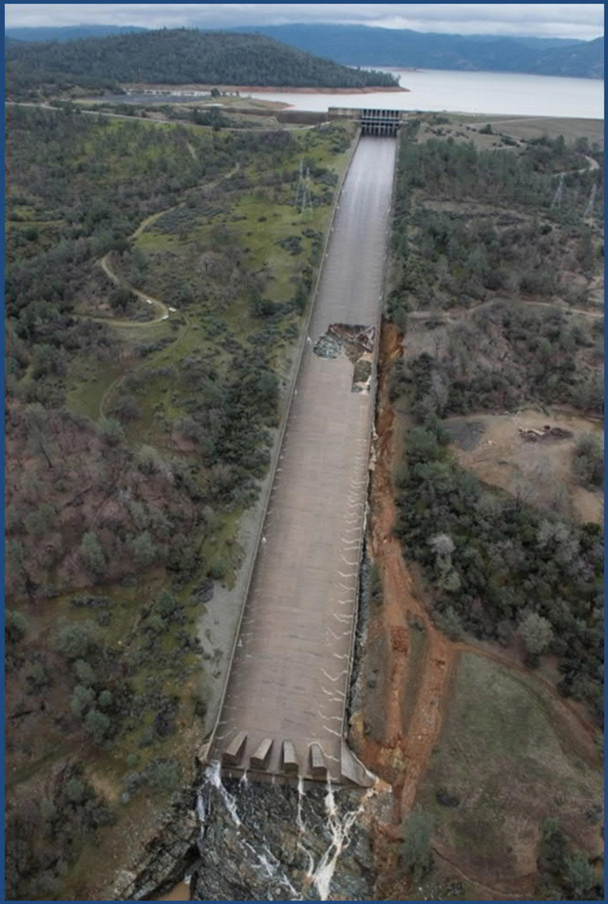
Spillway Chute Failure

Gates Nearly Closed

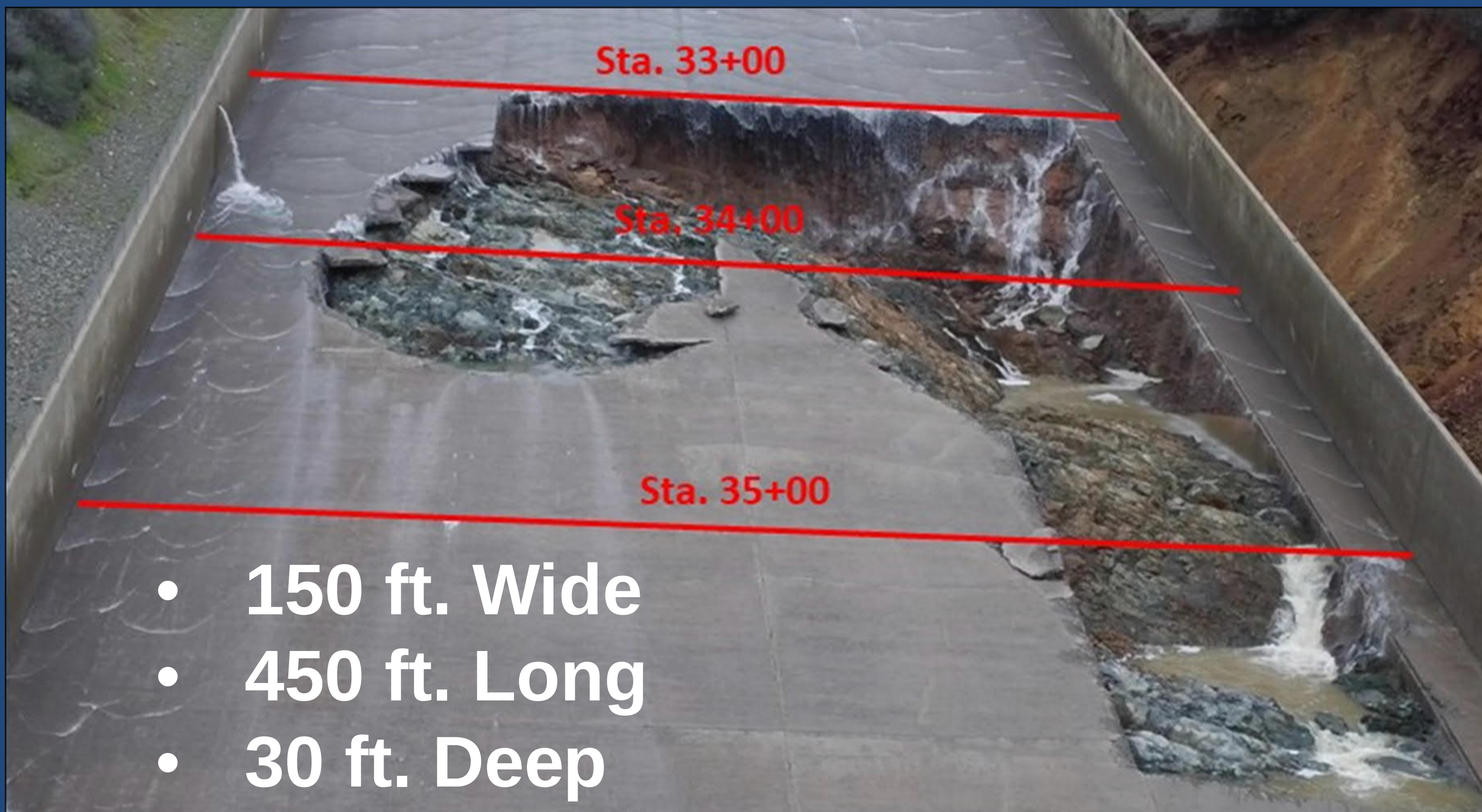
Incident Chronology



Initial Damage – February 7

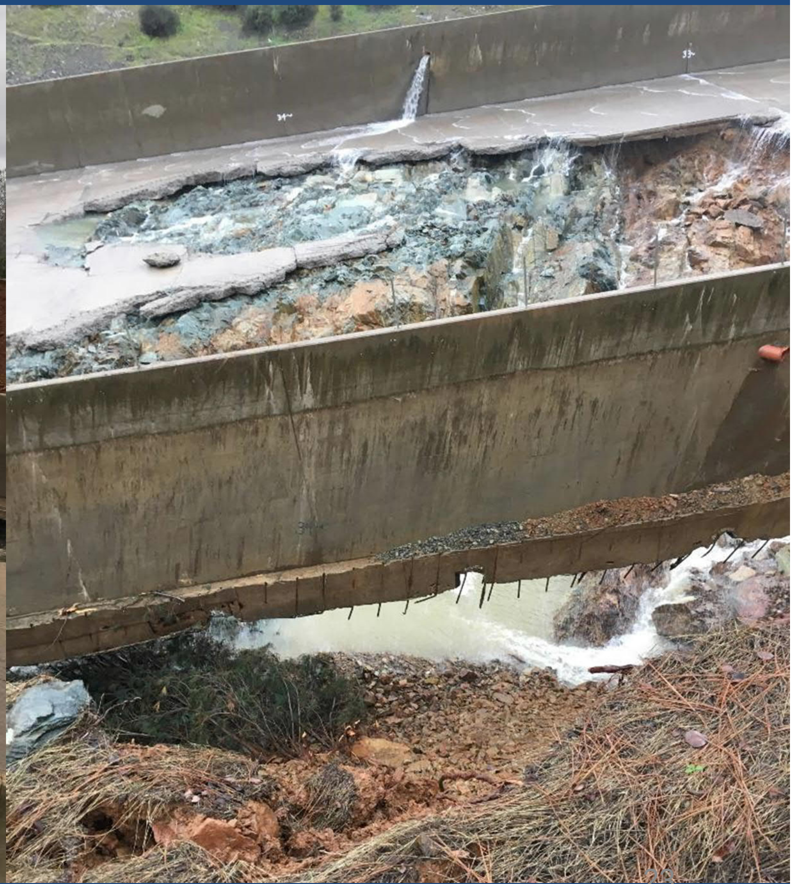


Initial Damage – February 7



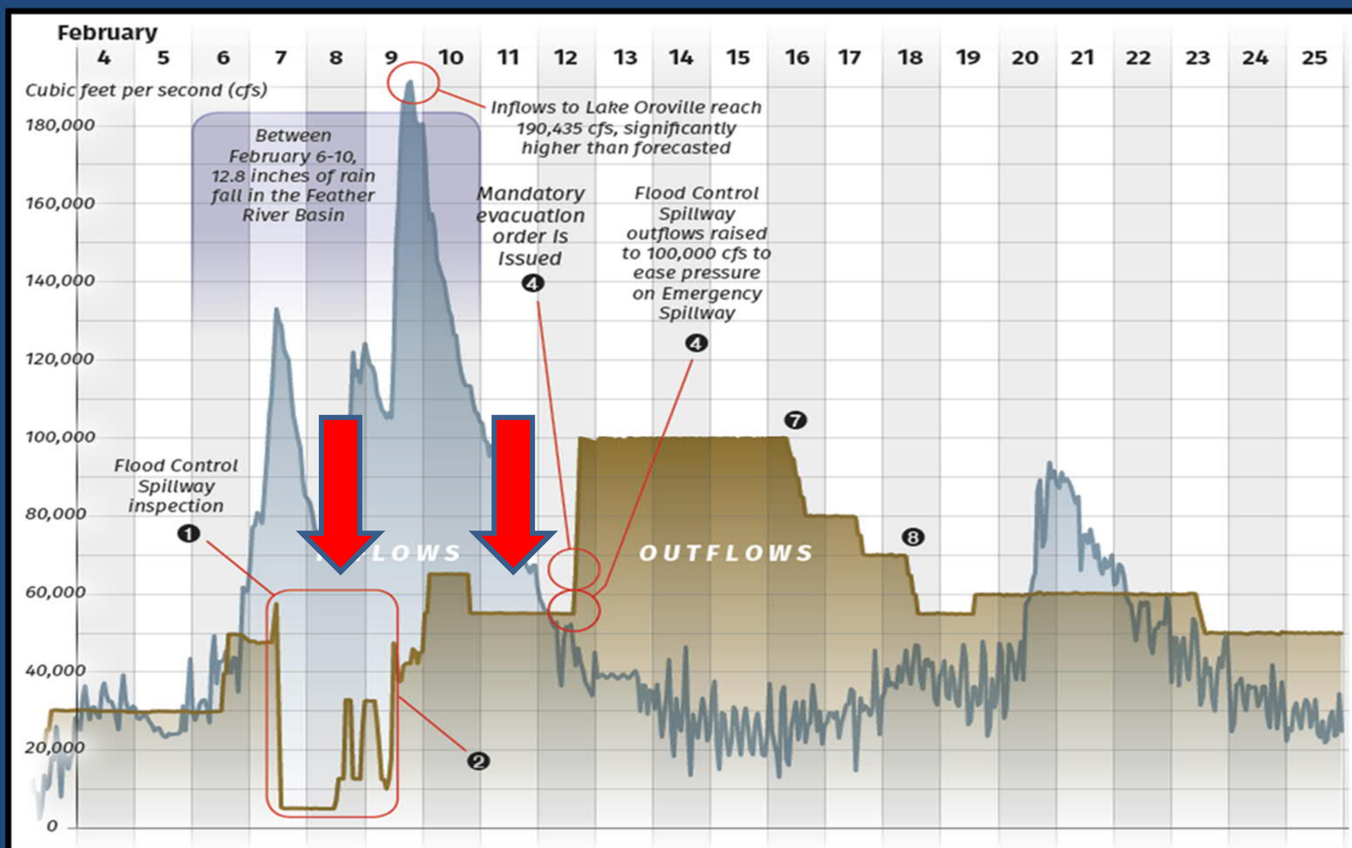
- 150 ft. Wide
- 450 ft. Long
- 30 ft. Deep

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

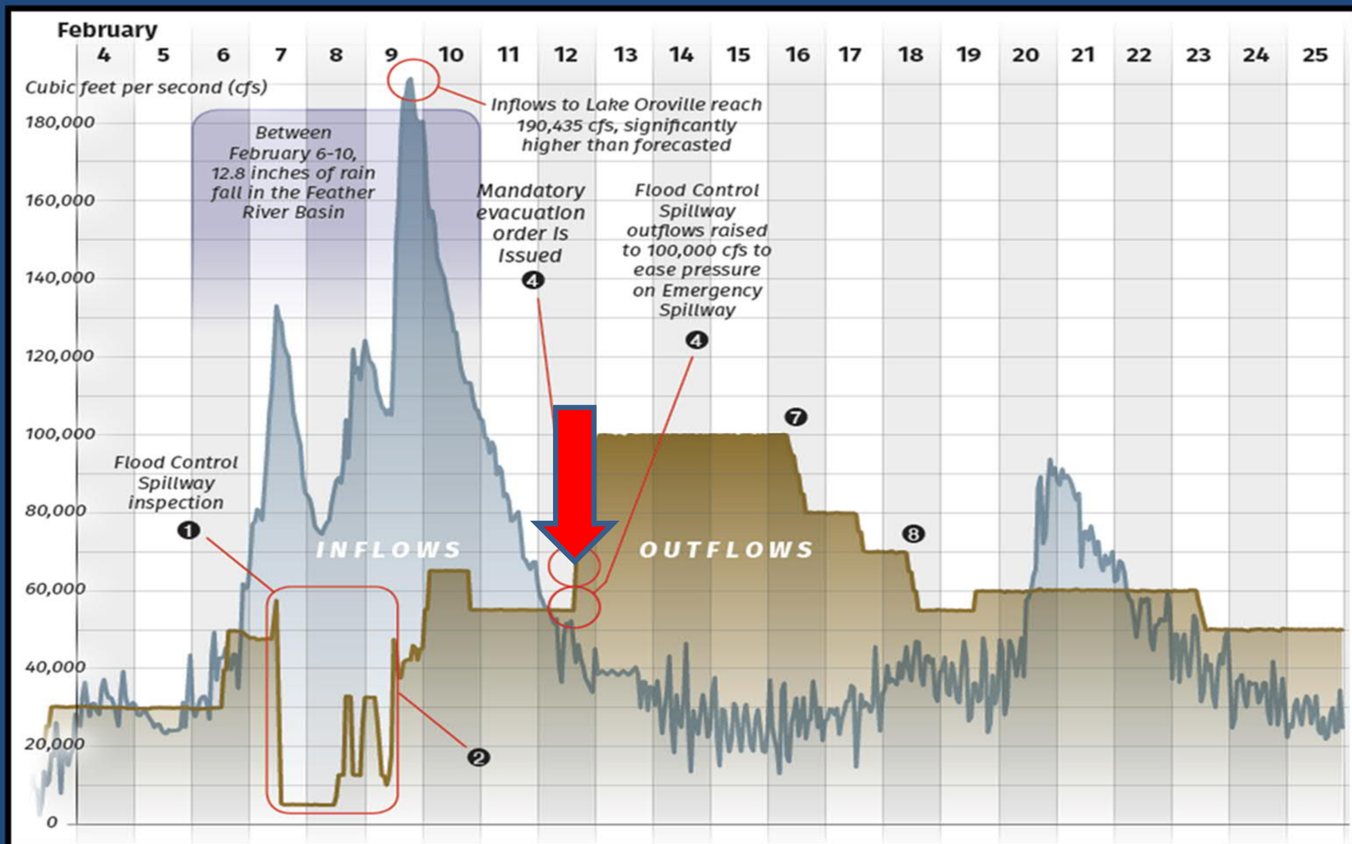
Flow Begins Over Emergency Spillway

February 11, AM

Flow Begins Over Emergency Spillway

February 11, AM

Incident Chronology

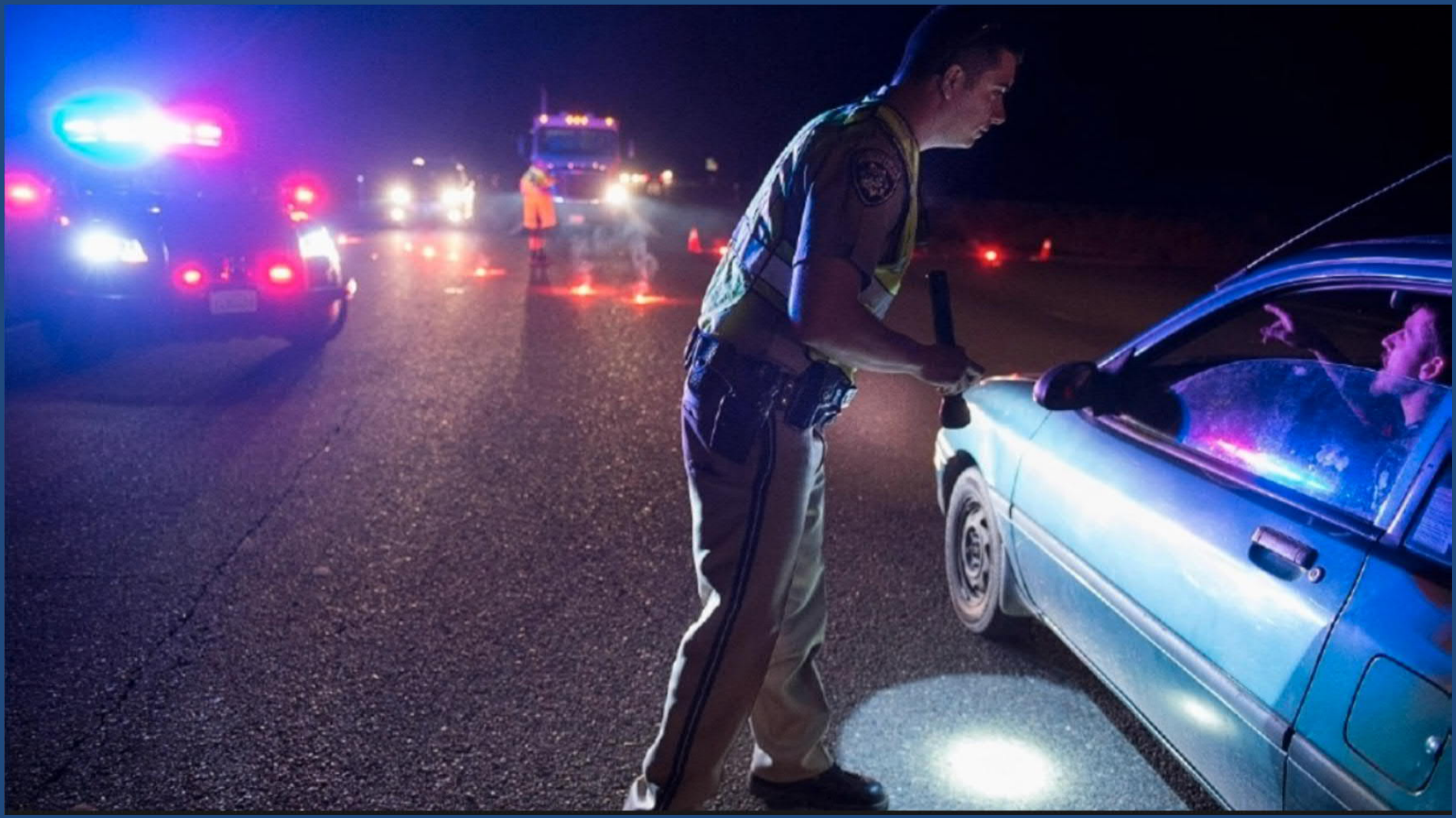


Headcutting Erosion at ES
February 12

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

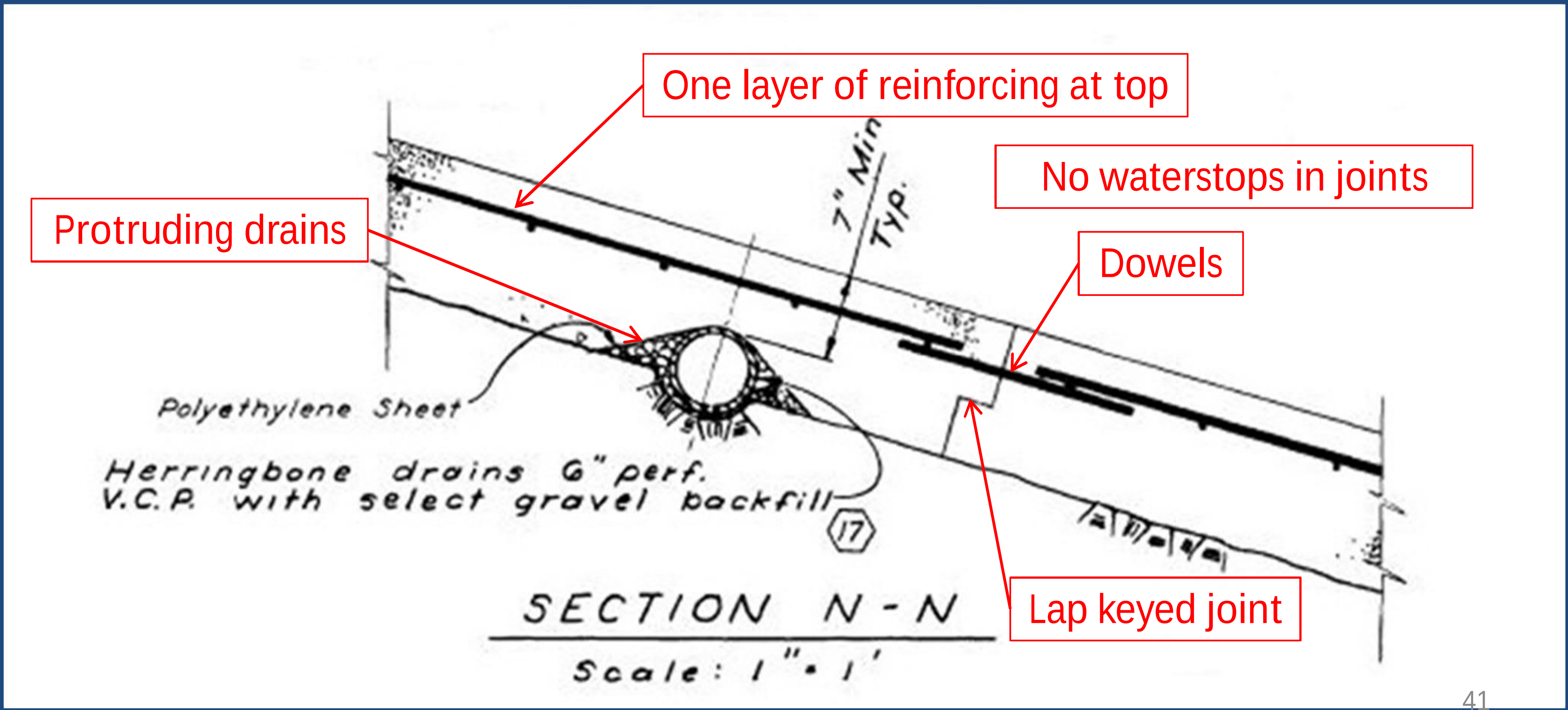
- SS chute design and construction
- SS chute repairs
- SS chute drain flows

SS Chute Design and Construction

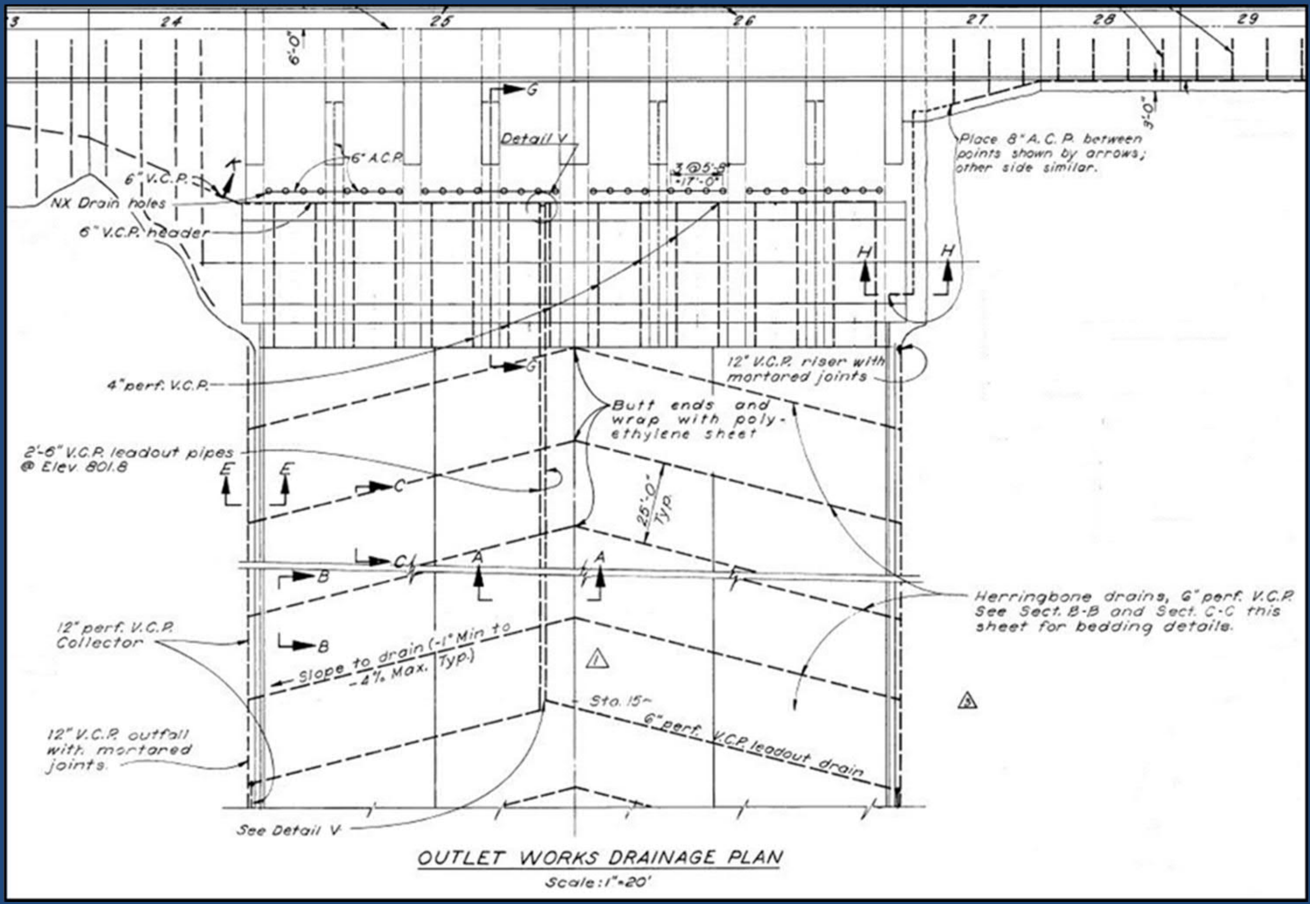
- Nominal 15-inch thickness
- No waterstops in joints
- Dowels in joints
- Single layer of reinforcement near top of slab
- Lapped keys in transverse joints
- Keyed longitudinal joints
- VCP drains protruding into the slab
- Foundation anchors at 10-foot spacing, 5 feet into foundation
- 6-inch maximum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

Slipforming

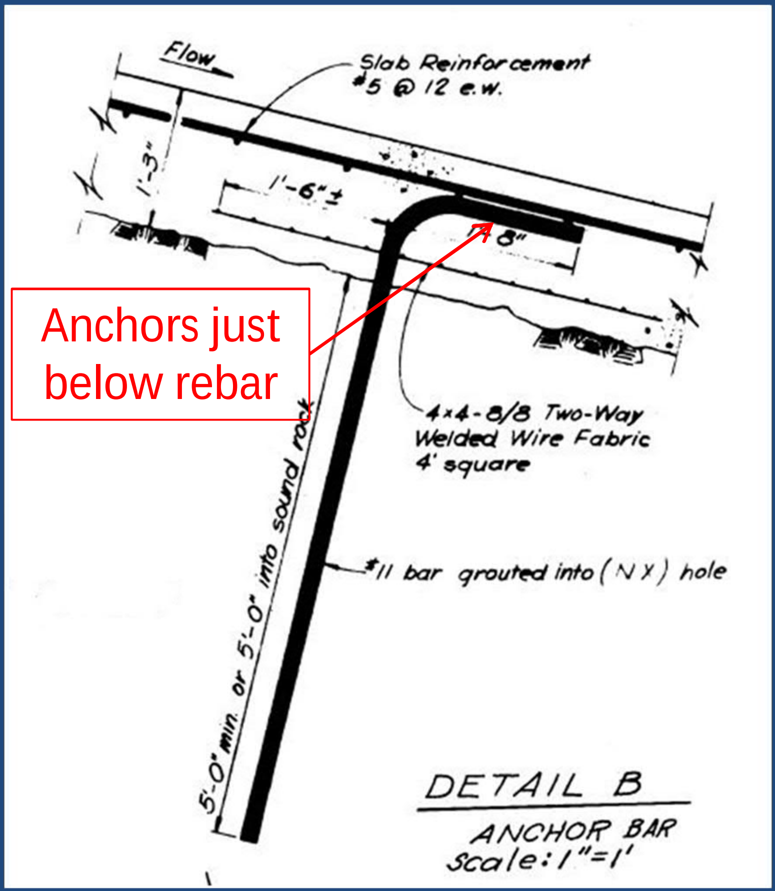
Drain and Joint Details



Herringbone Drains



Chute Slab Anchors



Practice of the 1960s

- Compared Oroville chute design to 110 designs from between 1955 and 1975
- Numerous factors considered:
  - Slab thickness
  - Joint details
  - Reinforcing
  - Dowels
  - Drains

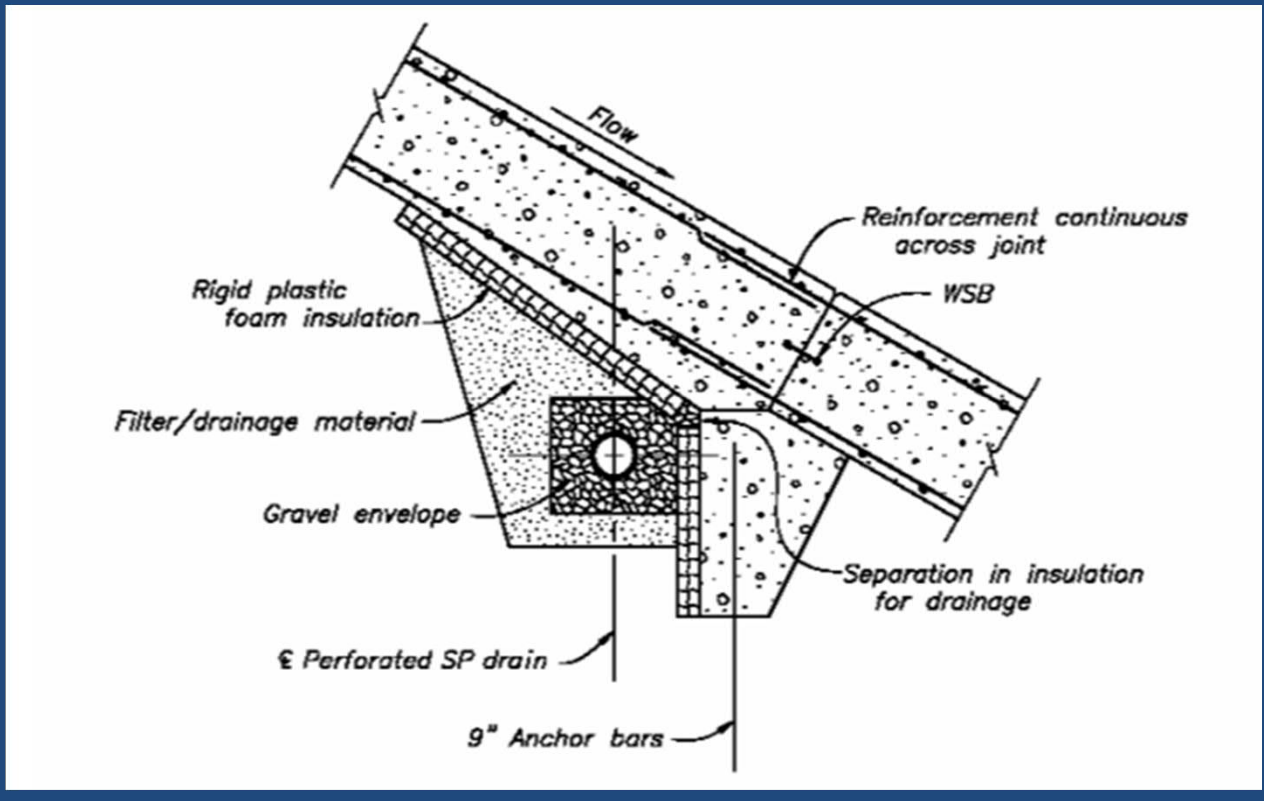
Results for 1960s Comparison

Feature	Designs Reviewed	Oroville
Slab thickness	8” to 48” (12” to 18”)	15”
Keyed joints	75%	Yes
Joint waterstops	35%	No
Cutoffs	66%	No
Two layers of rebar	69%	No (one layer at top)
Continuous rebar at joints	24%	No
Dowels at joints	35%	Yes
Anchors	79%	Yes
Drains	95%	Yes
Drains entirely below slab	87% (92% of those w/ drains	No

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

Modern Best Practices for Spillway Chute Joint and Drain Design



Design Shortcomings Further Compromised During Construction

- 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

Foundation Preparation

Foundation Preparation

Foundation Preparation

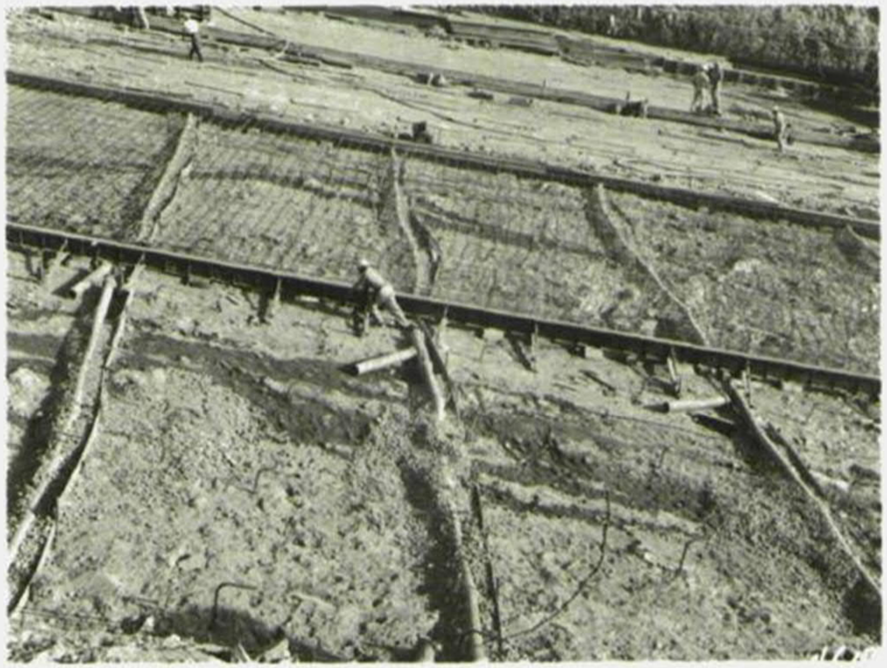
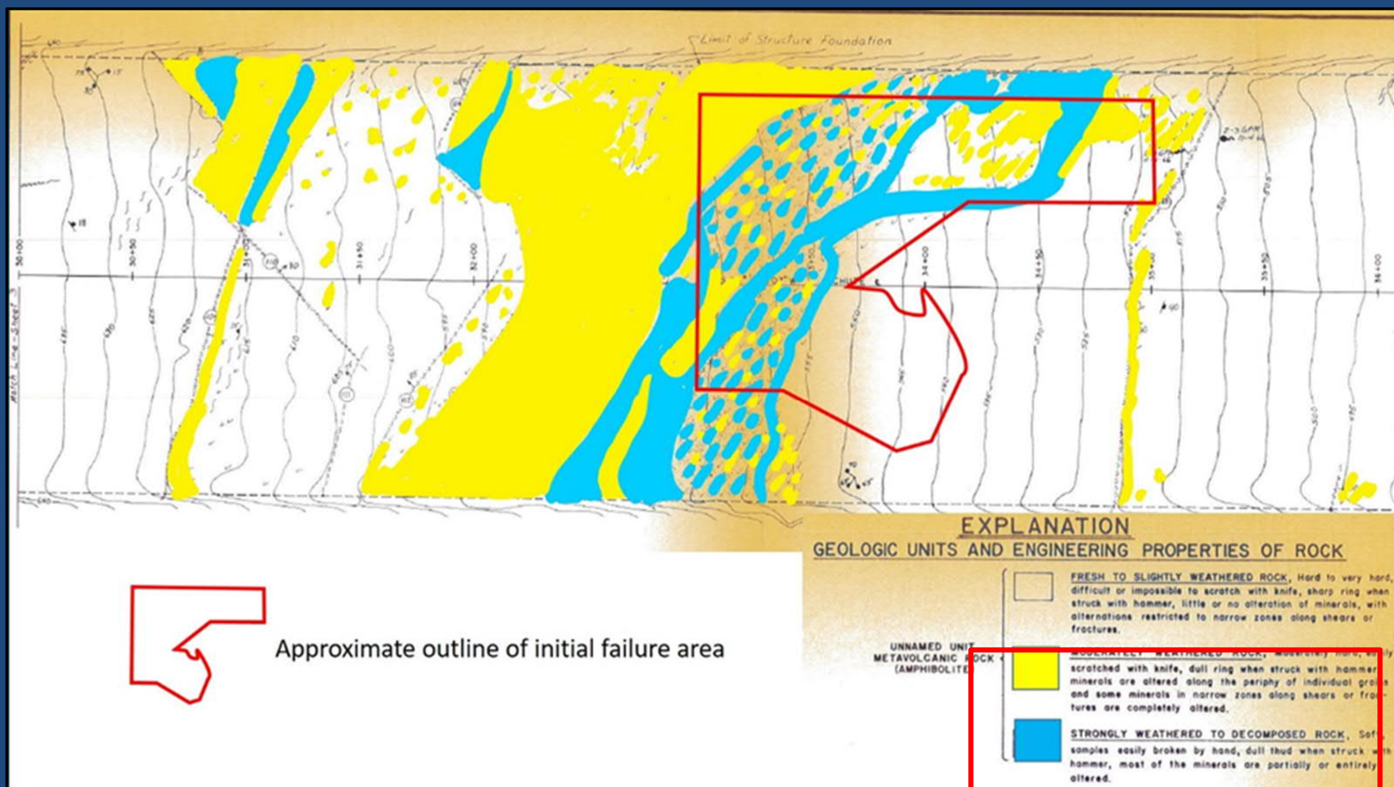
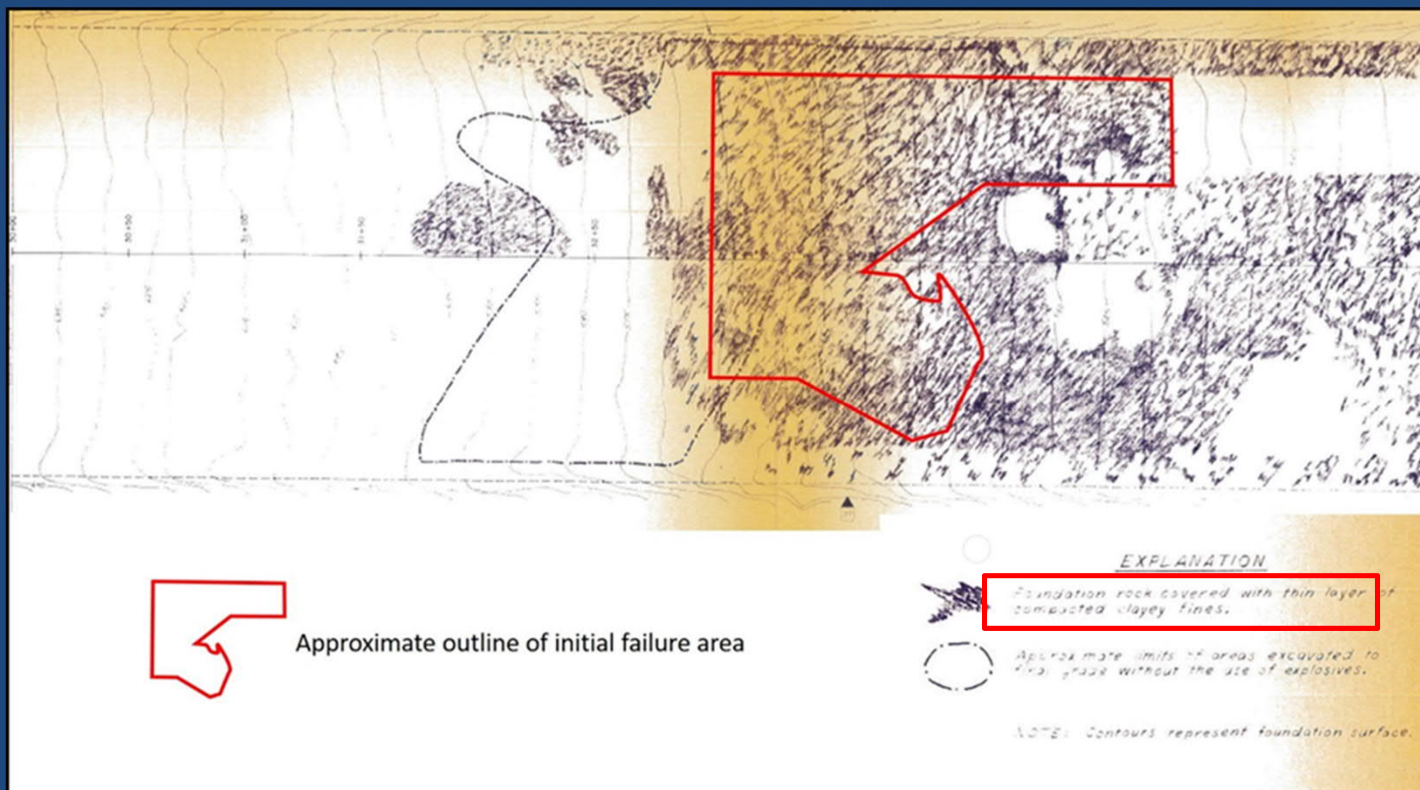


Photo 39. Chute foundation in vicinity of Sta. 33+60. Tile and gravel underdrains in lanes 2 and 3, rebar in lane 3. View southeast.
Neg. No. 4644 11-2-66

Foundation at Initial Chute Failure Location



Foundation at Initial Chute Failure Location



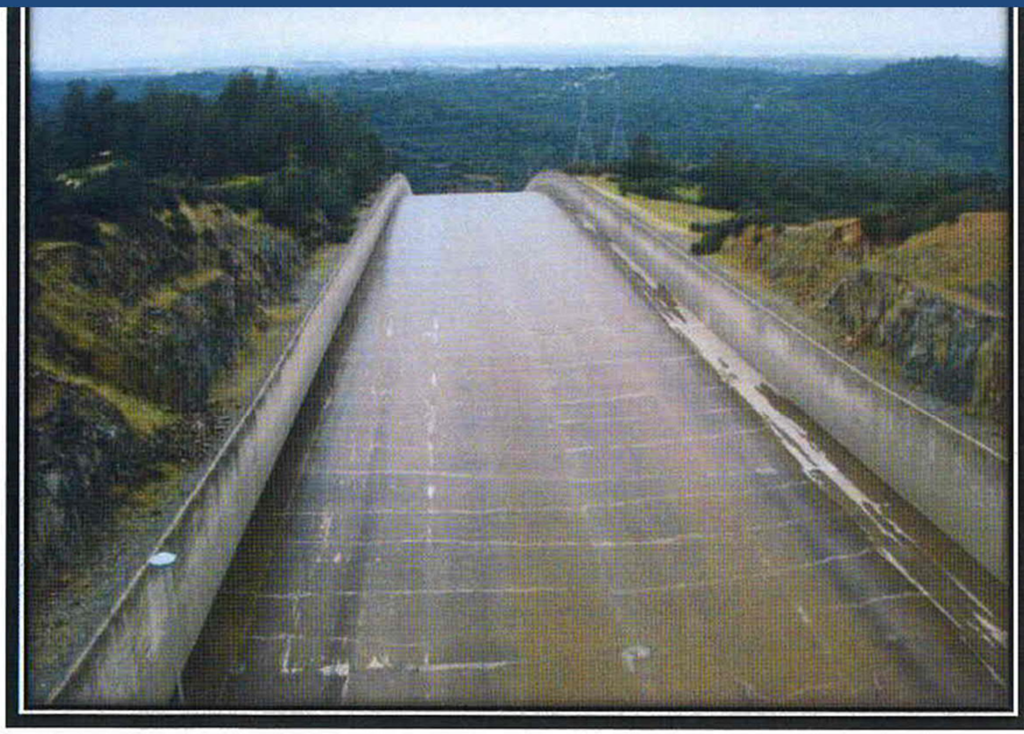
History of SS Chute Repairs

- Five documented repair programs
  - 1977
  - 1985
  - 1997
  - 2009
  - 2013

SS Chute Repairs

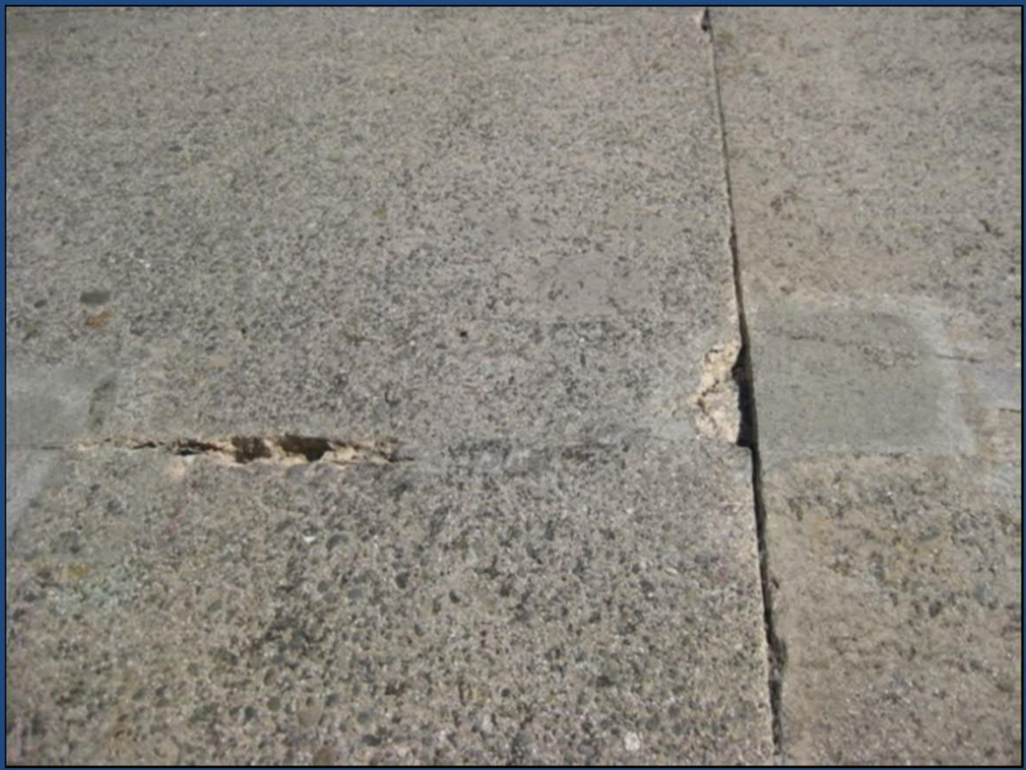
- Cracks
- Spalls
- Delaminations
- Ruptured reinforcing bars

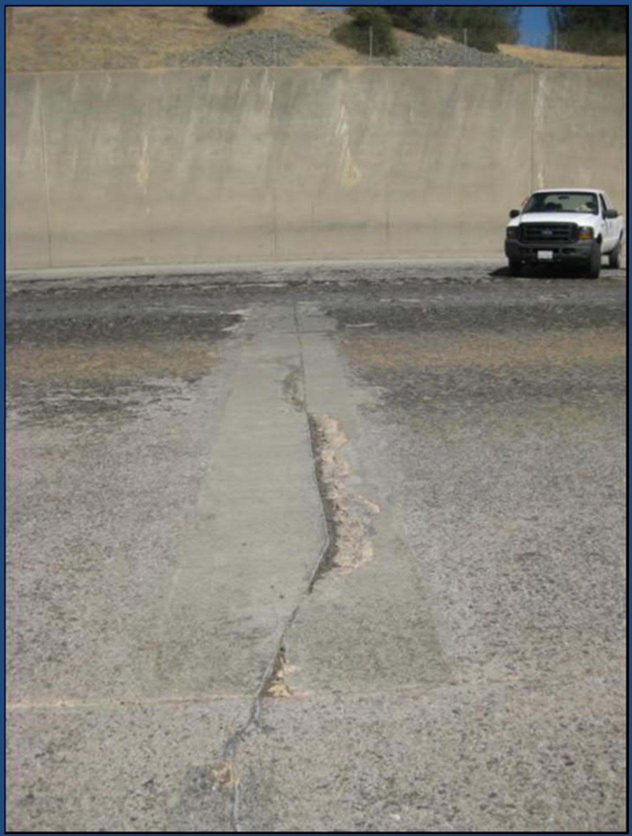
Crack Pattern in SS Chute



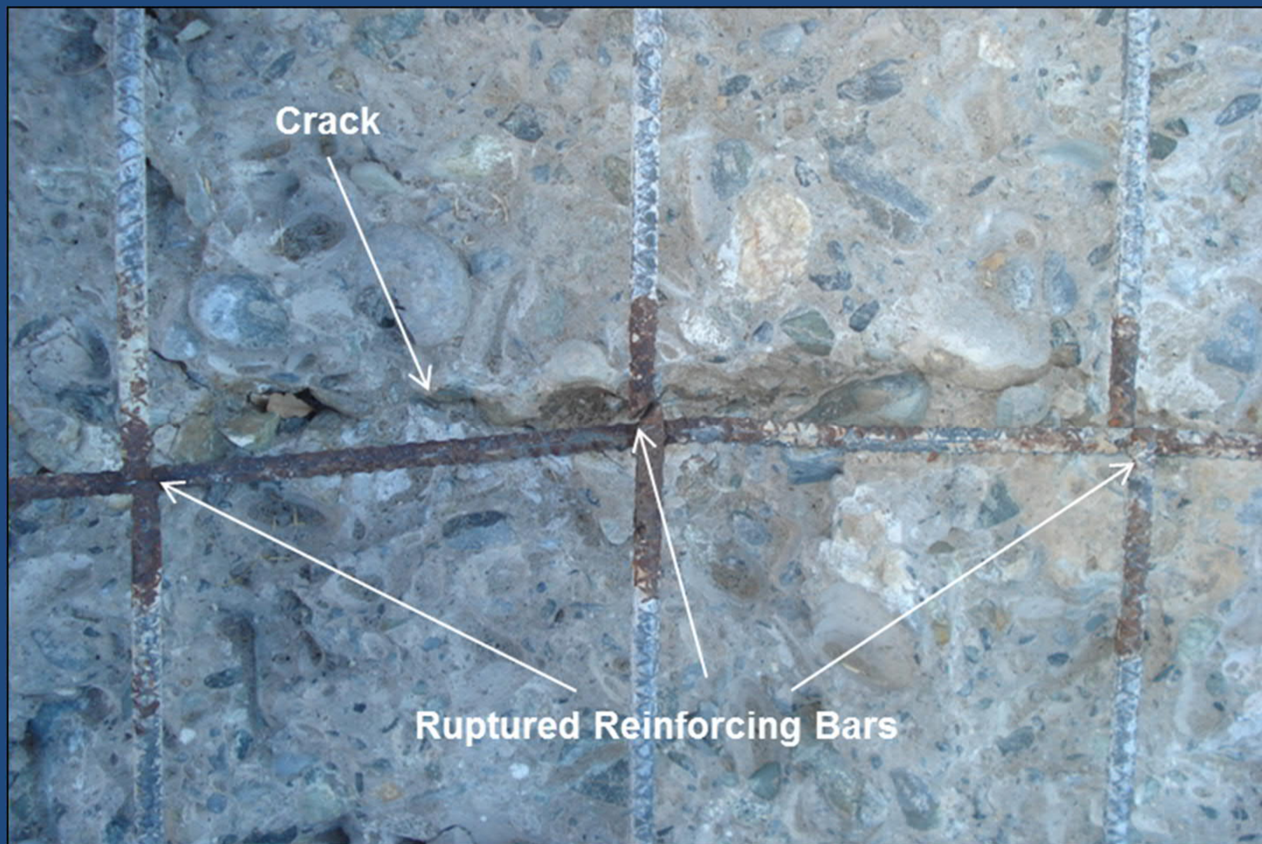
12. The concrete along the spillway chute has been repaired. The repaired herringbone crack pattern is said to reflect the underlying drain system.

Spalls and Failed Prior Repairs





Ruptured Rebar



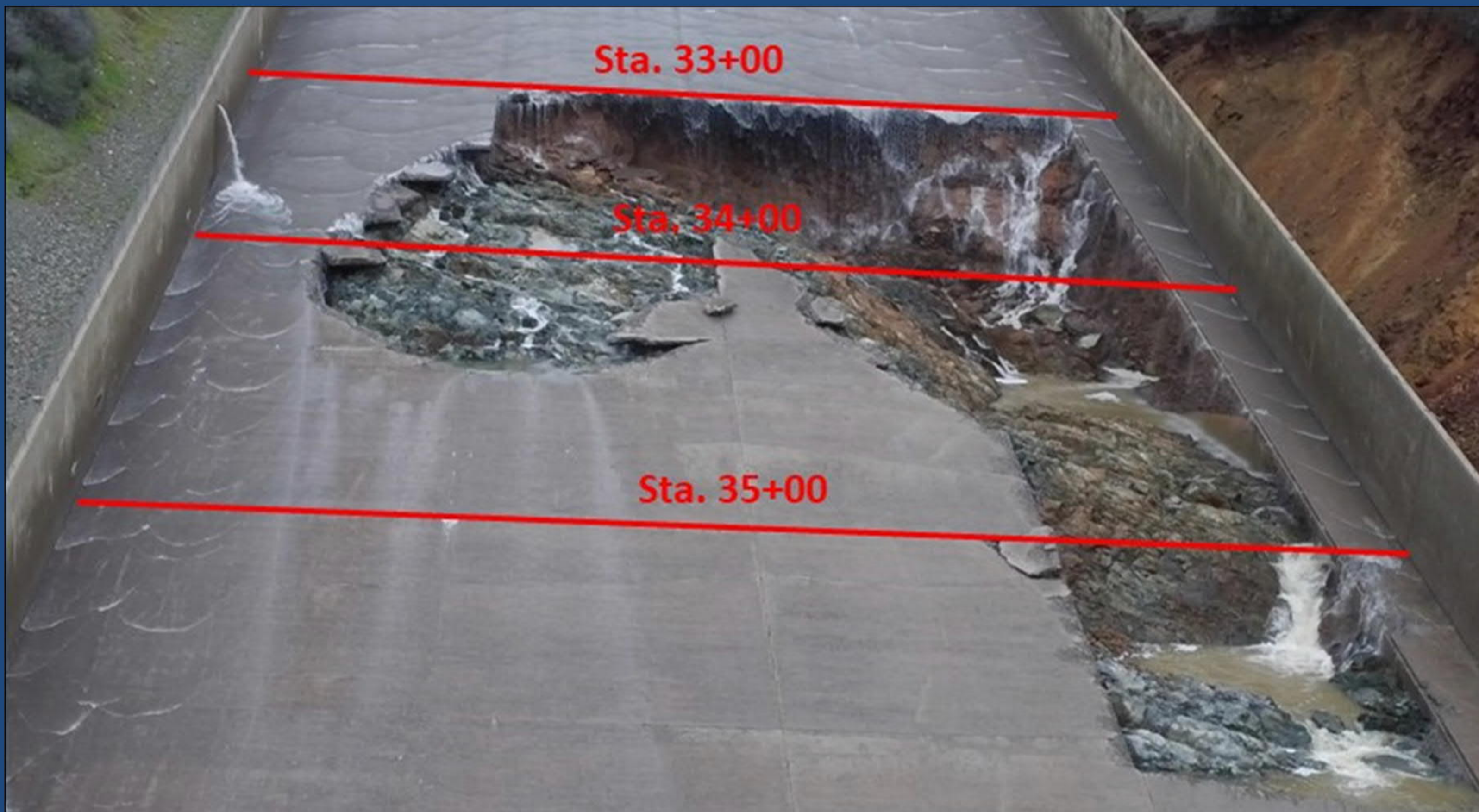
SS Underdrain Flows

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?

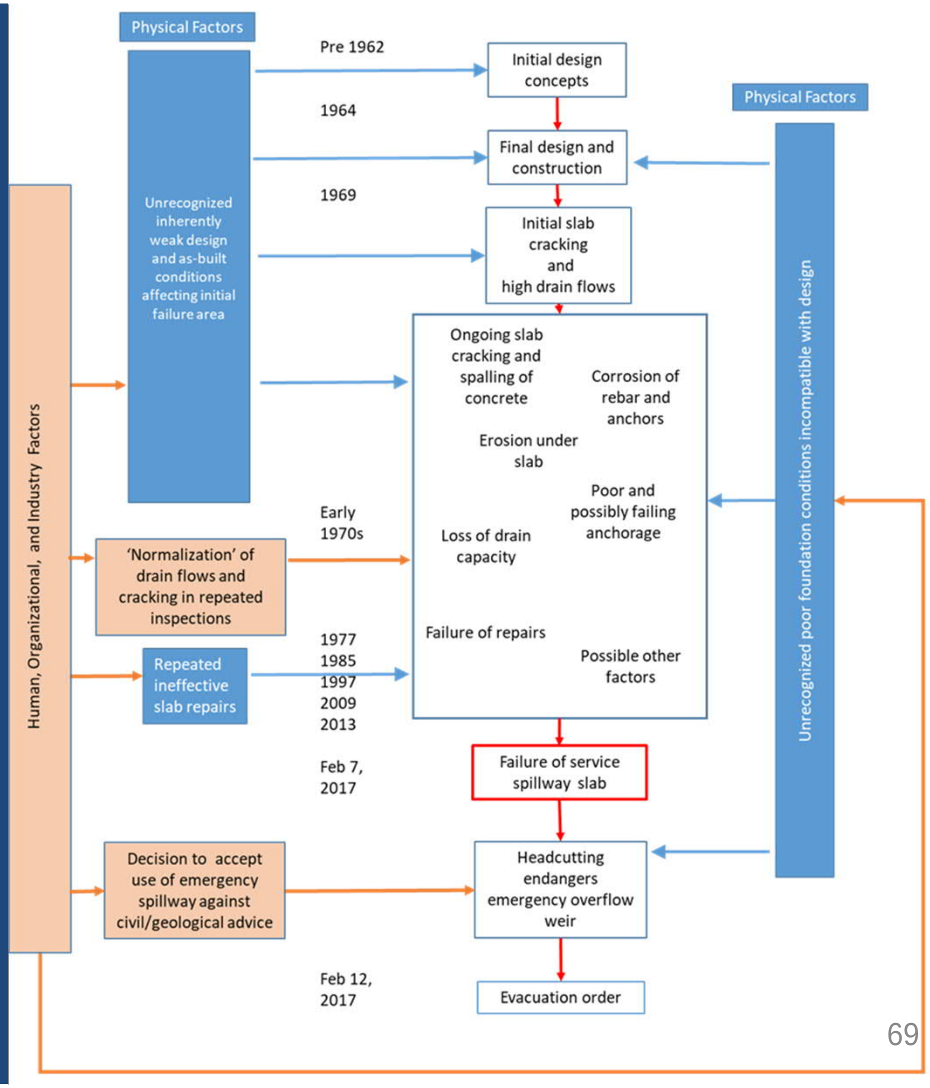
Contributory Physical Factors

- Unfavorably oriented 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

The Oroville Dam spillway incident was caused by a long-term systemic failure of the California Department of Water Resources (DWR), regulatory, and general industry practices to recognize and address inherent spillway design and construction weaknesses, poor bedrock quality, and deteriorated service spillway chute conditions. The incident cannot reasonably be “blamed” mainly on any one individual, group, or organization.

Timeline



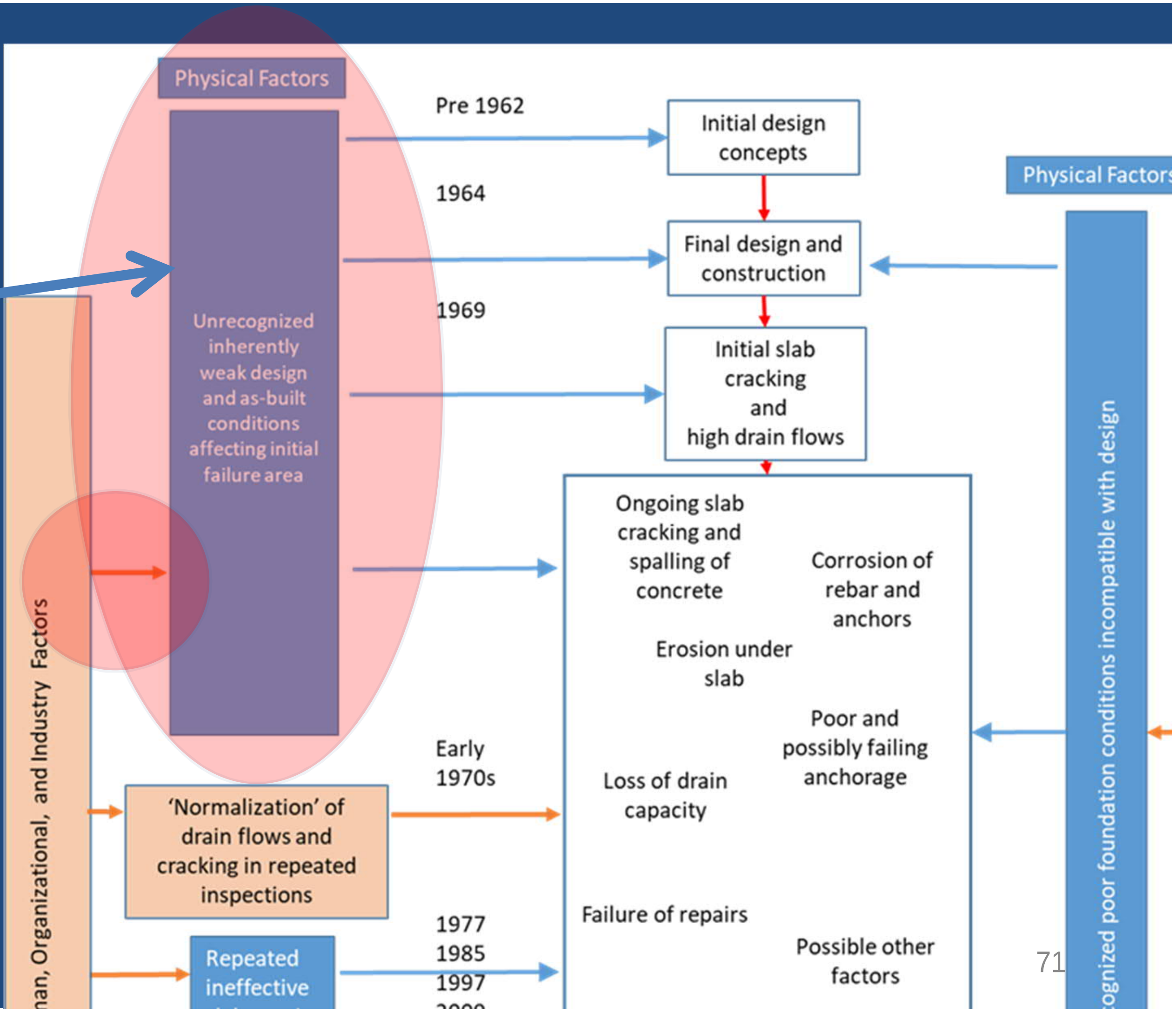
Physical Factors
Unrecognized inherently weak design and as-built conditions affecting initial failure area
Pre 1962
Initial design concepts
1964
Final design and construction
1969
Initial slab cracking and high drain flows
Physical Factors
Unrecognized poor foundation conditions incompatible with design
Human, Organizational, and Industry Factors
Ongoing slab cracking and spalling of concrete
Corrosion of rebar and anchors
Erosion under slab
Poor and possibly failing anchorage
Loss of drain capacity
Failure of repairs
Possible other factors
Early 1970s
'Normalization' of drain flows and cracking in repeated inspections
Repeated ineffective slab repairs
1977
1985
1997
2009
2013
Feb 7, 2017
Failure of service spillway slab
Decision to accept use of emergency spillway against civil/geological advice
Headcutting endangers emergency overflow weir
Feb 12, 2017
Evacuation order

Why the Incident Happened – SS

- Incompatibility of as-constructed spillway with foundation and hydraulic conditions
- Chute slab cracking and drain flows were "normalized"
- Geology was misunderstood
- Repairs were not sufficiently robust and durable
- Subsequent inspections and evaluations, including potential failure modes analyses (PFMAs), did not identify the vulnerability

Timeline

- Thin slab
- Protruding drains
- No waterstops
- Incompatible with foundation



Comparison to 1960s Practice

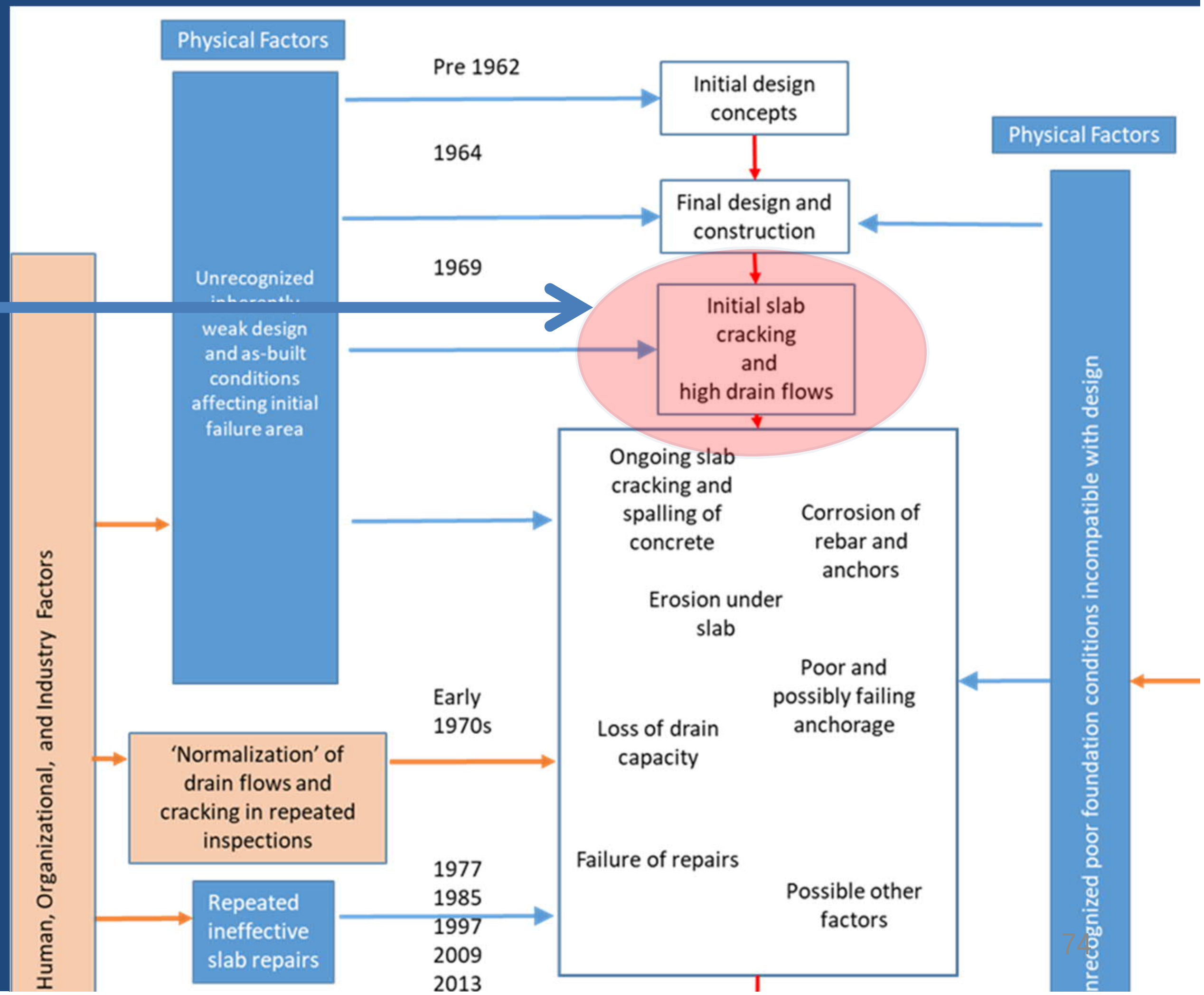
- Within the range of other chute spillways of the time on rock, but generally in mid to low-mid range
- Drains protruding into section were at low end – 8^{th} percentile
- Did not include typical details for soil foundations
- Not “best practices” of the time

Service Spillway Design and Construction

- Poor Communication During Design and Construction
  - Geologist and designer(s) did not communicate
  - Construction team and designer(s) did not communicate
  - Not atypical of the era, but very problematic
  - Design for rock, but overexcavation not understood
  - Lack of adaptation/consultation during construction

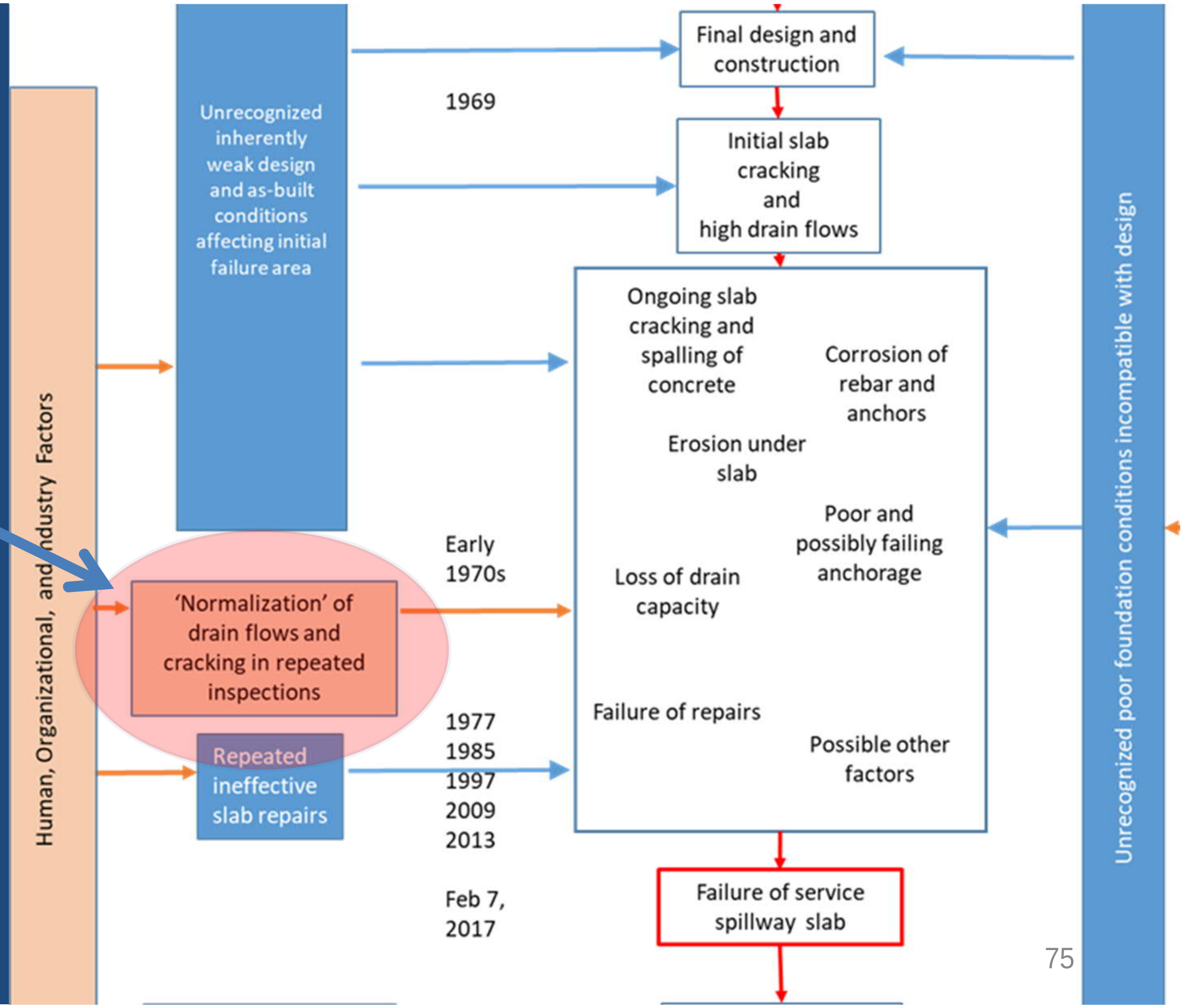
Timeline

Major concerns in 1969
“Should consult designer”



Timeline

From “mystifying” to normal

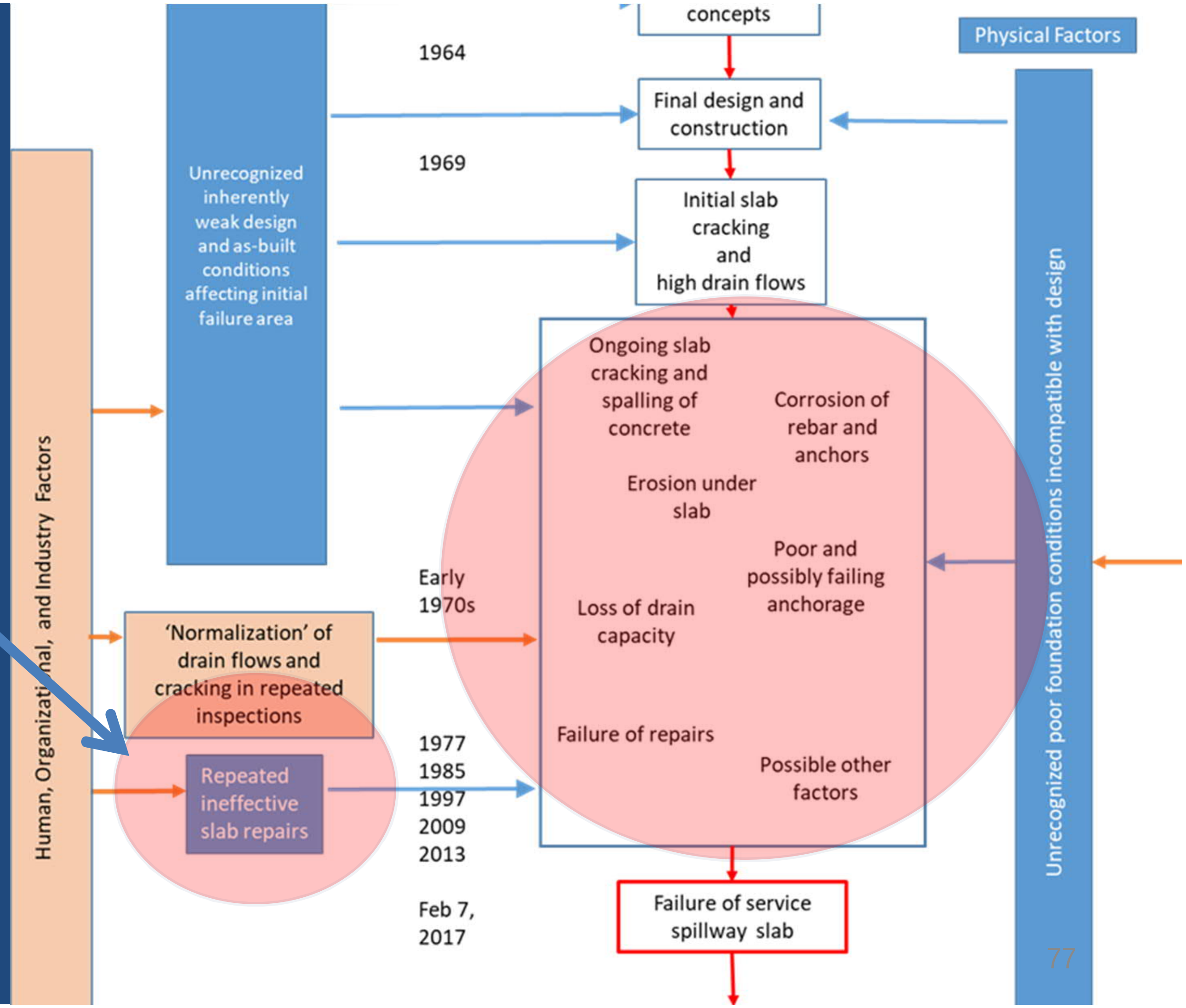


Normalization of Cracking and Underdrain Flows

- 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

Timeline


PATCH
PATCH
06 . 02 . 2017


concepts
Physical Factors
1964
Final design and construction
1969
Initial slab cracking and high drain flows
Unrecognized inherently weak design and as-built conditions affecting initial failure area
Human, Organizational, and Industry Factors
Ongoing slab cracking and spalling of concrete
Corrosion of rebar and anchors
Erosion under slab
Poor and possibly failing anchorage
Early 1970s
Loss of drain capacity
'Normalization' of drain flows and cracking in repeated inspections
Failure of repairs
Possible other factors
Repeated ineffective slab repairs
1977
1985
1997
2009
2013
Feb 7, 2017
Failure of service spillway slab
Unrecognized poor foundation conditions incompatible with design

Lack of Durability of Repairs

- Repeated cracking and spalling in old locations plus cracking and spalling in new locations
- Relationship to original design not clearly recognized
- Long term deterioration of slab condition not recognized
- Repairs were effectively “band aids” which did not address root causes

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."

Why the Incident Happened - ES

- 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

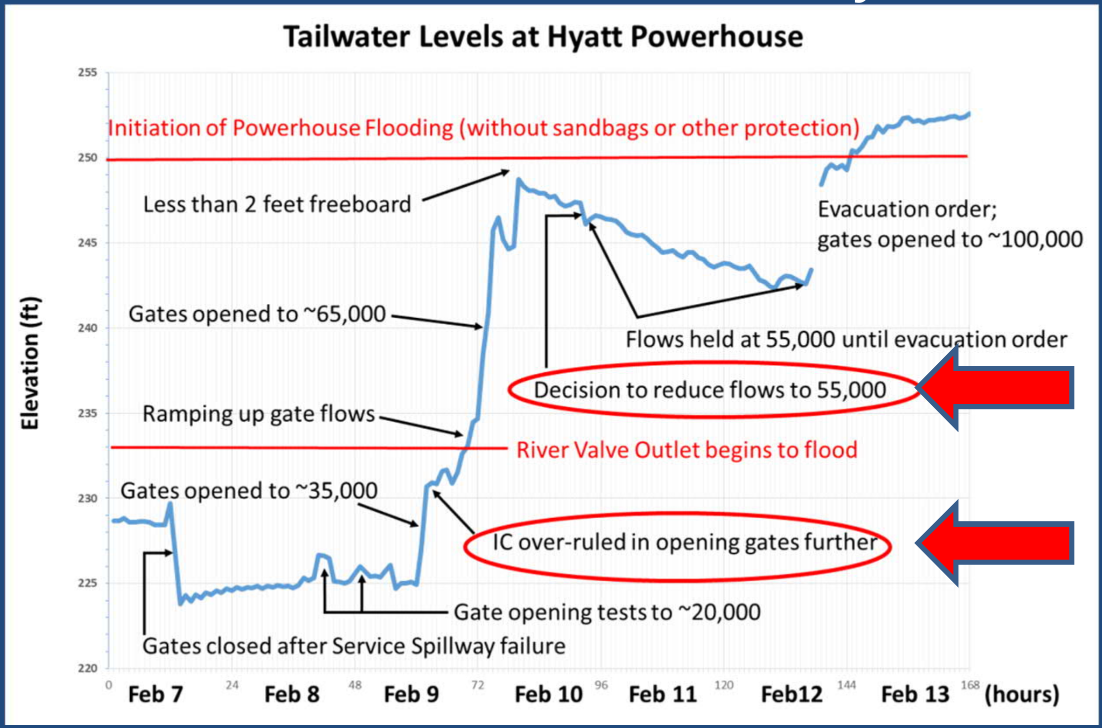
Emergency Spillway Operation

Powerplant Flooding

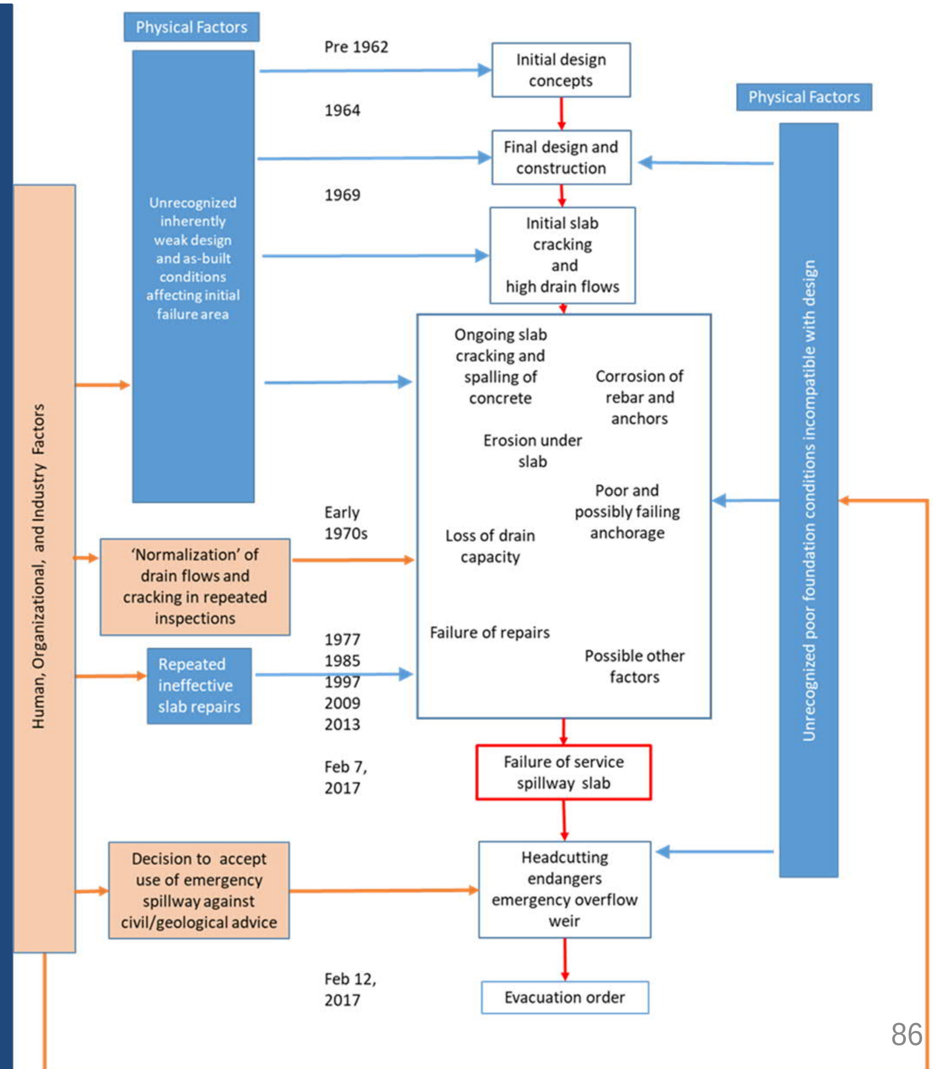
Power Transmission Towers

Why the Incident Happened - ES

Specific decisions were made to limit service spillway flows, when threat from tailwater was actually diminishing



Timeline



Physical Factors
Unrecognized inherently weak design and as-built conditions affecting initial failure area
Human, Organizational, and Industry Factors
Pre 1962
Initial design concepts
1964
Final design and construction
1969
Initial slab cracking and high drain flows
Physical Factors
Unrecognized poor foundation conditions incompatible with design
Ongoing slab cracking and spalling of concrete
Corrosion of rebar and anchors
Erosion under slab
Poor and possibly failing anchorage
Loss of drain capacity
Failure of repairs
Possible other factors
Early 1970s
'Normalization' of drain flows and cracking in repeated inspections
1977
1985
1997
2009
2013
Repeated ineffective slab repairs
Feb 7, 2017
Failure of service spillway slab
Decision to accept use of emergency spillway against civil/geological advice
Headcutting endangers emergency overflow weir
Feb 12, 2017
Evacuation order

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
  – Differing response to question of who fulfilled this role
- Informed by regular communication from dedicated dam safety professionals
  – DWR dam safety program was in an intermediate state of maturity
- Dam safety culture embedded with the organization

Maturity Level of DWR Program

Using Maturity Matrices to Evaluate Dam Safety Programs, Dam Safety Interest Group (DSIG), Project No. T132700-0234

Sub-Matrix 10: Governance Maturity Matrix

8 December 2014

Governance is defined as the organizational commitment to, and resourcing and oversight of, the effective delivery of a dam safety program and management of dam safety risk.

CEATI INTERNATIONAL
Centre for Energy Advancement through Technological Innovation

Sub-elements	Maturity Level 1. Needing Development [Lacks conformance to applicable guidelines, standards and industry practice]	2. Intermediate [Conforms to applicable guidelines, standards and industry practice in some areas]	3. Good Industry Practice [Generally conforms to applicable guidelines, standards and industry practice]	4. Best Industry Practice [High degree of understanding and conformance with applicable guidelines, standards and industry practice]	5. Leading Edge [Developing, trialing and implementing new technology, methods and systems]
10-A. Regulation* [Regulation of legislated dam safety requirements, specific to the dam Owner's country or state]	(a) Regulatory requirements are not well recognized and may not be met (b) Little or no monitoring of changes in regulatory requirements	(a) Regulatory requirements are recognized and partially met (b) Incomplete monitoring of and response to changes in regulatory requirements	(a) Regulatory requirements are generally well understood and met, and satisfactory relationship is maintained with Regulators (b) Regular monitoring of and active response to changes in regulatory requirements	(a) Regulatory requirements are well understood and met, and productive relationship is maintained with Regulators (b) Proactive monitoring of and high level of engagement with changes in regulatory requirements	Generally meeting Best Practice level, and also developing, trialing and implementing new technology, methods and systems
10-B. Policy, Goals, Values and Risk Management [Policy, goals and values that underpin, and provide directive for, delivery of the Dam Safety Program. Risk management policy and practice for the management of dam safety risks.]	(a) Poorly defined or documented with dam safety requirements inadequately addressed, with little or no review and update (b) Poor understanding of Dam Safety issues and risks (c) Little or no organizational commitment to dam safety awareness (d) Continuous improvement absent	(a) Defined and documented with dam safety requirements partially addressed, with irregular review and update (b) Incomplete understanding of Dam Safety issues and risks, and risk management considered generally in isolation from the organization's risk management policy and practice (c) Limited organizational commitment to dam safety awareness (d) Continuous improvement is rare	(a) Defined and documented with dam safety requirements addressed and referenced to good industry practice, with regular review and update, and largely integrated with organization policy, goals and values (b) Generally complete understanding of Dam Safety issues and risks, and risk management sometimes considered in conjunction with the organization's risk management policy and practice (c) Organization is commited to internal dam safety awareness (d) Continuous improvement is present	(a) Well defined and documented with dam safety requirements addressed and referenced to best industry practice, with regular review and update, and fully integrated with organization policy, goals and values (b) Comprehensive understanding of Dam Safety issues and risks throughout organization, and risk management fully integrated with the organization's risk management policy and practice (c) Organization committed to broader dam safety awareness - internal and external (d) Continuous improvement is embedded	Generally meeting Best Practice level, and also developing, trialing and implementing new technology, methods and systems
10-C. Delegated Roles & Responsibilities [Delegation of Roles and Responsibilities for delivery of the Dam Safety Program]	(a) Poorly defined or understood (b) Little or no linkage to Dam Safety objectives (c) Little or no attention by senior management to dam safety roles and responsibilities	(a) Limited definition and incomplete level of understanding (b) Limited linkage to Dam Safety objectives (c) Limited review of roles and responsibilities by senior management	(a) Defined and good level of understanding at operational levels in the organization (b) Generally linked to Dam Safety objectives, and personnel are empowered to deliver the objectives (c) Senior management reviews and confirms roles and responsibilities after organizational changes	(a) Defined, well structured and high level of understanding at all levels in the organization (b) Strong linkage to the Dam Safety objectives, and personnel are empowered to deliver the objectives, and influence dam safety outcomes in wider organization (c) Senior management regularly reviews roles and responsibilities, including after organizational changes	Generally meeting Best Practice level, and also developing, trialing and implementing new technology, methods and systems
10-D. Internal & External Communication [Communications within the organization, and the community, to support delivery of the Dam Safety Program]	(a) Little or no communication between levels and reporting of dam safety issues and risks to Senior and Executive managers (b) Little or no provision of dam safety education and awareness information for external communication	(a) Limited communication between levels and reporting of dam safety issues and risks to Senior and Executive managers (b) Dam Safety team provides necessary dam safety education and awareness information for communication to external parties	(a) Structured communication between levels and reporting of dam safety issues and risks to Senior and Executive managers with some feedback. (b) Dam Safety team involved in external communication of dam safety education and awareness information	(a) No impediments to effective and prompt communication across organization. Reporting of dam safety issues and risks to Senior and Executive managers with feedback. (b) High level of Dam Safety team involvement with planning and external communication of dam safety education and awareness information	Generally meeting Best Practice level, and also developing, trialing and implementing new technology, methods and systems
10-E. Resourcing [Provision of appropriate personnel and financial resources for delivery of the Dam Safety Program]	(a) Little or no recognition of resourcing needs by organization (b) Dam safety program deliverables are commonly deferred due to lack of resources (c) Little or no consideration of succession requirements	(a) Minimum resourcing needs are met by organization (b) Limited timely completion of key dam safety program deliverables (c) Incomplete consideration and implementation of succession requirements	(a) Resources provided by organization are generally adequate (b) Timely completion of most key dam safety program deliverables (c) Generally complete succession planning and implementation	(a) Organization's dam safety resources provide high value and protection (b) Timely and thorough completion of all key dam safety program deliverables (c) Proactive implementation of succession planning to provide continuity of knowledge and capability	Generally meeting Best Practice level, and also developing, trialing and implementing new technology, methods and systems

* Evaluate 10-A only if in dam safety regulated jurisdiction

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 – never done for Oroville spillway
- 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 can be dominated by a single factor (e.g. geology for Oroville Dam spillways)
- Dependent on experience of team members' knowledge and experience
- Dependent on thoroughness of PFM identification - brainstorming
- May not fully address complicated systems

PFMs to be Considered

- Think about risks associated with events or component failures that may not result in uncontrolled release of reservoir, but could still be highly consequential.
  - No loss of water containment, no loss of life,
  - Non-catastrophic environmental effects
  - BUT – loss of flow control and a large public evacuation

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

- https://damsafety.org/sites/default/files/files/Independent%20Forensic%20Team%20Report%20Final%2001-05-18.pdf, or
- Google “Oroville Dam forensic report”

Thank You!