GANNETT FLEMING

UNDERSTANDING THE DAM BASICS: THE ROLE OF THE STRUCTURAL ENGINEER IN CONCRETE DAMS

Presented by:
Aimee Corn, PE

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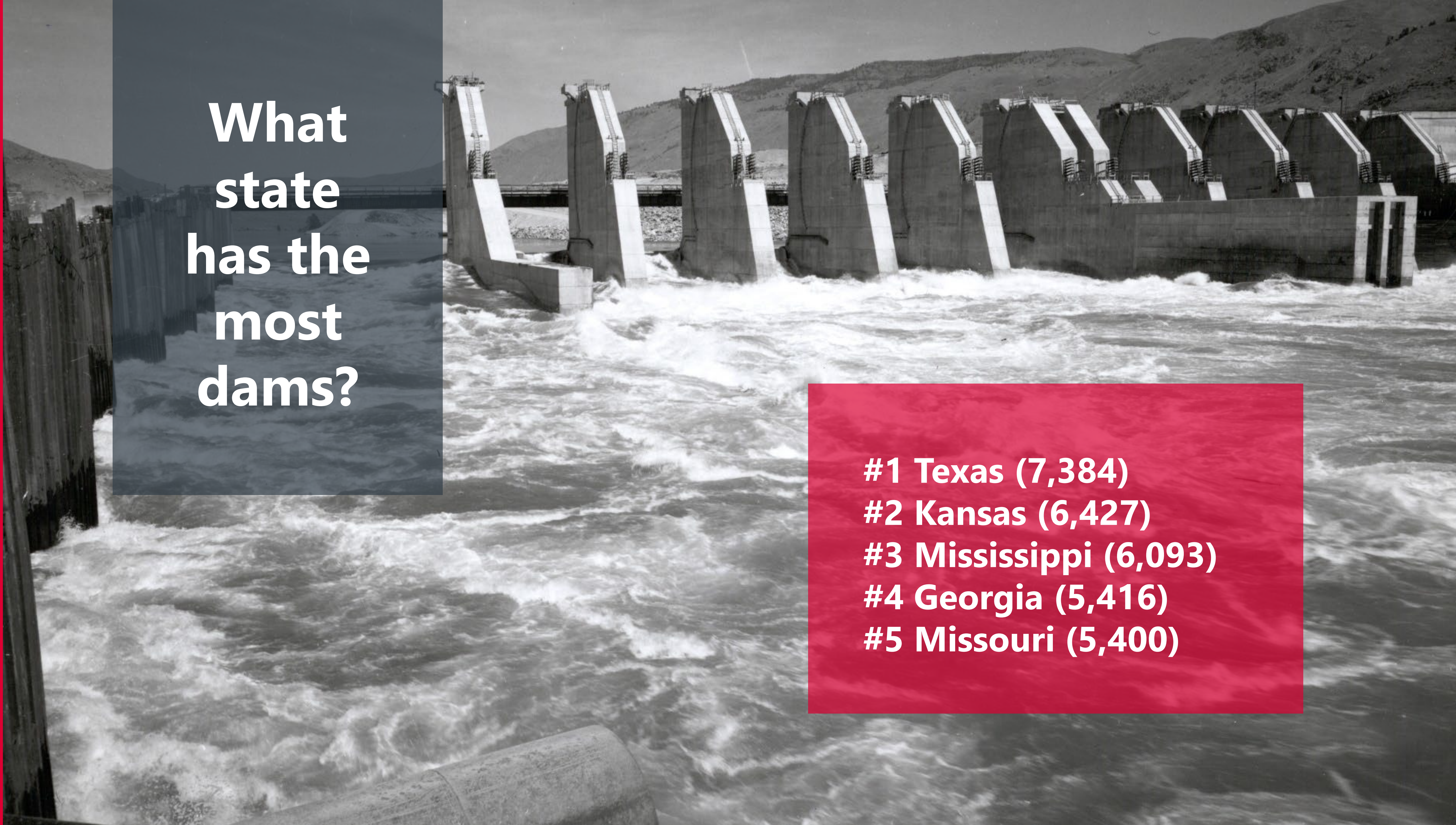
Before we begin… let’s play a little trivia!

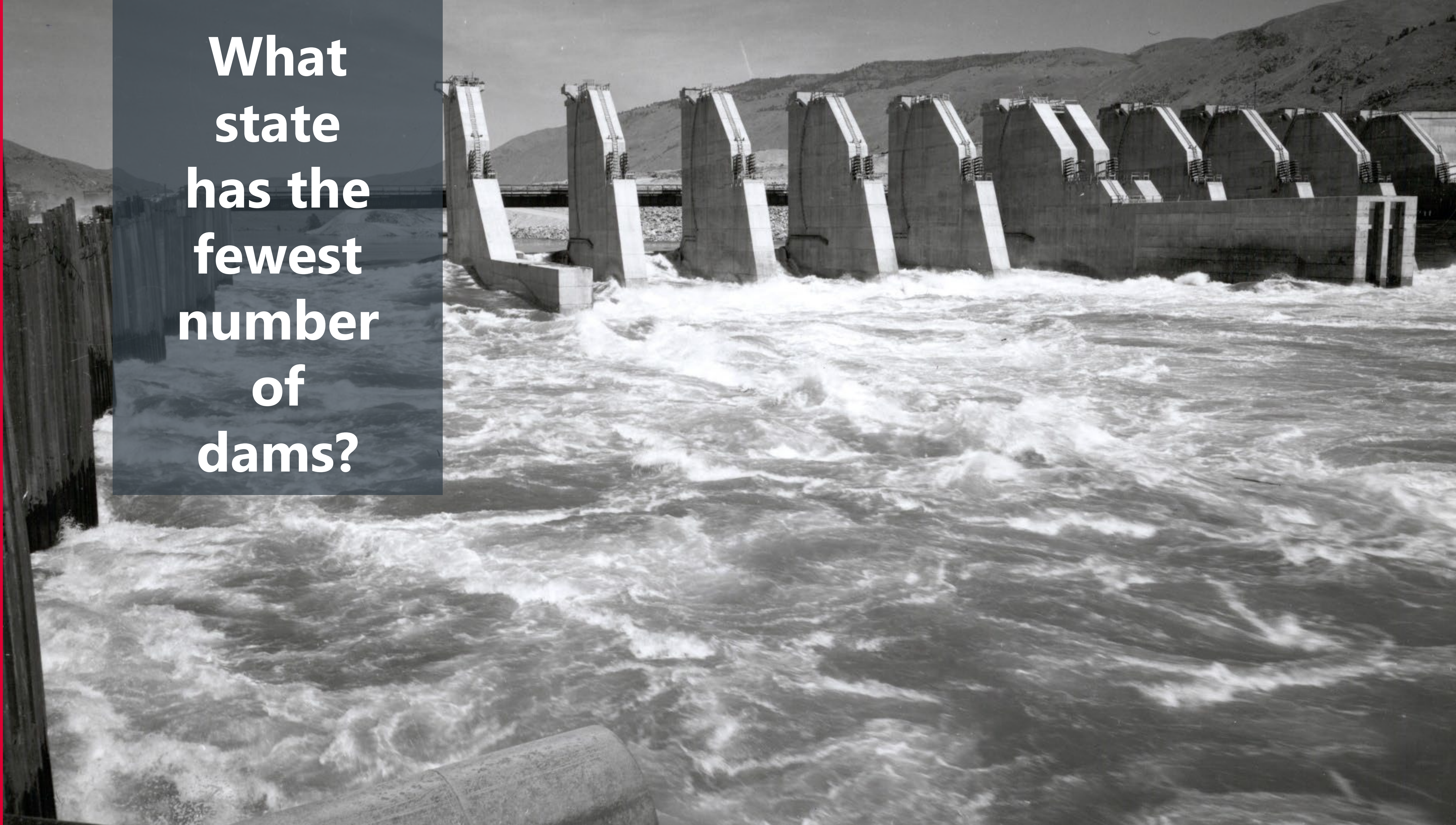
What state has the most dams?

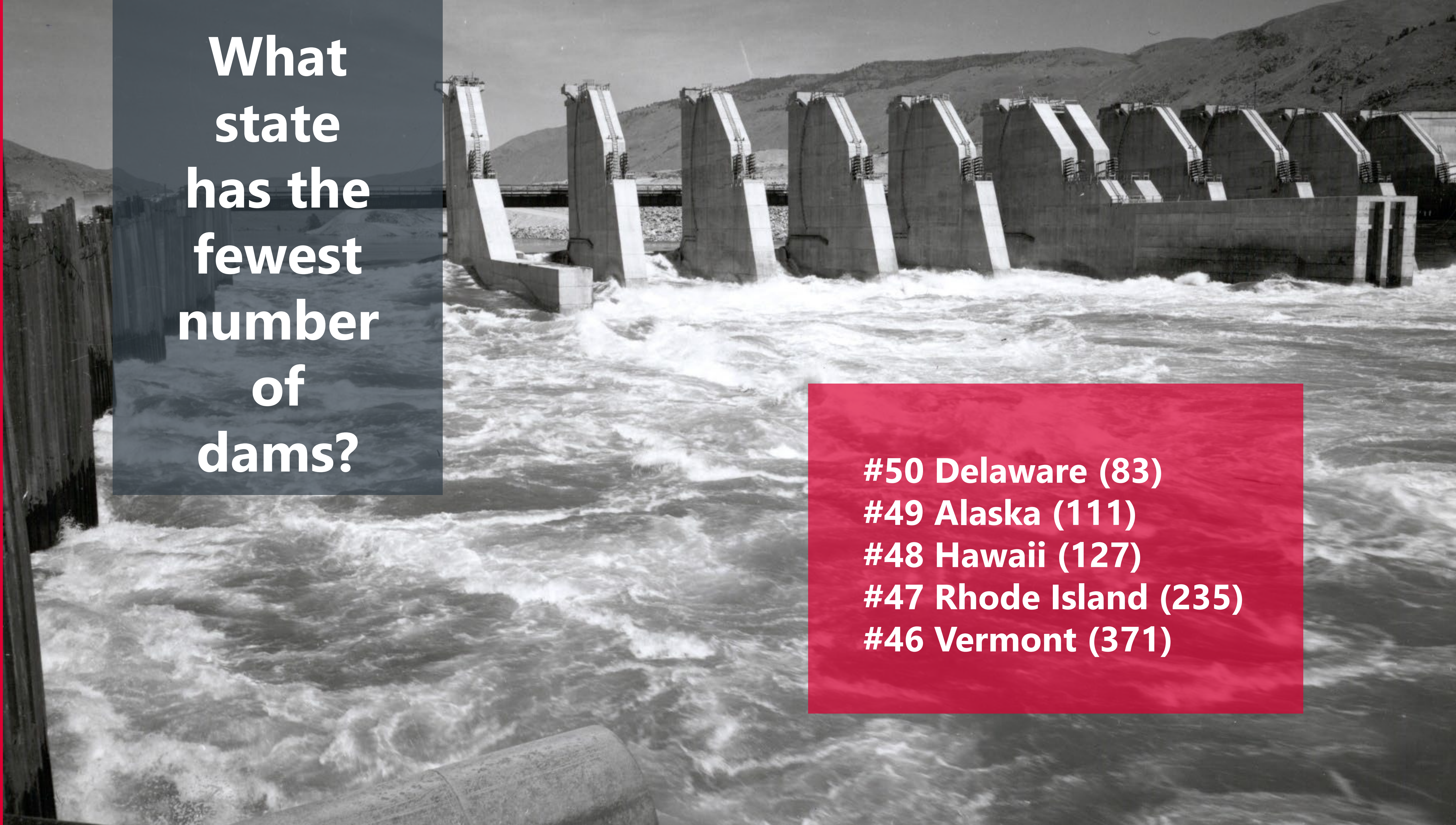


What state has the most dams?

#1 Texas (7,384)
#2 Kansas (6,427)
#3 Mississippi (6,093)
#4 Georgia (5,416)
#5 Missouri (5,400)

What state has the fewest number of dams?





What state has the fewest number of dams?

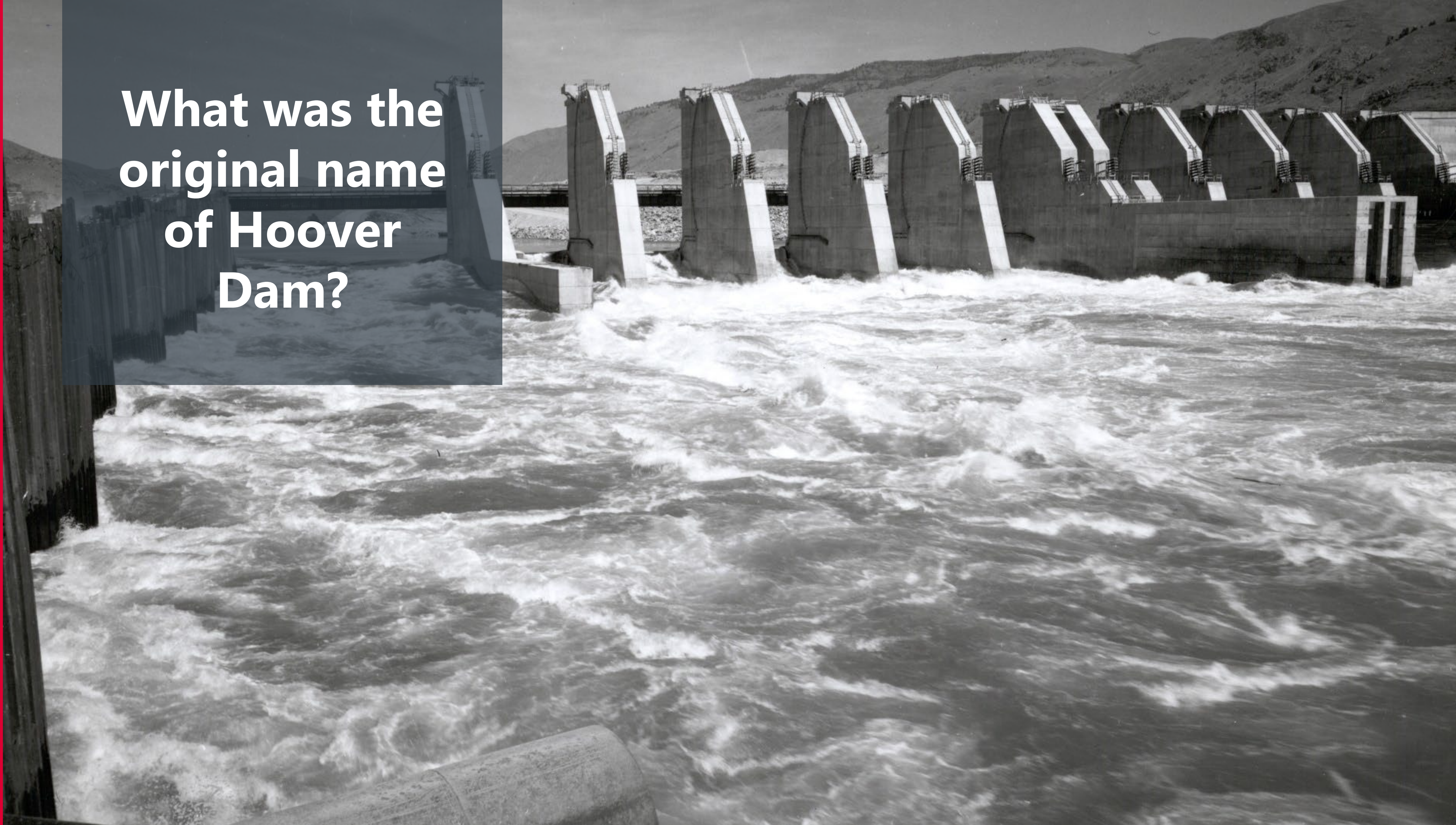
#50 Delaware (83)
#49 Alaska (111)
#48 Hawaii (127)
#47 Rhode Island (235)
#46 Vermont (371)

What state produces the most hydropower?

What state produces the most hydropower?

#1 Washington
#2 Oregon
#3 New York
#4 California
#5 Montana

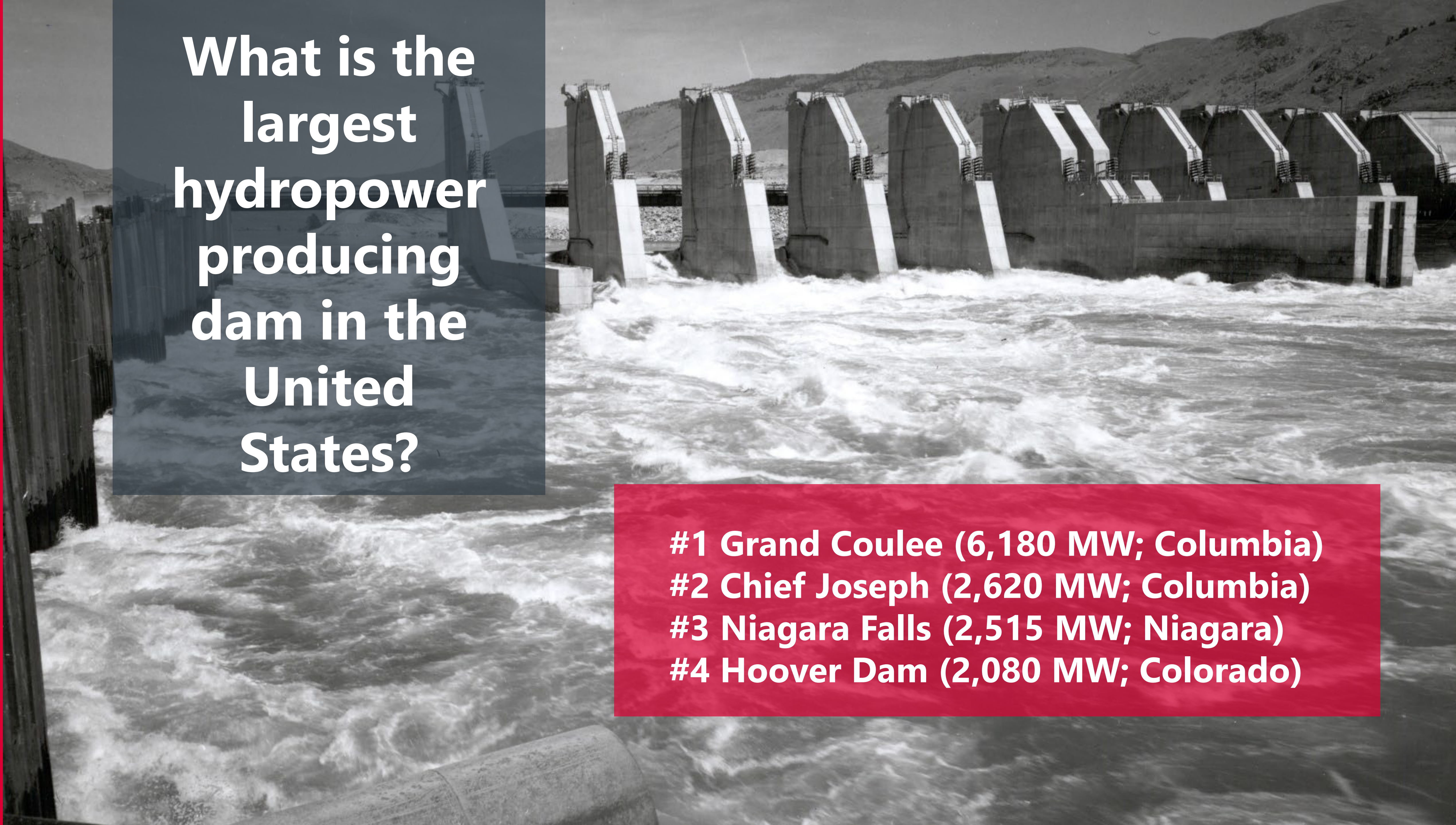
What was the original name of Hoover Dam?



What was the original name of Hoover Dam?

Boulder Dam

What is the largest hydropower producing dam in the United States?



What is the largest hydropower producing dam in the United States?

#1 Grand Coulee (6,180 MW; Columbia)
#2 Chief Joseph (2,620 MW; Columbia)
#3 Niagara Falls (2,515 MW; Niagara)
#4 Hoover Dam (2,080 MW; Colorado)

What year was the oldest dam in the United States completed?

What year was the oldest dam in the United States completed?

1640

LET'S BEGIN…

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- Dams – The Big Picture
- Previous Dam Failures
- How and for what are dams analyzed?
- Basic Concrete Dam Failure Modes
- Analysis Options
- Examples
- A few last things
- Questions

DAMS: THE BIG PICTURE

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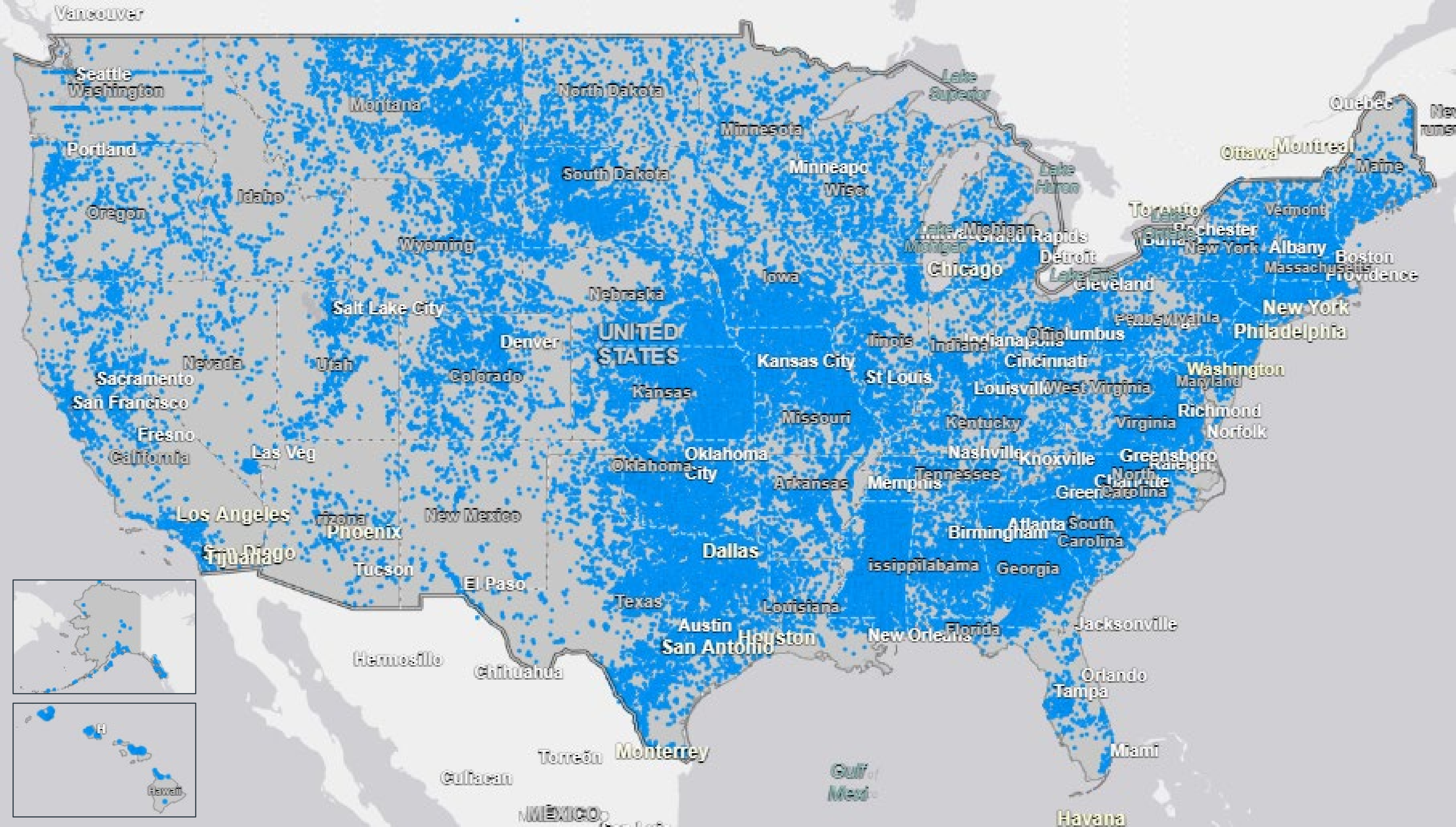
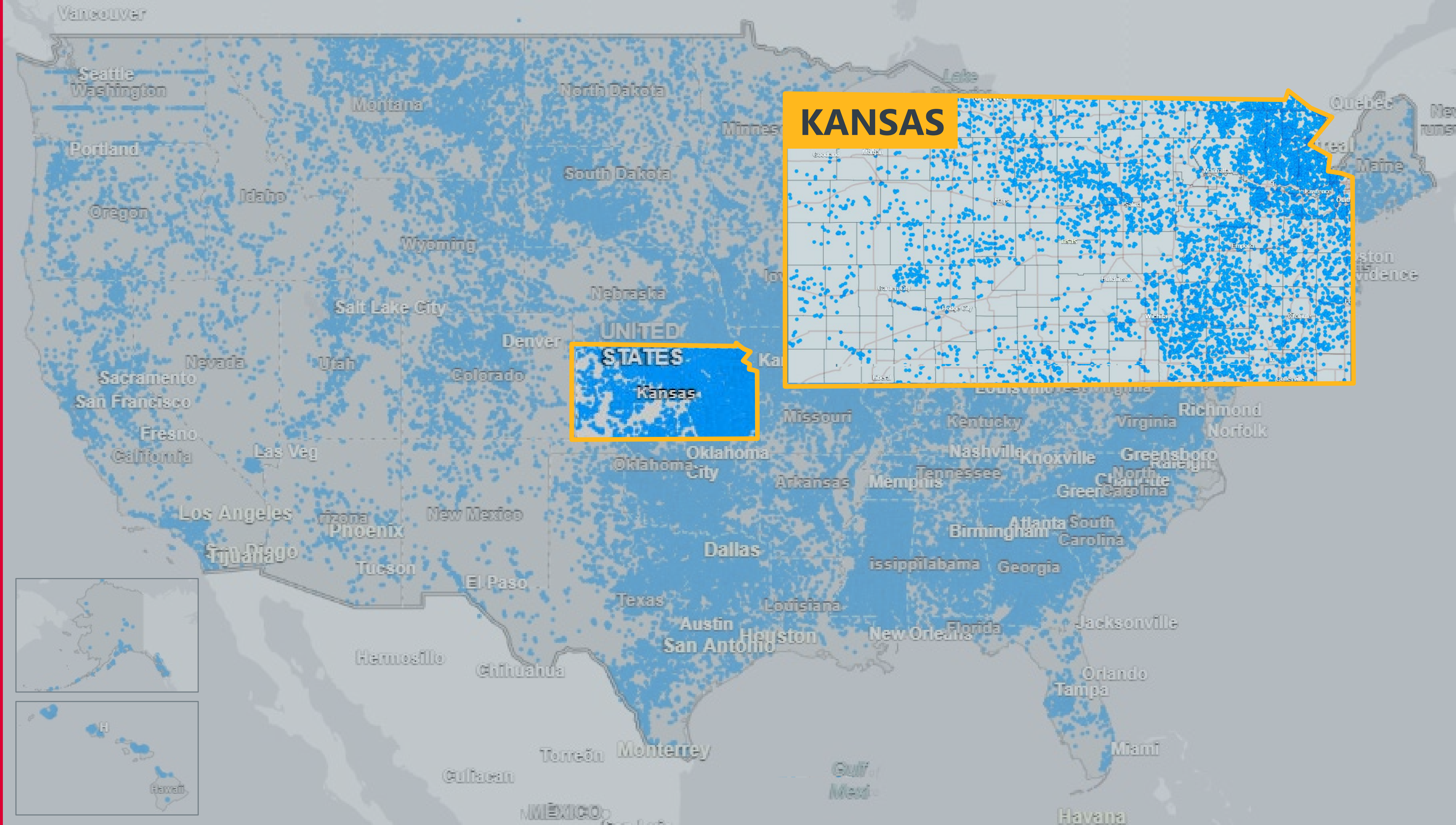
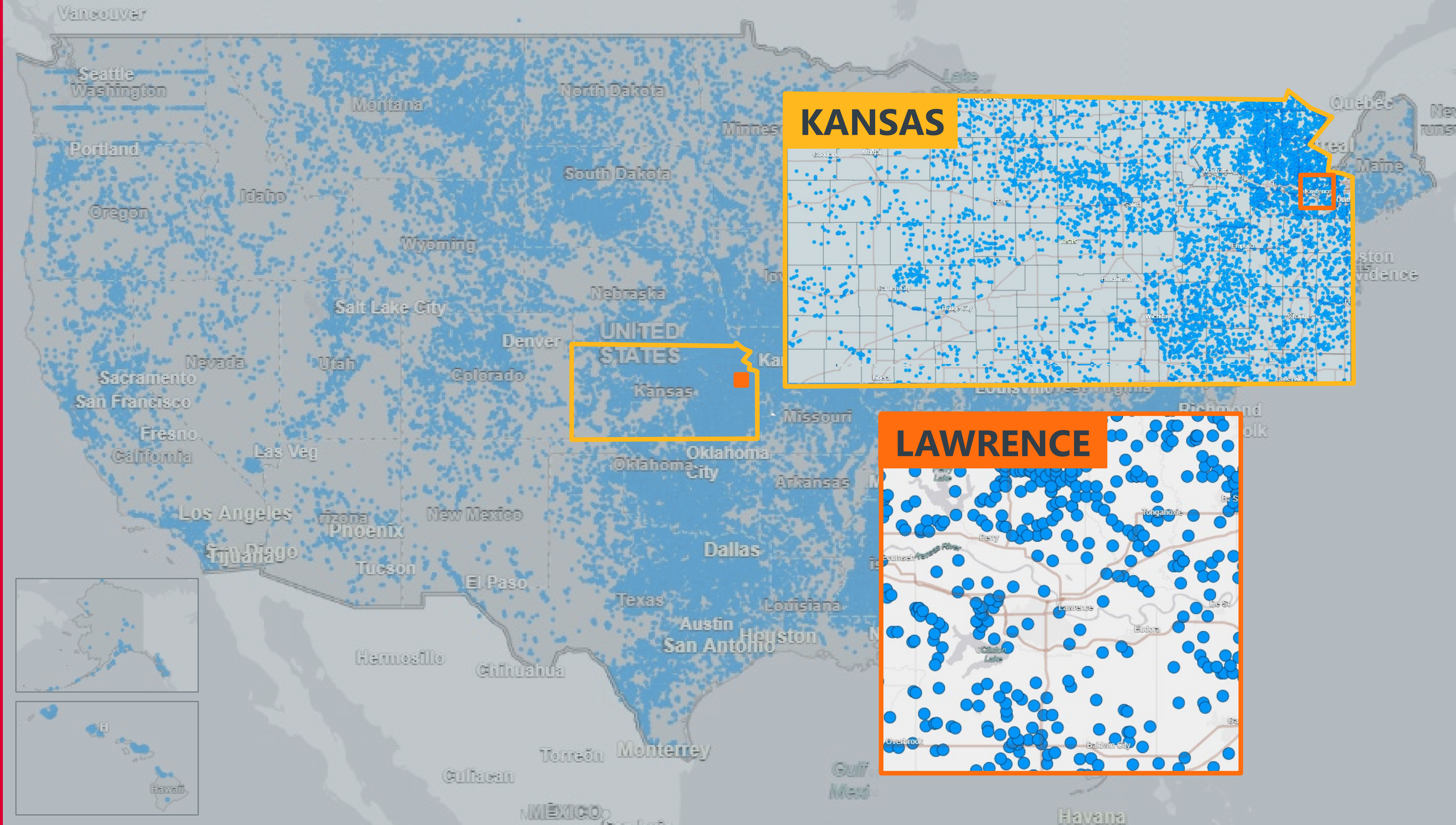


Vancouver
Seattle
Washington
Portland
Oregon
Idaho
Montana
Wyoming
North Dakota
South Dakota
Minnesota
Minneapo
Wisc
Nebraska
Iowa
UNITED STATES
Salt Lake City
Denver
Nevada
Utah
Colorado
Kansas
Kansas City
St Louis
Missouri
Sacramento
San Francisco
Fresno
California
Las Veg
Los Angeles
San Diego
Tijuana
Phoenix
Tucson
New Mexico
El Paso
Oklahoma
Oklahoma City
Arkansas
Memphis
Dallas
Texas
Austin
San Antonio
Houston
Louisiana
New Orleans
Hermosillo
Chihuahua
Torreón
Monterrey
Culiacan
MÉXICO
Lake Superior
Lake Huron
Lake Michigan
Chicago
Grand Rapids
Detroit
Cleveland
Illinois
Indiana
Indianapolis
Columbus
Cincinnati
Louisville
West Virginia
Kentucky
Nashville
Knoxville
Tennessee
Birmingham
Atlanta
Georgia
Florida
Jacksonville
Orlando
Tampa
Miami
Gulf of Mexico
Havana
Toronto
Rochester
New York
Albany
Vermont
Maine
Boston
Massachusetts
Providence
New York
Philadelphia
Pennsylvania
Washington
Maryland
Virginia
Richmond
Norfolk
Greensboro
Raleigh
North Carolina
Charlotte
South Carolina
Ottawa
Montreal
Quebec
Hawaii


KANSAS


KANSAS
LAWRENCE


2021
REPORT CARD
FOR AMERICA'S INFRASTRUCTURE
America's Infrastructure Scores a
C-
D
DAMS

DAMS: THE BIG PICTURE

DAM HAZARD POTENTIAL CLASSIFICATION	LOW HAZARD POTENTIAL	SIGNIFICANT HAZARD POTENTIAL	HIGH HAZARD POTENTIAL
LOSS OF HUMAN LIFE	None Expected	None Expected	Probable
ECONOMIC LOSSES	Low and generally limited to owner	Yes	Yes *(but not necessary for this classification)*
ENVIRONMENTAL DAMAGES	Low and generally limited to owner	Yes	Yes *(but not necessary for this classification)*
LIFELINE INTERESTS IMPACTED	No	Yes	Yes *(but not necessary for this classification)*

Adapted from the National Inventory of Dams

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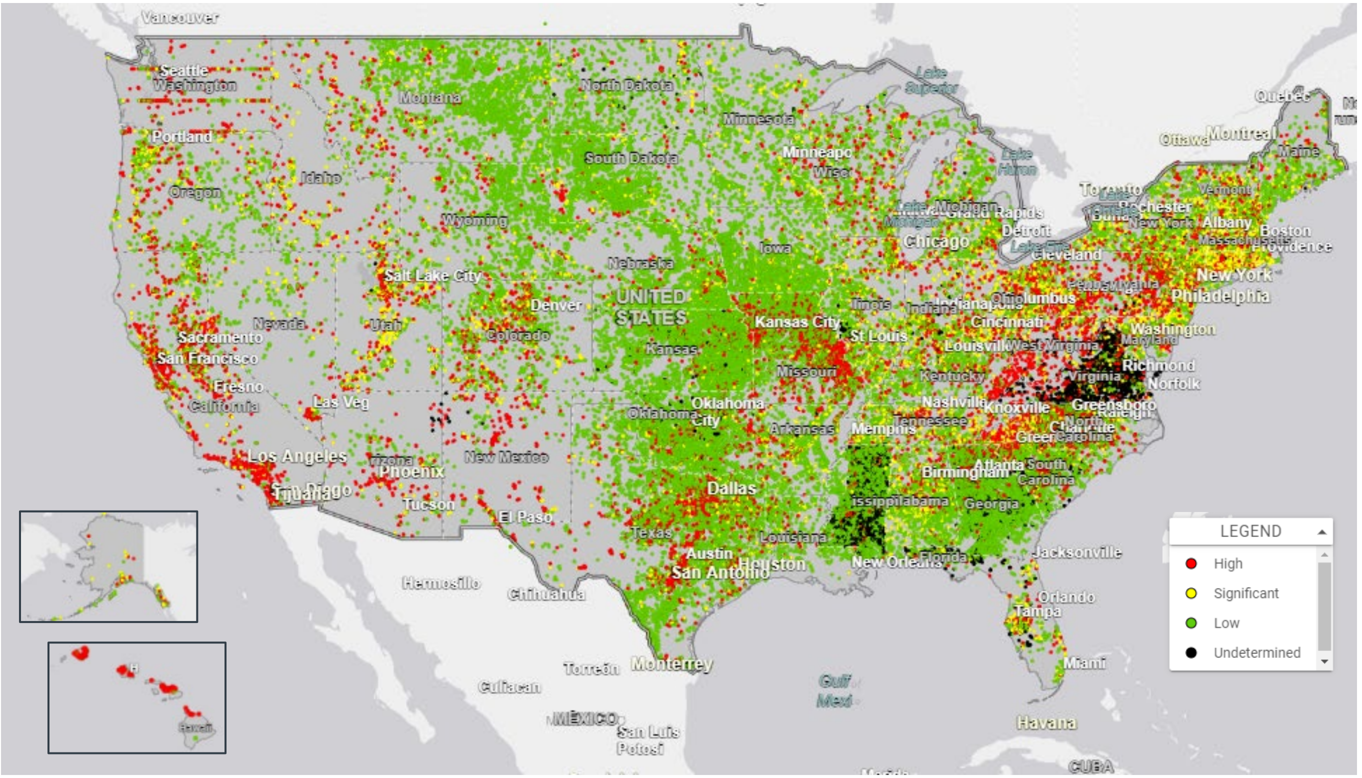
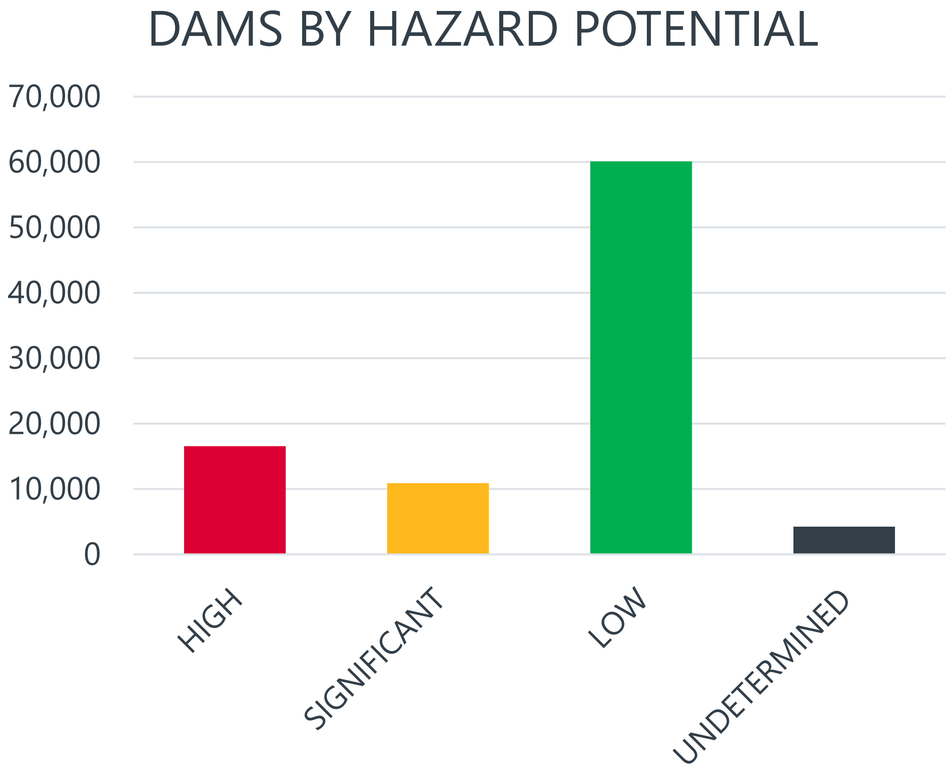
https://damsafety.org/sites/default/files/FEMA%20Federal%20Guidelines%20HazPotential%20333_04.pdf

DAMS: THE BIG PICTURE





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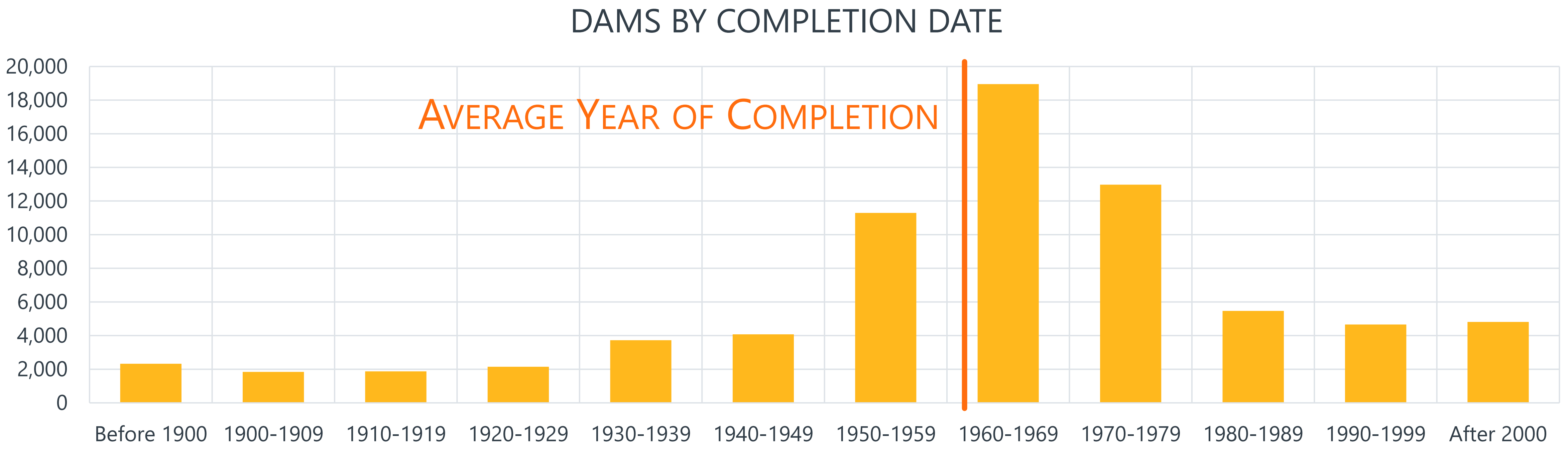
http://nid.usace.army.mil

DAMS: THE BIG PICTURE



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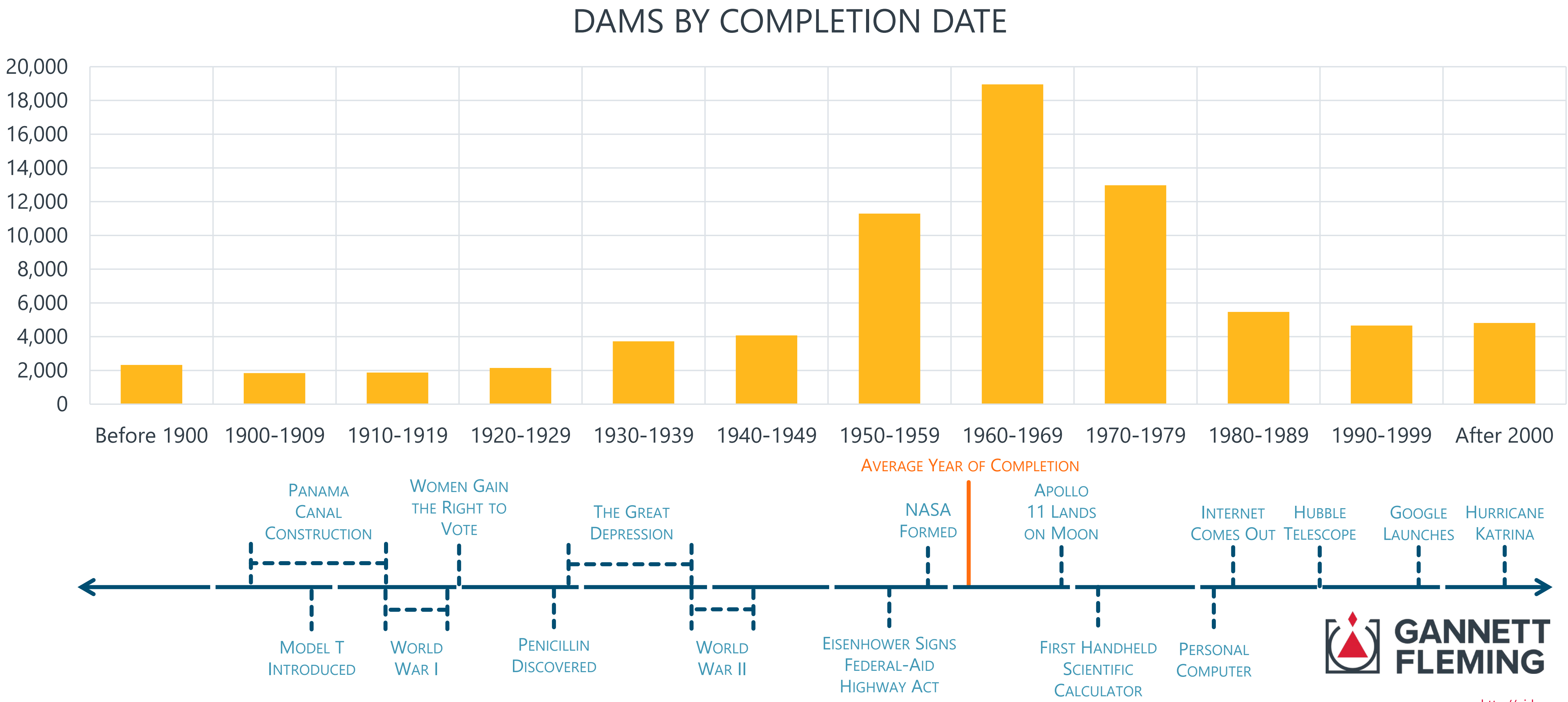
DAMS: THE BIG PICTURE



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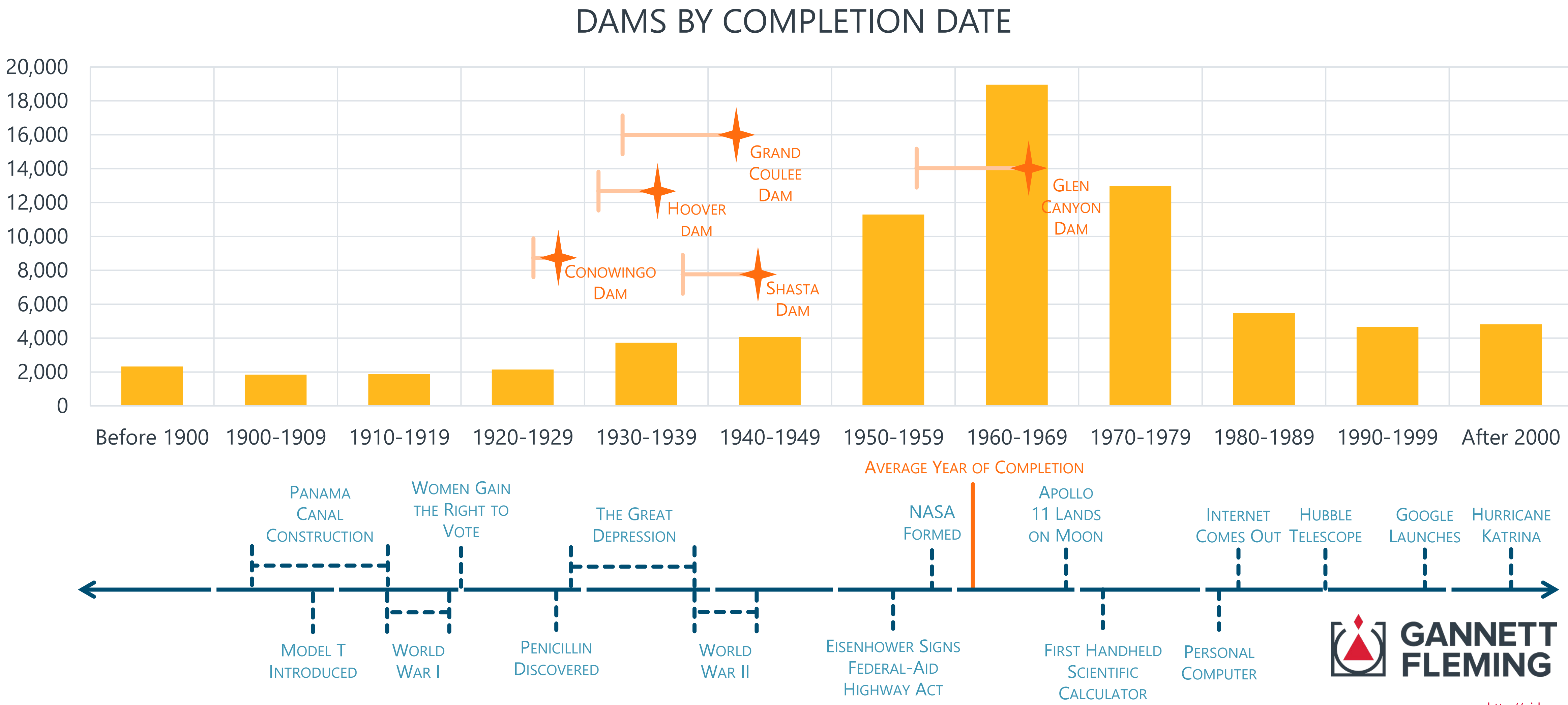
DAMS: THE BIG PICTURE



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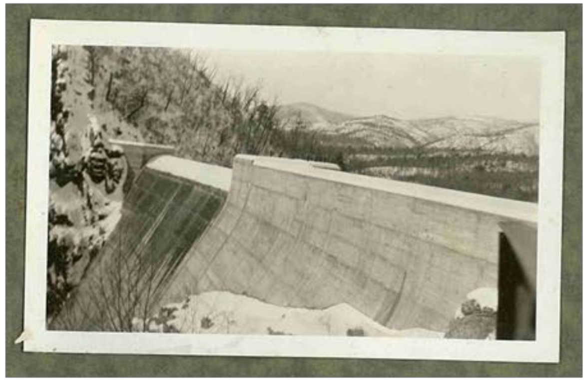
http://nid.usace.army.mil

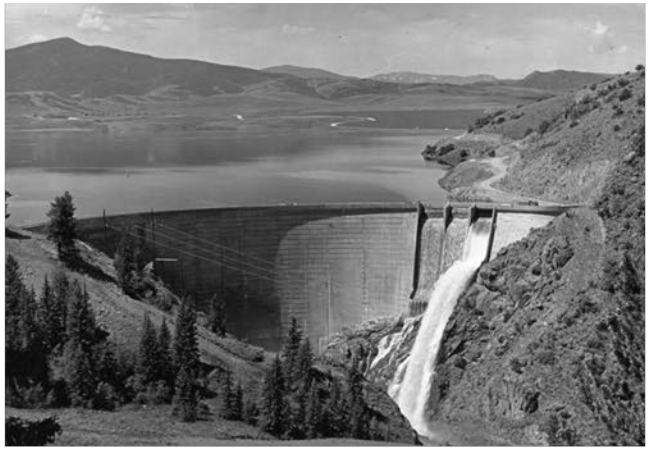
DAMS: THE BIG PICTURE

GRAVITY



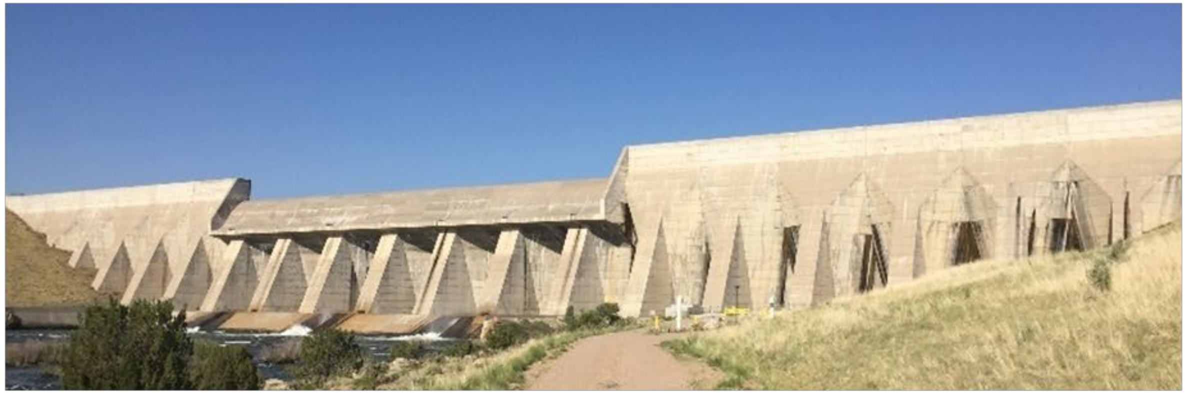
DAMS: THE BIG PICTURE

ARCH



DAMS: THE BIG PICTURE

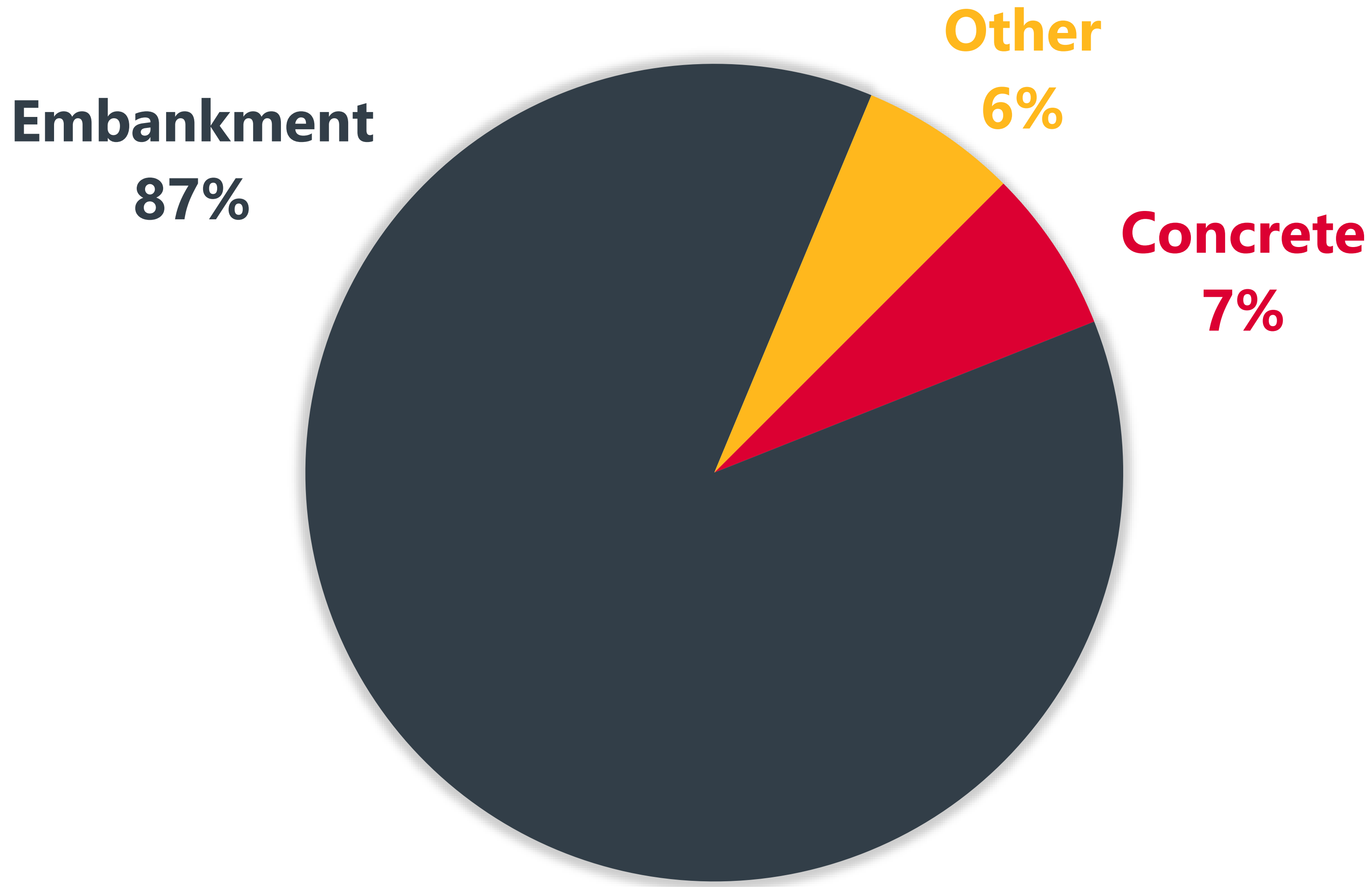
SLAB AND BUTTRESS



DAMS: THE BIG PICTURE

EMBANKMENT

DAMS: THE BIG PICTURE



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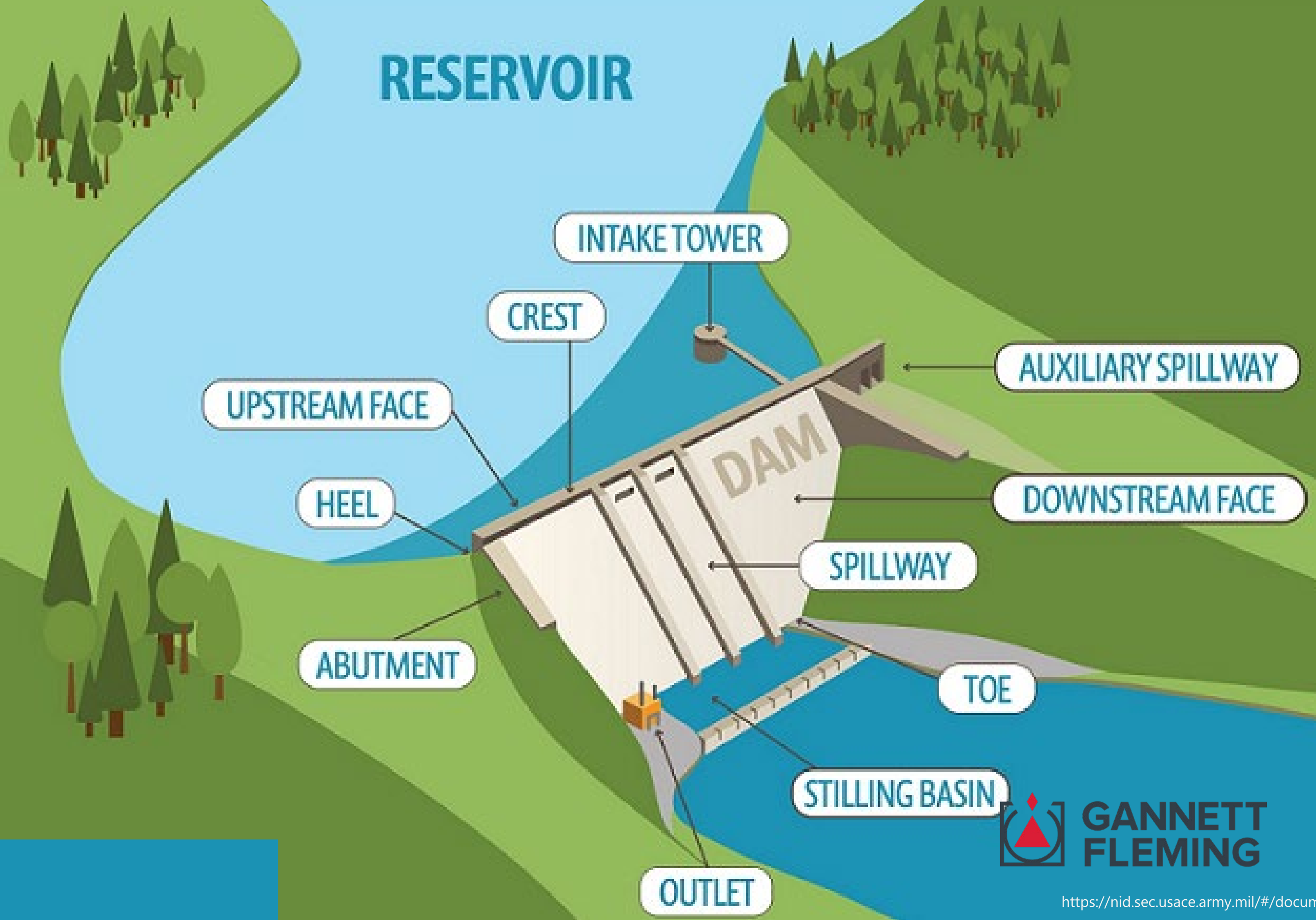
http://nid.usace.army.mil

DAMS: THE BIG PICTURE



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ANATOMY OF A DAM

https://nid.sec.usace.army.mil/#/documents

PREVIOUS DAM FAILURES

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'All the News All the Time
LARGEST HOME-DELIVERED CIRCULATION
LARGEST ADVERTISING VOLUME

Los Angeles Times

In Three Parts — 44 Pages
PART I—TELEGRAPH SHEET—12 PAGES

Liberty Under Equal Rights True Industrial Freedom

Vol. XLVII. WEDNESDAY MORNING, MARCH 14, 1928. DAILY, FIVE CENTS SUNDAY, TEN CENTS

200 DEAD, 30[illegible] MISSING, $7,000,000 LOSS IN ST. FRANCIS DAM DISASTER

https://www.smithsonianmag.com/history/occasions-i-envy-dead-st-francis-dam-disaster-180954543/

PREVIOUS DAM FAILURES: ST. FRANCIS

Location: California

Completed: 1926

Failure: March 12, 1928

Deaths: 470

- Designed with no oversight
- Exempt from 1917 Dam Safety

Nuss, 2015

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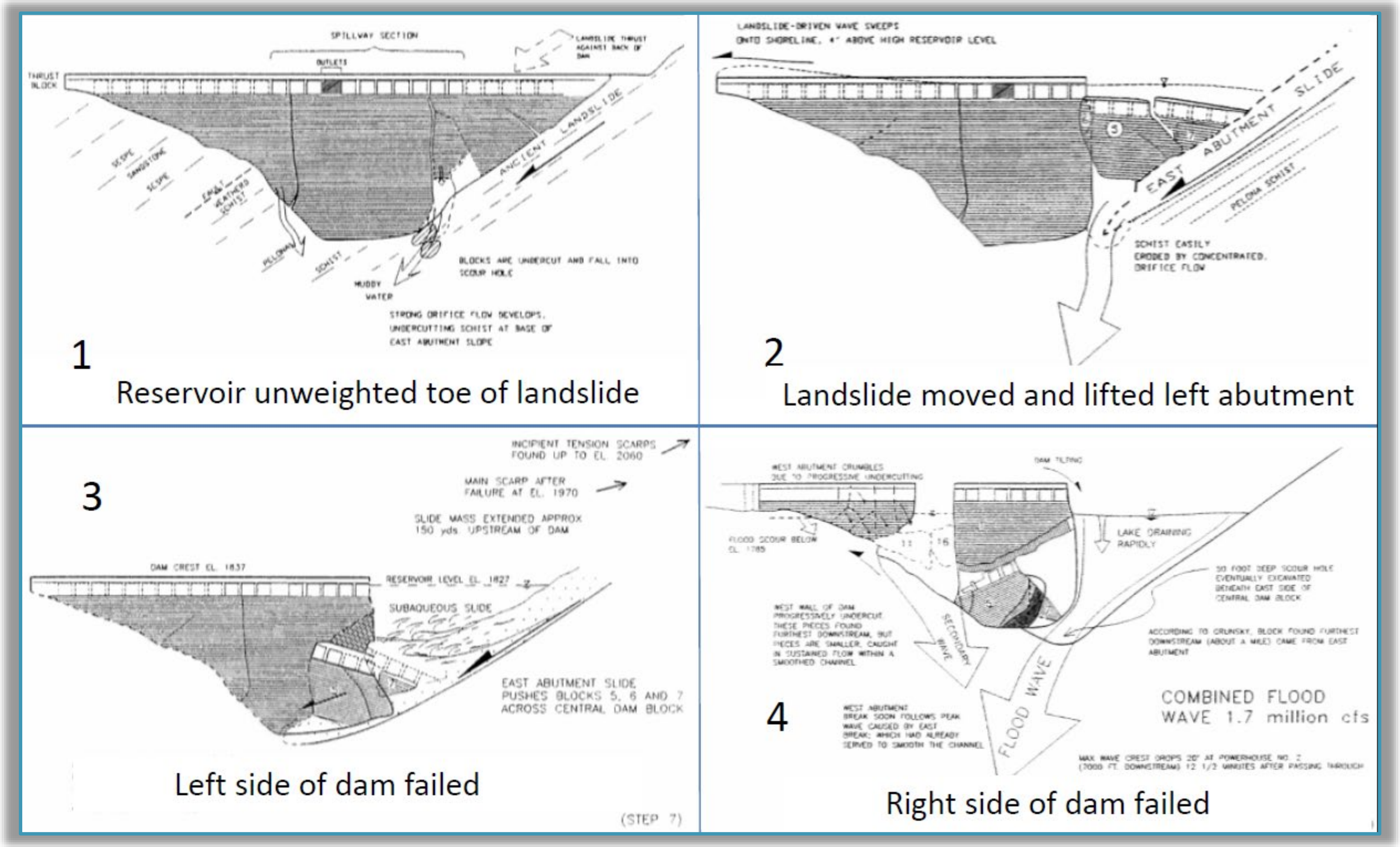
PREVIOUS DAM FAILURES:
ST. FRANCIS

- Left abutment unknowingly constructed on massive mega-paleo-landslide.
- Uplift pressure led to movement causing foundation failure and imminent dam failure.



Nuss, 2015

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PREVIOUS DAM FAILURES: ST. FRANCIS

Outcomes:

- Comprehensive oversight by the California Division of Dam Safety
- Required Professional Engineering Licensing
- Independent peer review of new designs including Geologic assessments
- All Federal and California dams higher than 50 feet were reviewed

Significant drop in concrete dam failures after 1929

https://damfailures.org/case-study/st-francis-dam-california-1928/

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La DC salva Bonomi
PCI e PSI votano insieme
A pagina 3

l'Unità

ORGANO DEL PARTITO COMUNISTA ITALIANO

L'Unità processata perchè denunciò il pericolo della diga

La tragedia del Vaiont

Sono migliaia i morti
È una strage che si poteva evitare!

Responsabilità

<u>THE TRAGEDY OF VAJONT</u>

THERE ARE THOUSANDS DEAD

IT WAS A MASSACRE THAT COULD HAVE BEEN AVOIDED

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https://www.giornalistitalia.it/vajont-la-tragedia-annunciata-da-tina-merlin/

PREVIOUS DAM FAILURES: VAJONT

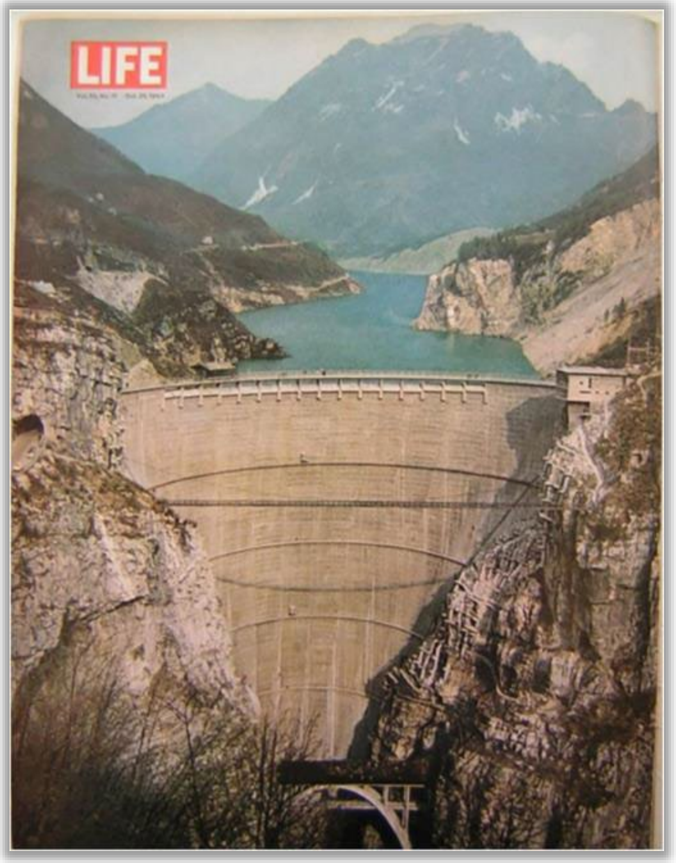
Location: Italy

Completed: 1960

Failure: October 9, 1963

Deaths: 2,600

- Massive upstream landslide caused overtopping.
- Dam did not fail.



https://damfailures.org/case-study/vajont-dam-italy-1963/

https://en.wikipedia.org/wiki/Vajont_Dam/

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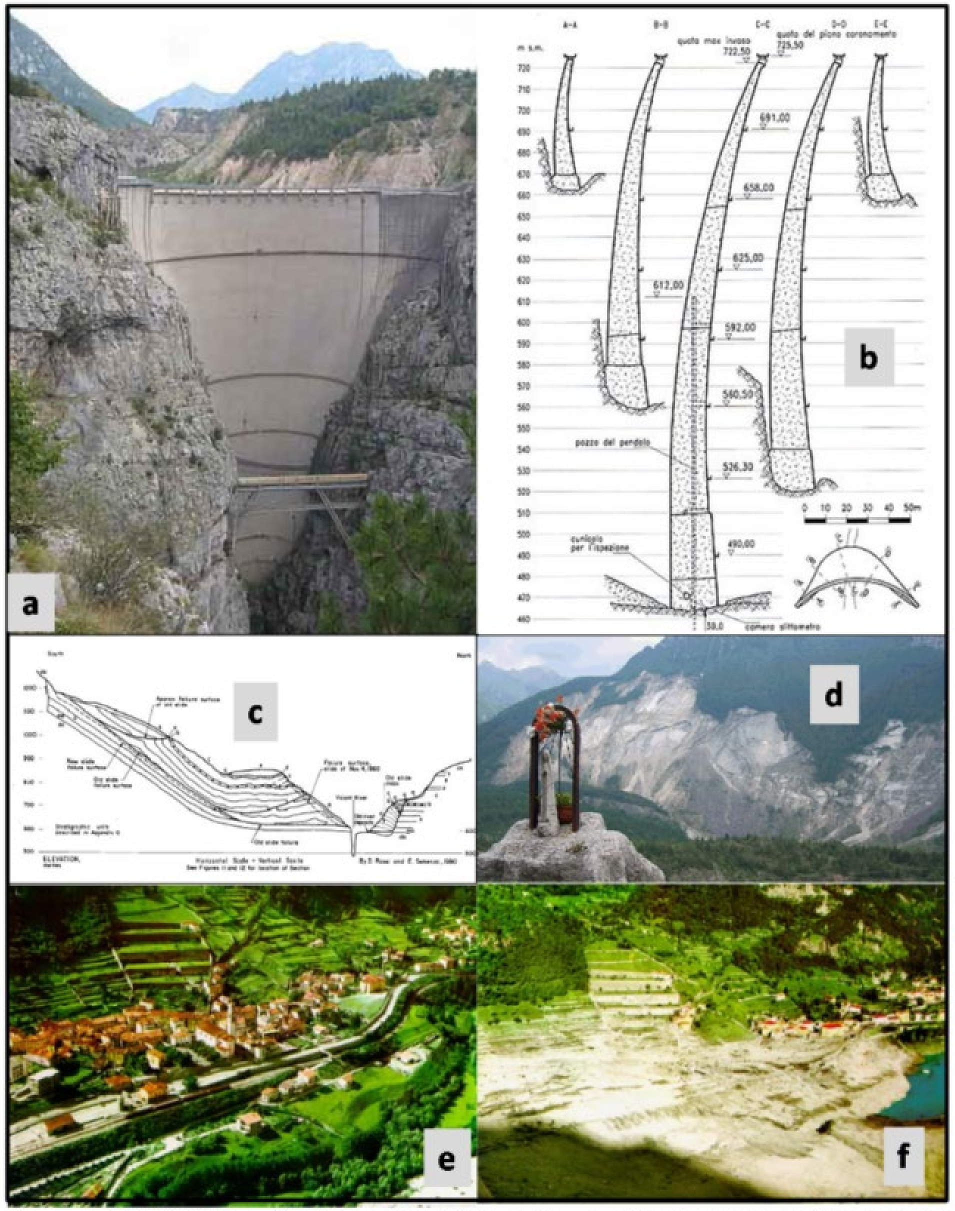
PREVIOUS DAM FAILURES: VAJONT

- Volume of slide more than twice volume of reservoir. Landslide was 400 times larger than previous landslide.
- Risks due to scale and magnitude of landslide not recognized.
- Hazards can exist, even if a structure is considered safe and does not fail.
- 1.2 mile landslide



a. Vaiont Dam, b. Section, c. Landslide, d. Scarp, e.&f. Longarone before and after

Nuss, 2015

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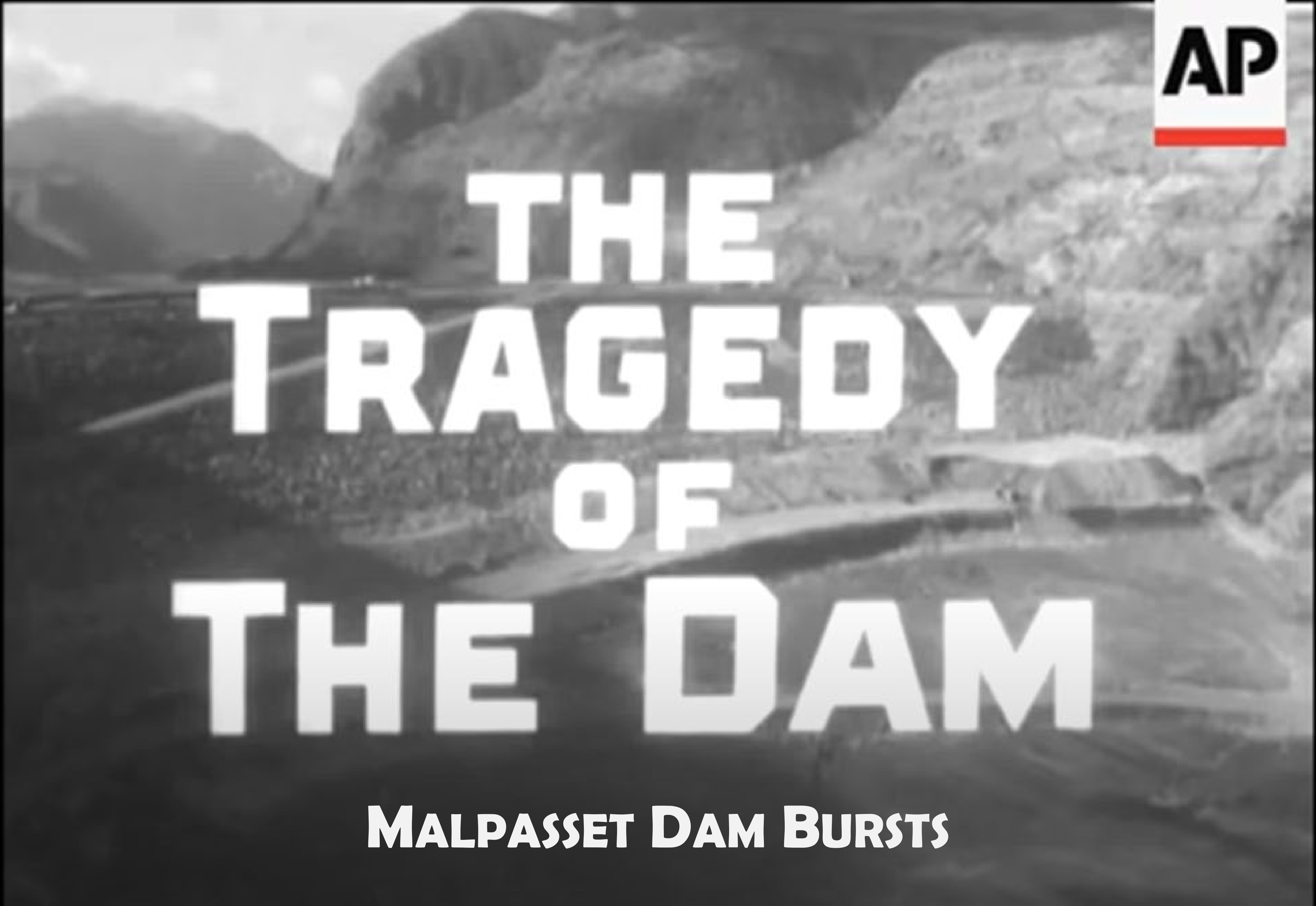
PREVIOUS DAM FAILURES: VAJONT

"Any damsite investigation should include a detailed study of the proposed reservoir slopes. If old slides or areas susceptible to sliding are identified, a detailed evaluation of their relative stability under reservoir conditions should be required. The lesson afforded by (Vajont) need not be relearned by another generation."
– Hendron and Patton, 1986

https://www.geotech.hr/en/vajont-a-tragedy-that-killed-more-than-2000-people/



Malpasset Dam Bursts

PREVIOUS DAM FAILURES: MALPASSET

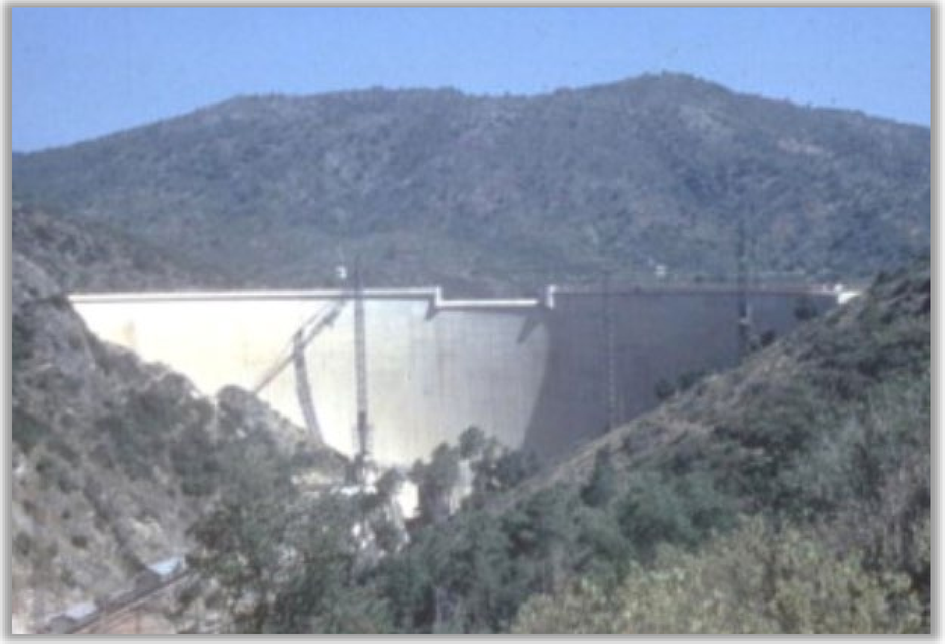
Location: France

Completed: 1954

Failure: December 2, 1959

Deaths: 421

- Left abutment failed due to increased uplift pressures.



https://doi.org/10.1016/j.jrmge.2013.07.004

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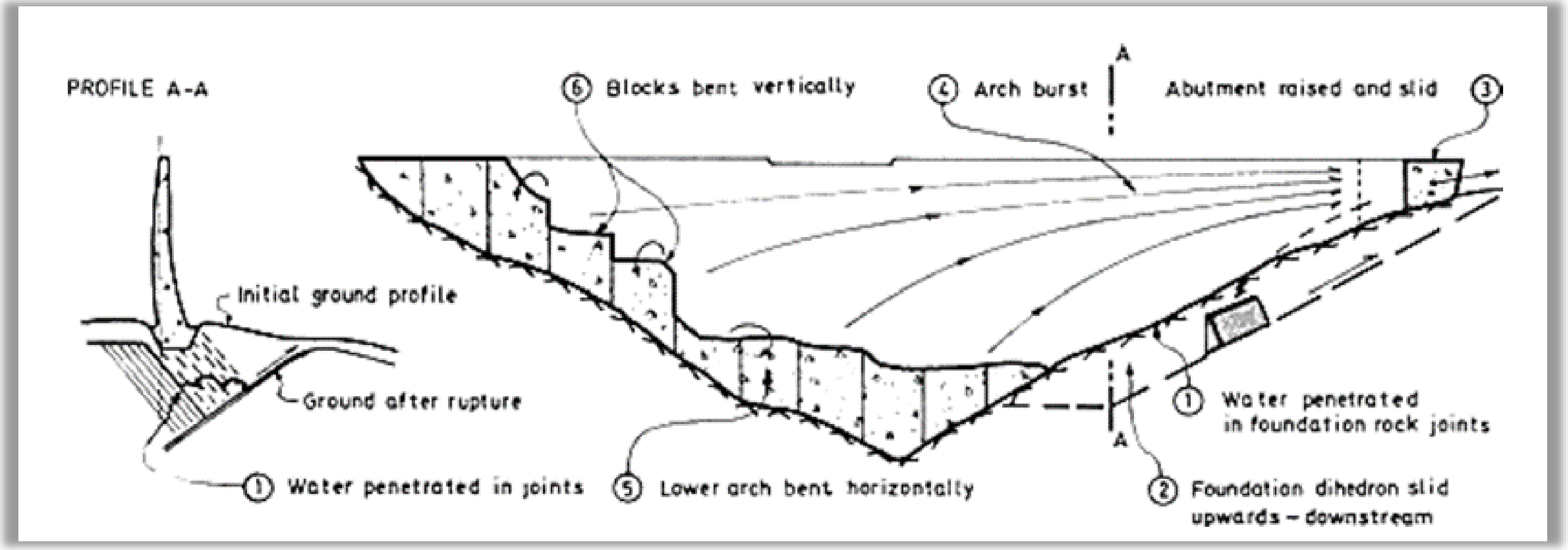
PREVIOUS DAM FAILURES: MALPASSET

- Double-curvature arch structure spanned the Reyran River.
- At time of completion in 1954, thinnest arch dam of its height (218 feet) with a maximum thickness of 22.2 feet.
- Designed by Andre Coyne with the primary goal of optimizing its shape and thinning its structure.
- Little effort devoted to analyzing the geology of the foundation.



https://doi.org/10.1144/qjegh2018-186

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PREVIOUS DAM FAILURES: MALPASSET

- Foundation deficiencies and human oversight led to the instability issues at the Malpasset Dam.
- Fault discovered downstream of the dam.
- Foliation pattern of the foundation led to increased uplift as dam was loaded.
- Uplift pressure at left abutment dislodged the thrust block.
- Failure of abutment led to the ultimate failure of dam.

https://en.wikipedia.org/wiki/Malpasset_Dam

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HOW AND FOR WHAT ARE DAMS ANALYZED?

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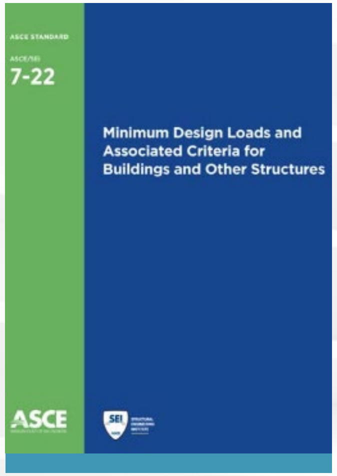
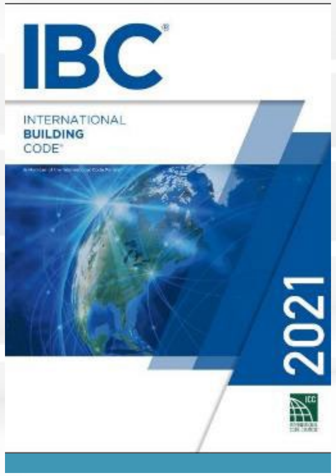
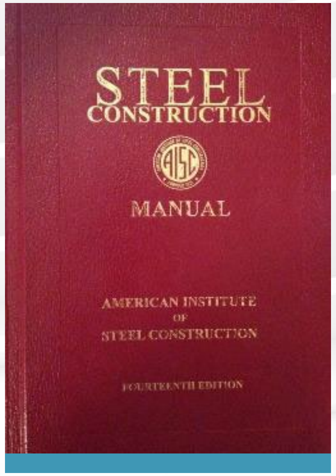
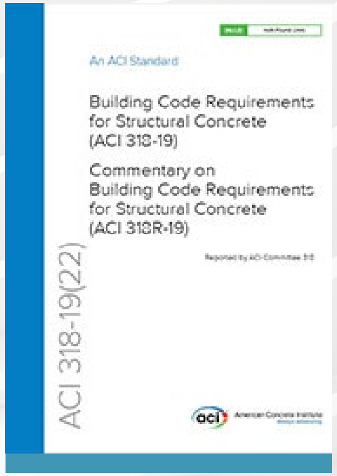
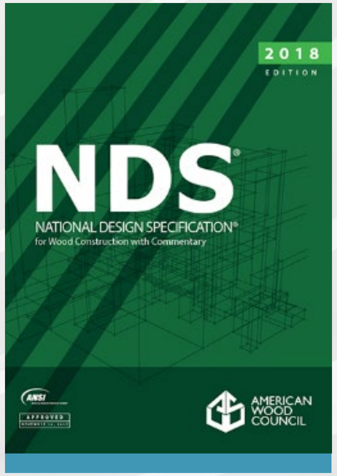
HOW AND FOR WHAT ARE DAMS ANALYZED?











HOW AND FOR WHAT ARE DAMS ANALYZED?

United States Bureau of Reclamation

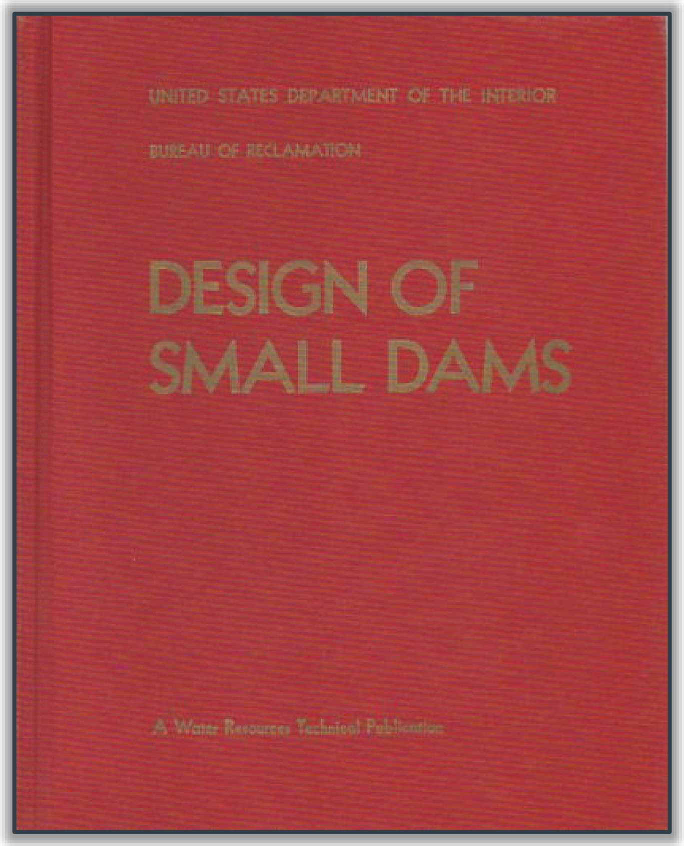
Federal Energy Regulatory Commission

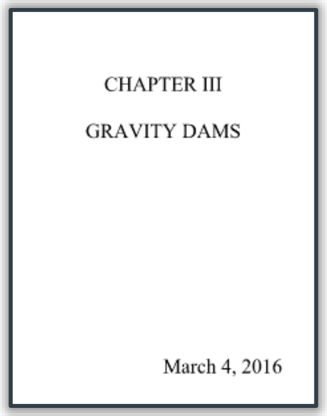
United States Army Corps of Engineers

HOW AND FOR WHAT ARE DAMS ANALYZED?

BUREAU OF RECLAMATION

US Army Corps of Engineers®

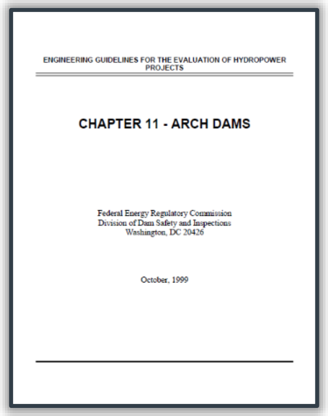




CHAPTER III

GRAVITY DAMS

March 4, 2016

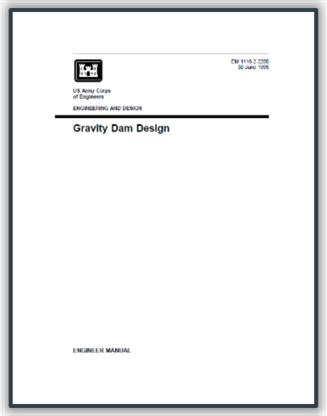


ENGINEERING GUIDELINES FOR THE EVALUATION OF HYDROPOWER PROJECTS

CHAPTER 11 - ARCH DAMS

Federal Energy Regulatory Commission
Division of Dam Safety and Inspections
Washington, DC 20426

October, 1999



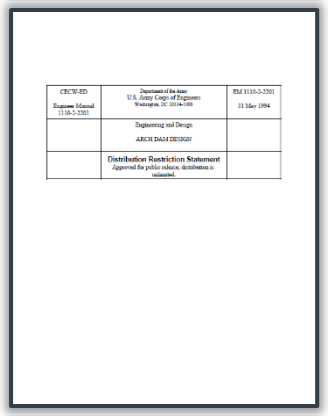
EM 1110-2-2200
30 June 1995

US Army Corps of Engineers

ENGINEERING AND DESIGN

Gravity Dam Design

ENGINEER MANUAL



CECW-ED Engineer Manual 1110-2-2201	Department of the Army U.S. Army Corps of Engineers Washington, DC 20314-1000	EM 1110-2-2201 31 May 1994
	Engineering and Design ARCH DAM DESIGN	
	Distribution Restriction Statement Approved for public release; distribution is unlimited.	

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HOW AND FOR WHAT ARE DAMS ANALYZED?

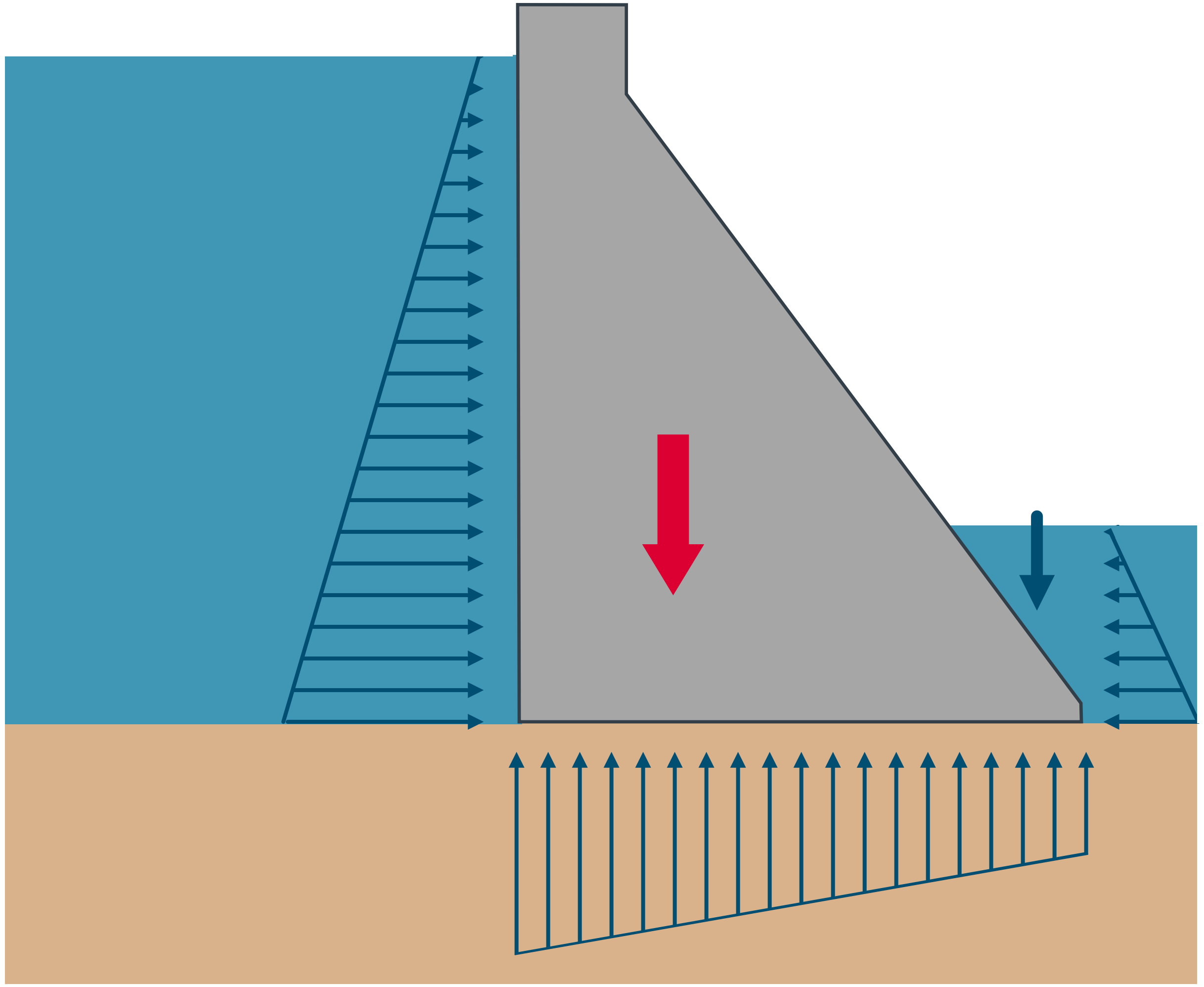
Typical Loads on a Dam

- Gravity
- Internal Water Pressure
- Silt Pressure
- Ice Pressure
- External Water Pressure
- Temperature
- Earthquake
- Gates or Appurtenant Structures

HOW AND FOR WHAT ARE DAMS ANALYZED?

Usual Load Combination

- Gravity
- Reservoir
- Tailwater
- Sediment
- Uplift



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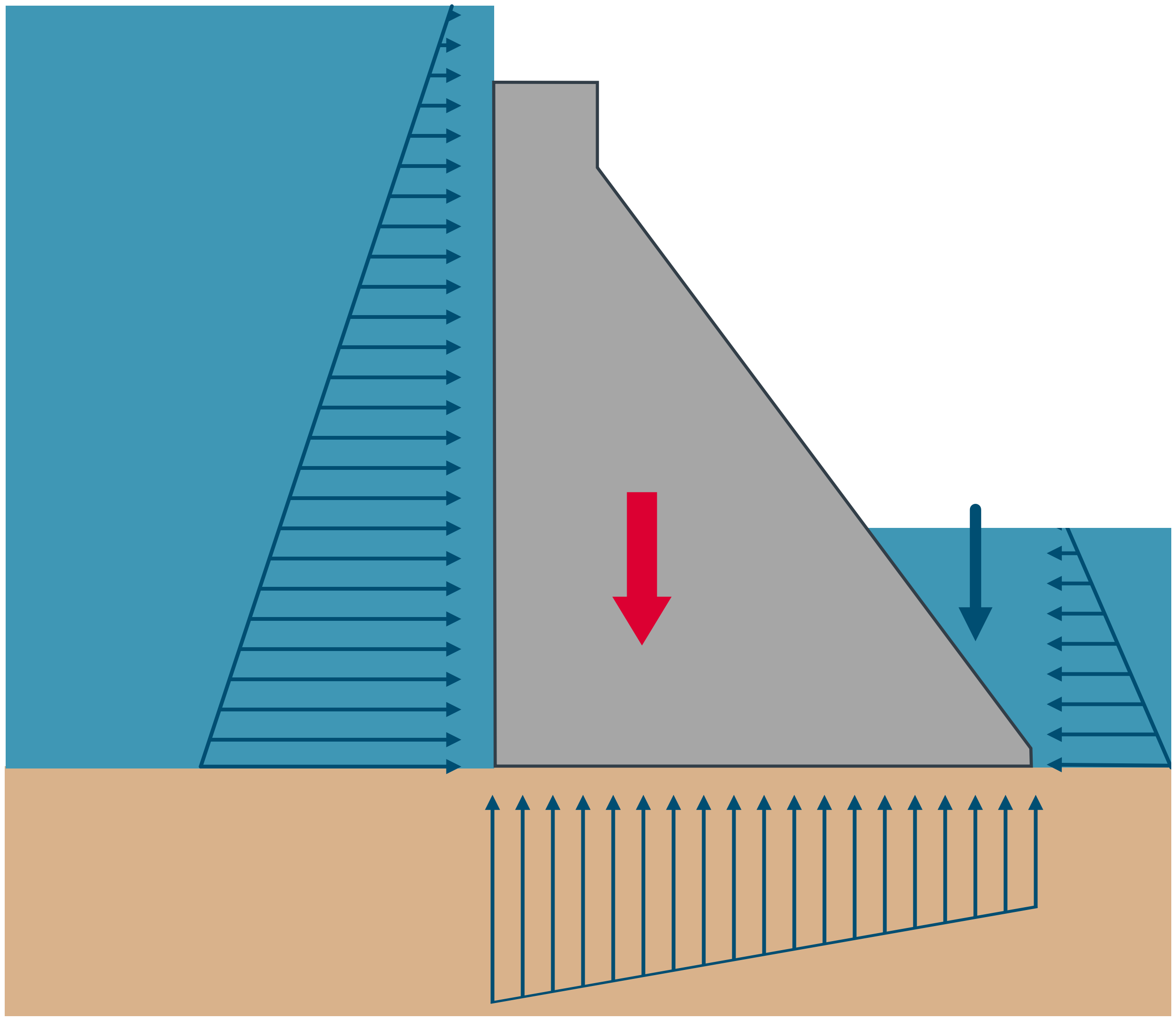
HOW AND FOR WHAT ARE DAMS ANALYZED?

Unusual Load Combination

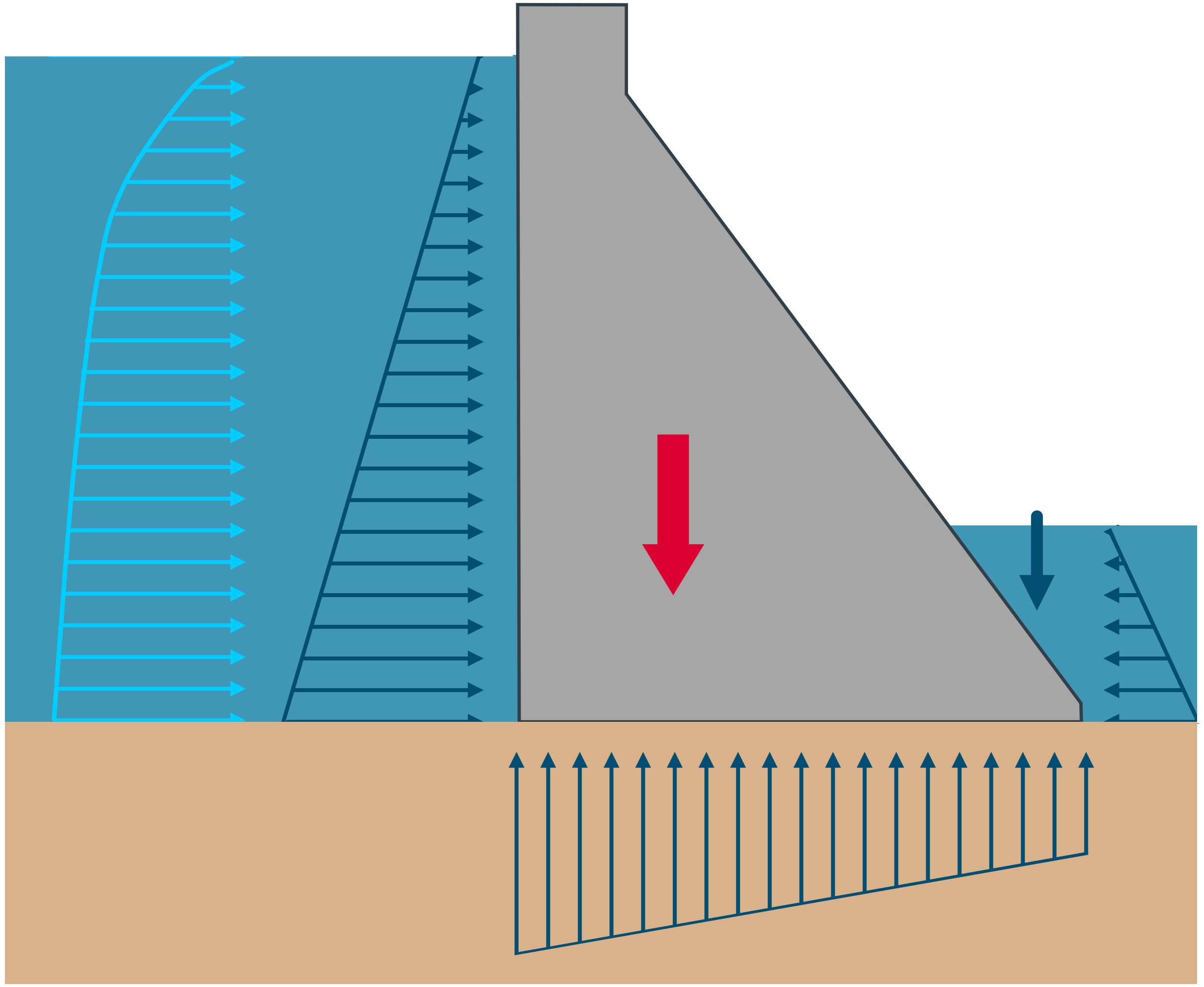
- Gravity
- Reservoir - Flood
- Tailwater
- Sediment
- Uplift



HOW AND FOR WHAT ARE DAMS ANALYZED?

Extreme Load Combination

- Gravity
- Reservoir
- Tailwater
- Sediment
- Uplift
- Reservoir added mass
- Earthquake



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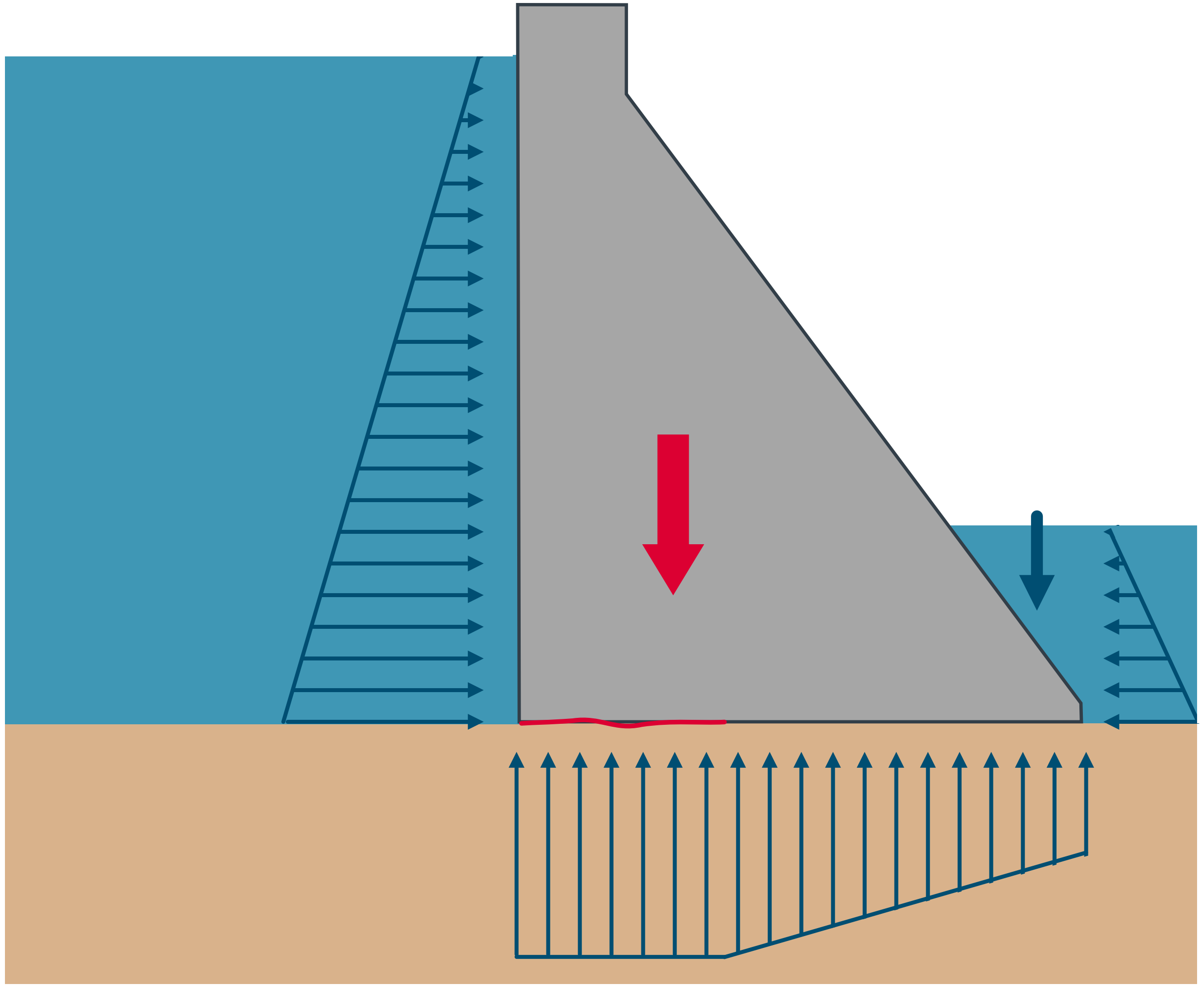
HOW AND FOR WHAT ARE DAMS ANALYZED?

Post-Earthquake Combination

- Gravity
- Reservoir
- Tailwater
- Sediment
- Uplift



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BASIC CONCRETE DAM FAILURE MODES

BASIC CONCRETE DAM FAILURE MODES

Overstressing

Computed Stresses < Allowable Strength

Rotational and Sliding Stability

Sliding Factor Of Safety

Developing a Failure Mode

Initiating Event

→ **Progression**

→ **Failure**

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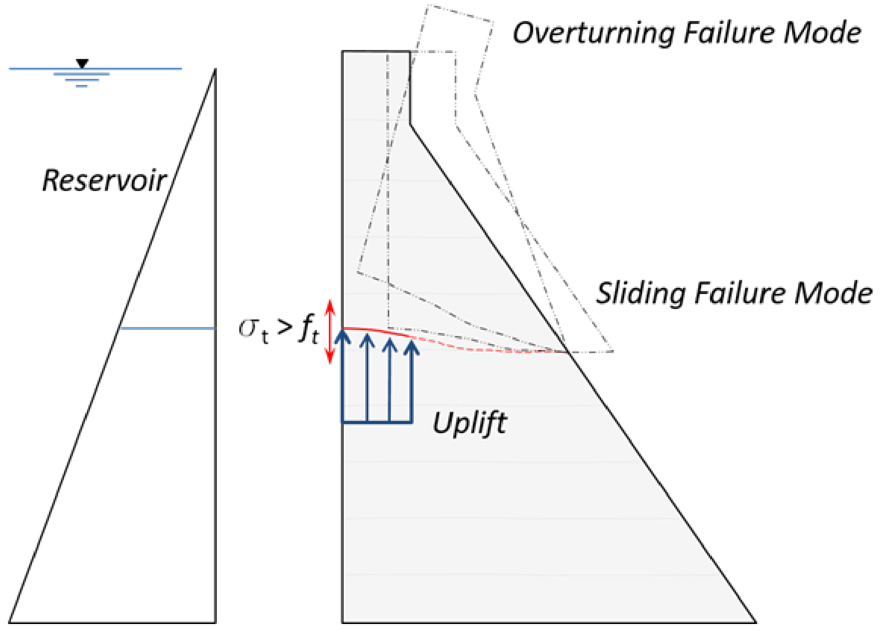
BASIC CONCRETE DAM FAILURE MODES

Dam Internal Instability (Overstressing)

- Hydrologic event up to and including the PMF event occurs.
- Inflows into the reservoir are greater than the outflow capacity causing an increase in the reservoir level.
- Higher reservoir level results in increased load on the dam which cause an increase in the stresses in the dam.
- Increased stresses are greater than the capacity of the concrete, resulting in crack development.
- Uplift develops within crack, resulting in crack propagation.
- Driving force is greater than the capacity resulting in instability along the cracked section causing breach and uncontrolled release of the reservoir.



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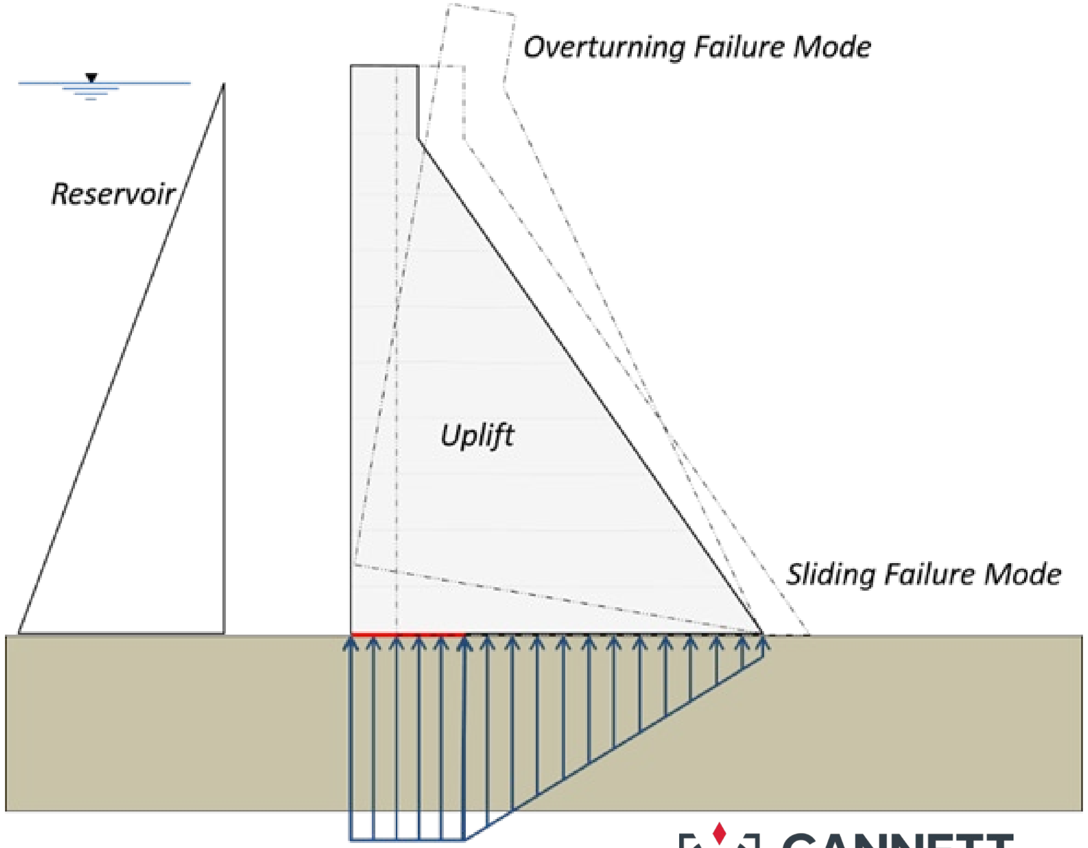
BASIC CONCRETE DAM FAILURE MODES

Dam External Instability

- Hydrologic event up to and including the PMF event occurs.
- Inflows into the reservoir are greater than the outflow capacity causing an increase in the reservoir level.
- Higher reservoir level results in increased load on the dam which cause separation along the dam/foundation interface.
- Separation along the interface at the upstream heel results in an increase in the uplift pressure.
- Driving force along the interface is greater than the capacity, and results in instability along the interface causing breach and uncontrolled release of the reservoir.



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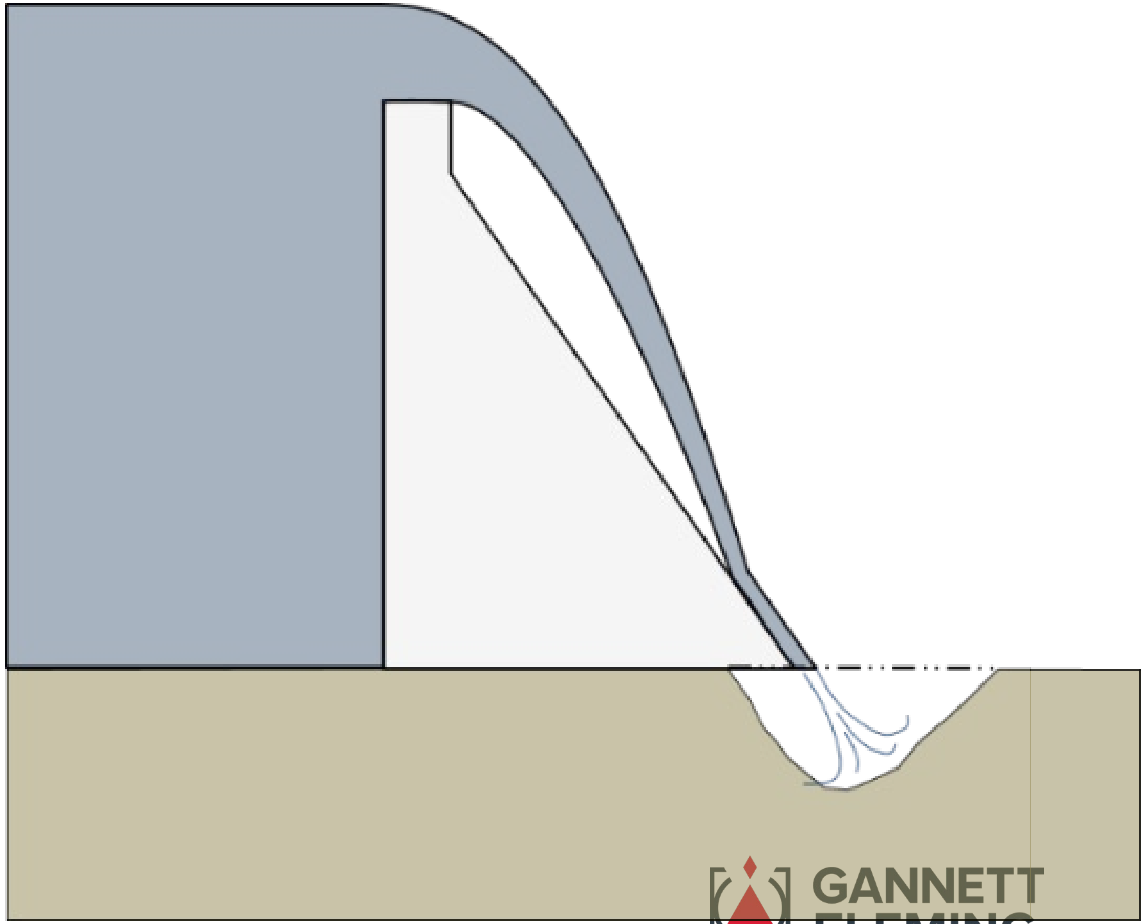
BASIC CONCRETE DAM FAILURE MODES

Dam Overtopping

- Hydrologic event up to and including the PMF event occurs.
- Inflows into the reservoir are greater than the outflow capacity causing an increase in the reservoir level.
- Higher reservoir level overtops crest of dam and overtopping jet impacts downstream foundation rock.
- Streampower from overtopping jet is greater than erodibility index of the rock abutments, resulting in scour.
- Rock scour progresses beneath the dam, resulting in reduced shear capacity.
- Driving force is greater than the capacity, and results in instability and uncontrolled release of the reservoir.



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BASIC CONCRETE DAM FAILURE MODES

BENEFITS OF THE PFMA PROCESS

- Understanding of how the dam functions and could fail
- Results help develop dam safety program
- Learn intimate details of the dam
- Identify knowledge gaps and missing analyses
- Operation and Maintenance
- Surveillance and Monitoring

BASIC CONCRETE DAM FAILURE MODES

SURVEILLANCE AND MONITORING

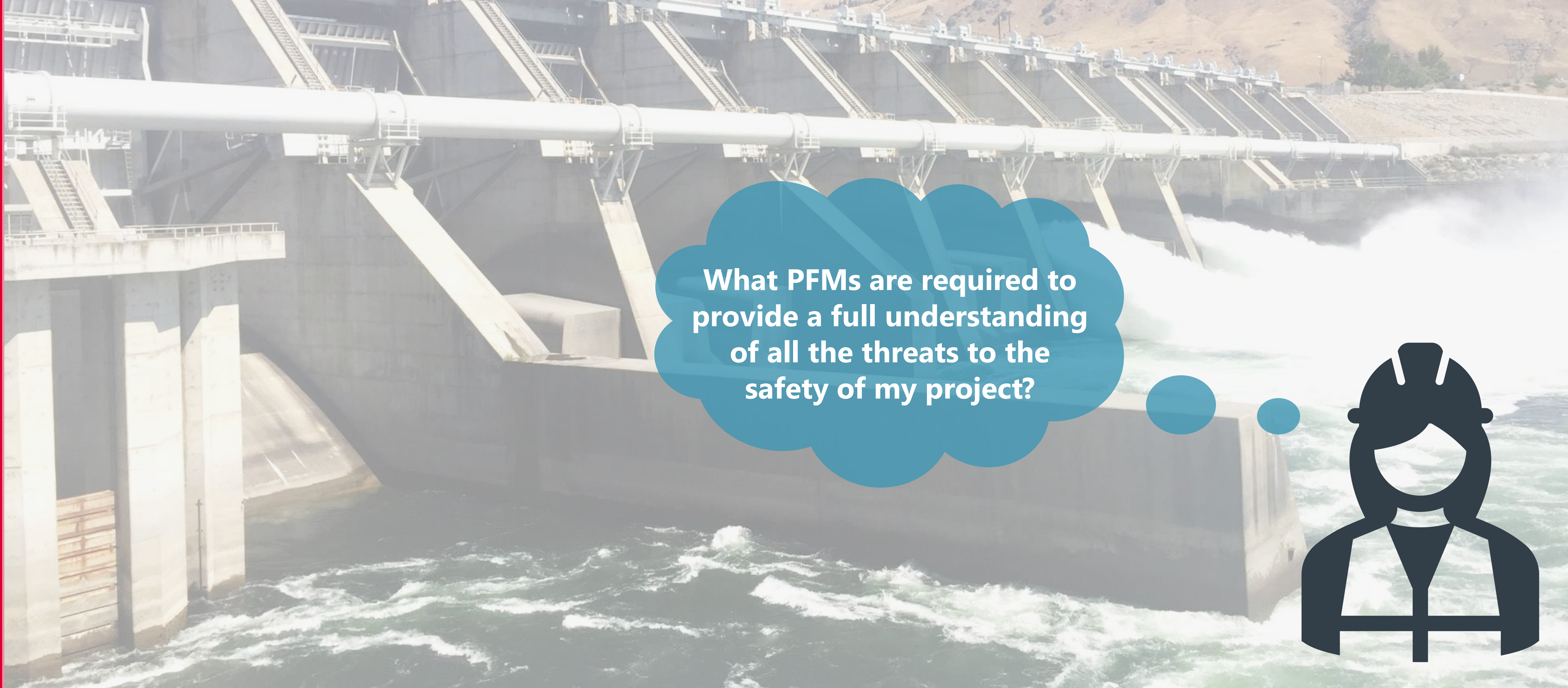
Defines what needs to be monitored

Performance Parameters

Risk reduction measures

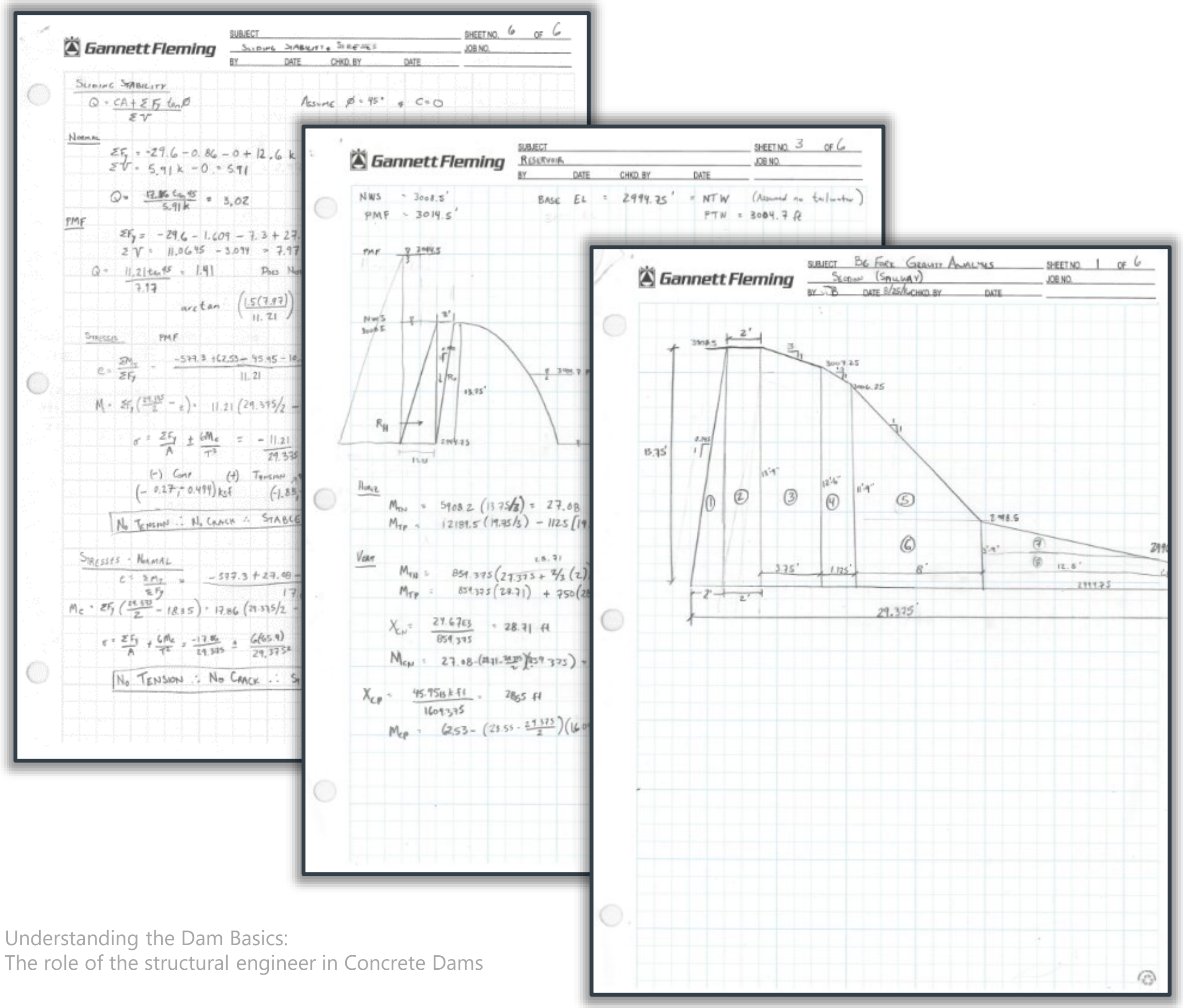
Identify unknown flaws

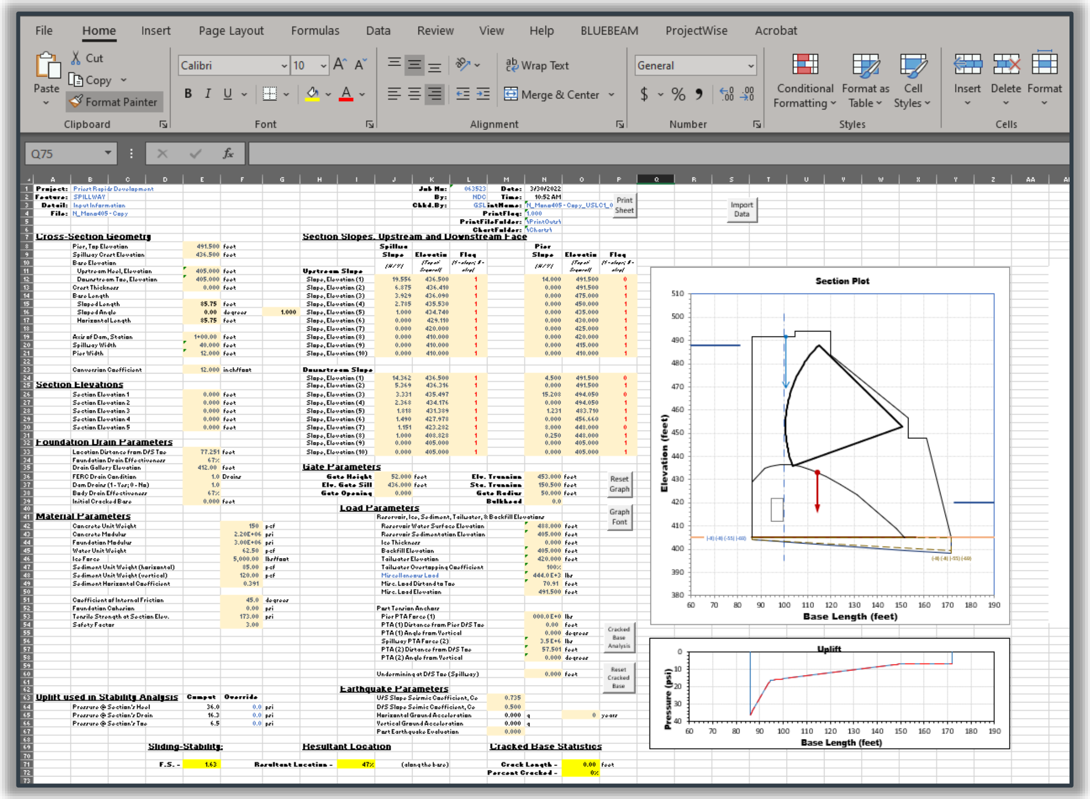
BASIC CONCRETE DAM FAILURE MODES



ANALYSIS OPTIONS

ANALYSIS OPTIONS





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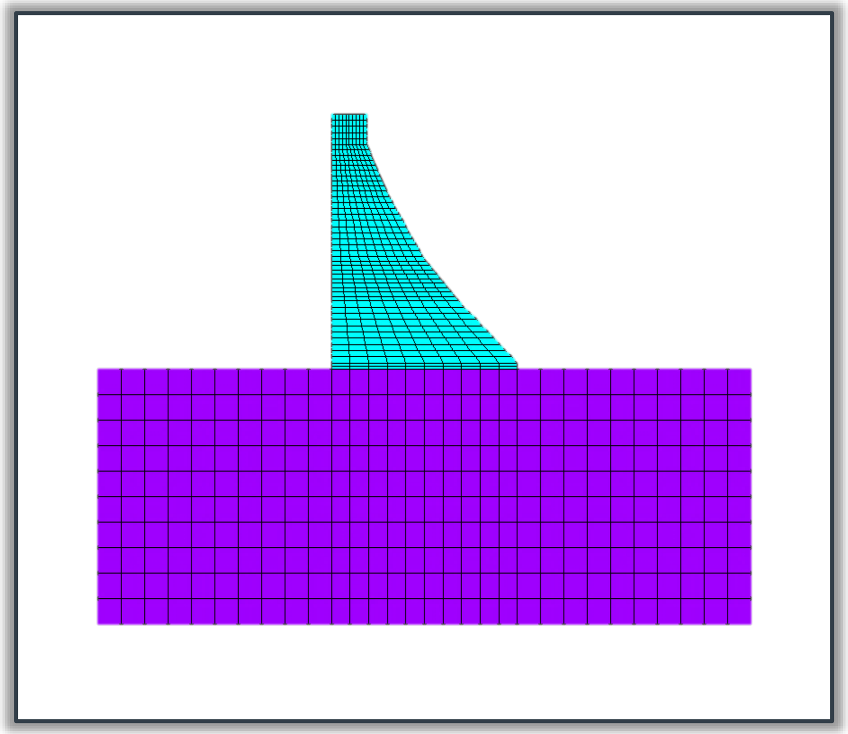
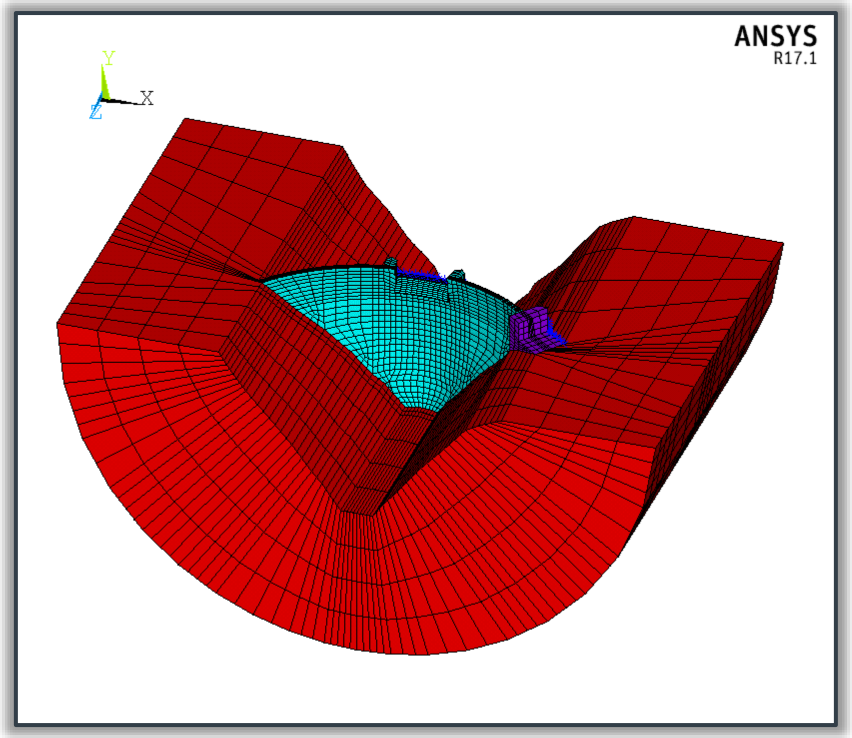
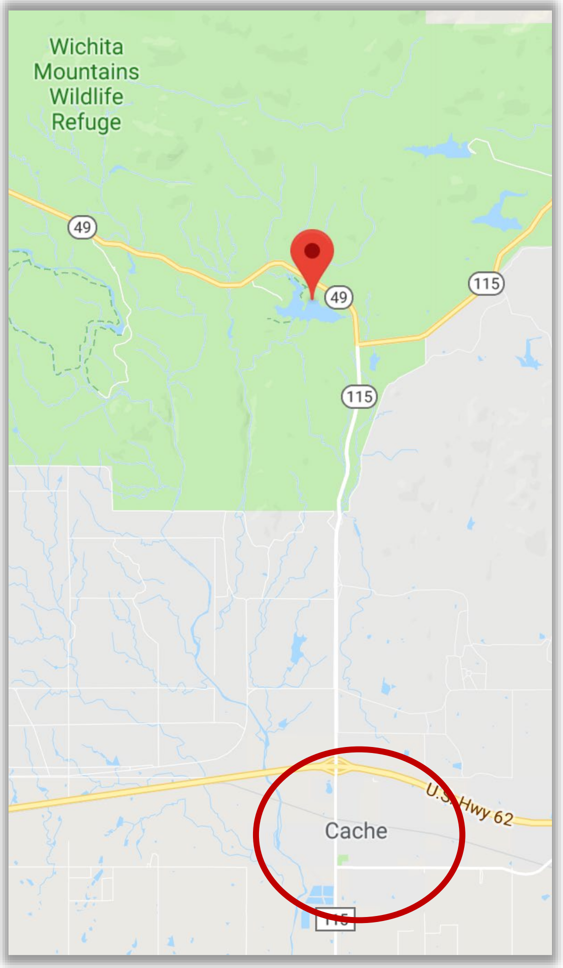
ANALYSIS OPTIONS

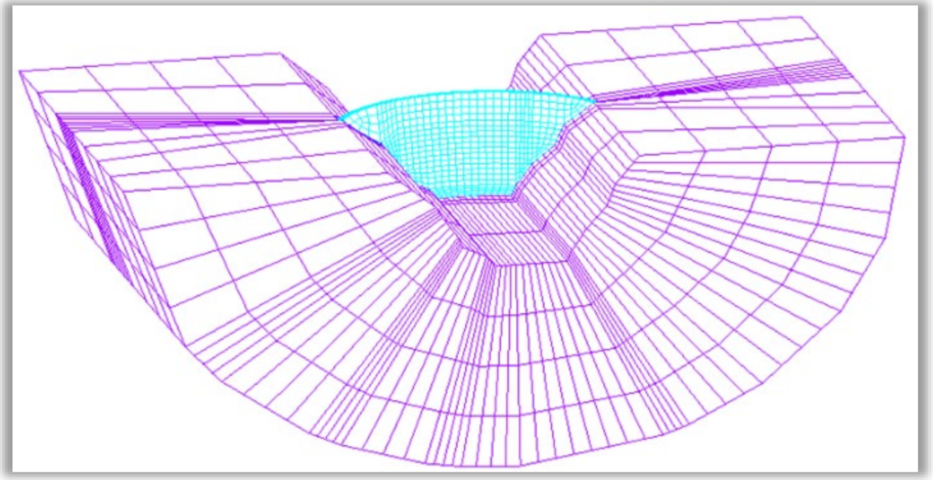




EXAMPLES: PULLING ALL THE PIECES TOGETHER

EXAMPLE #1





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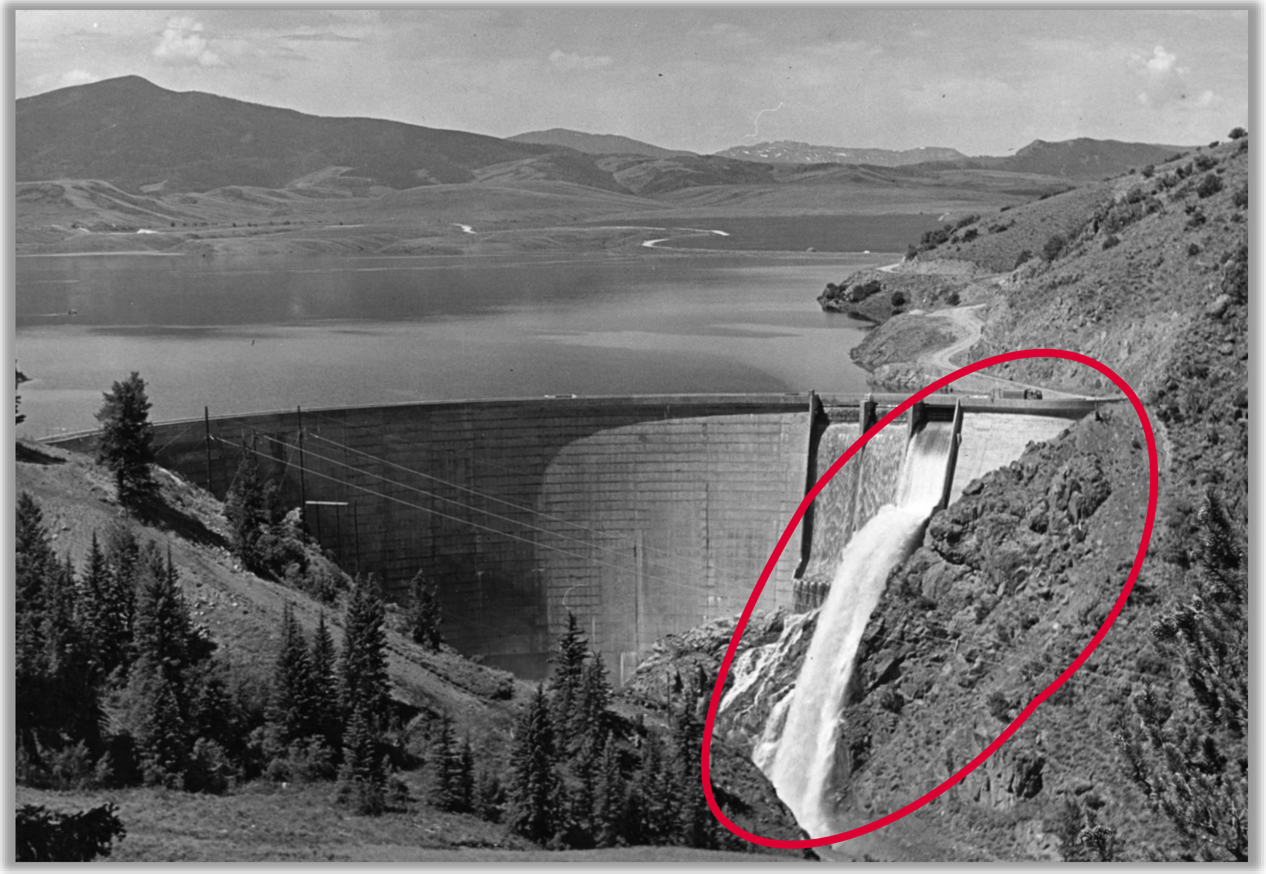
EXAMPLE #2



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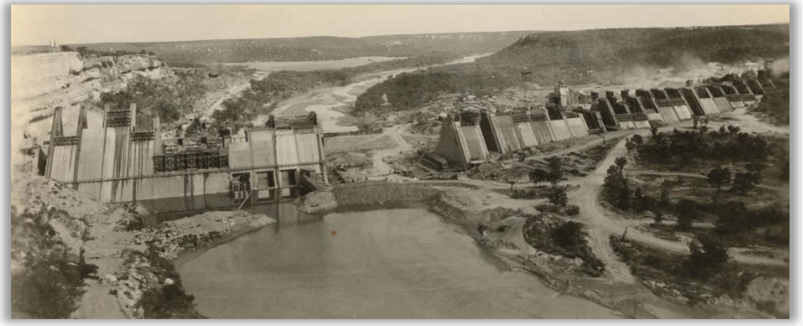
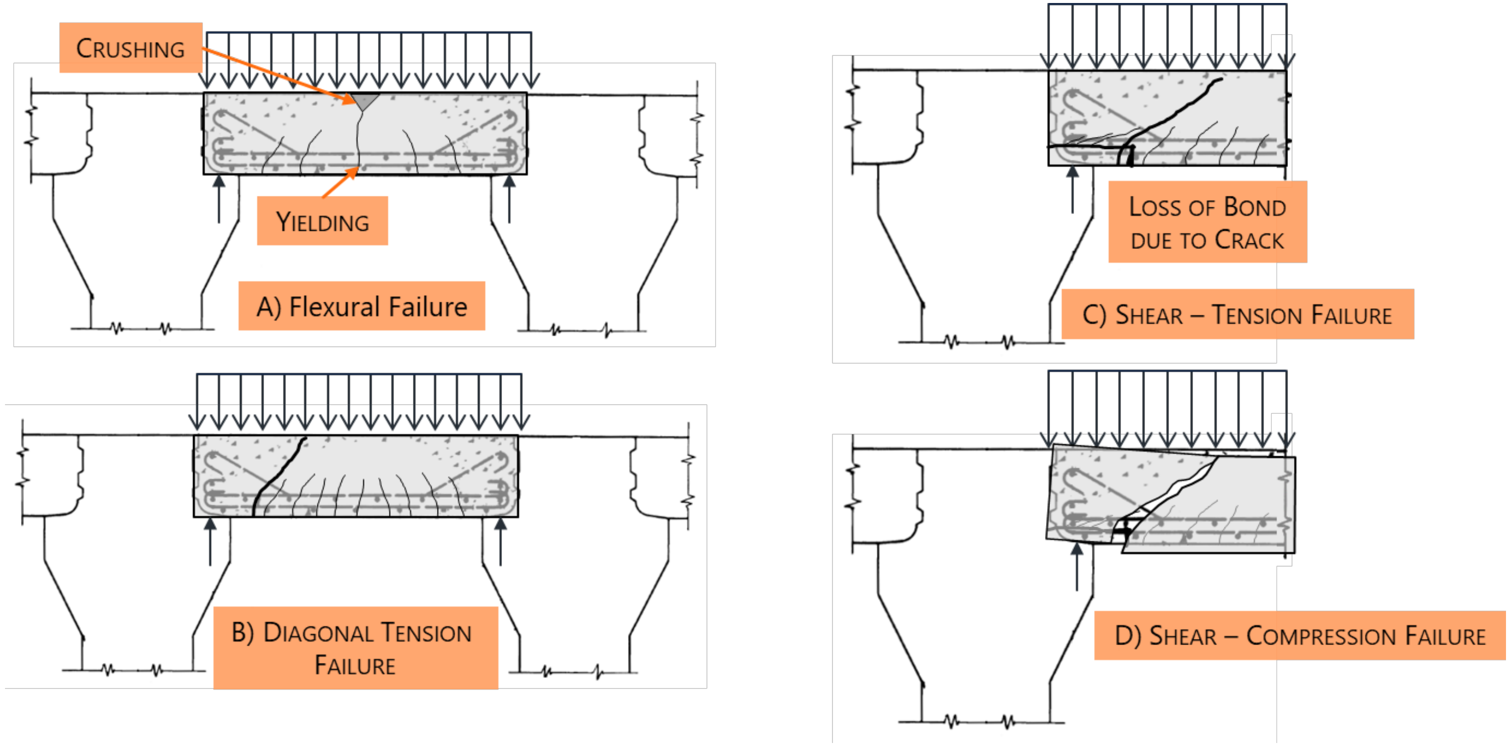
EXAMPLE #3





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Questions & Answers

THANK YOU!

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