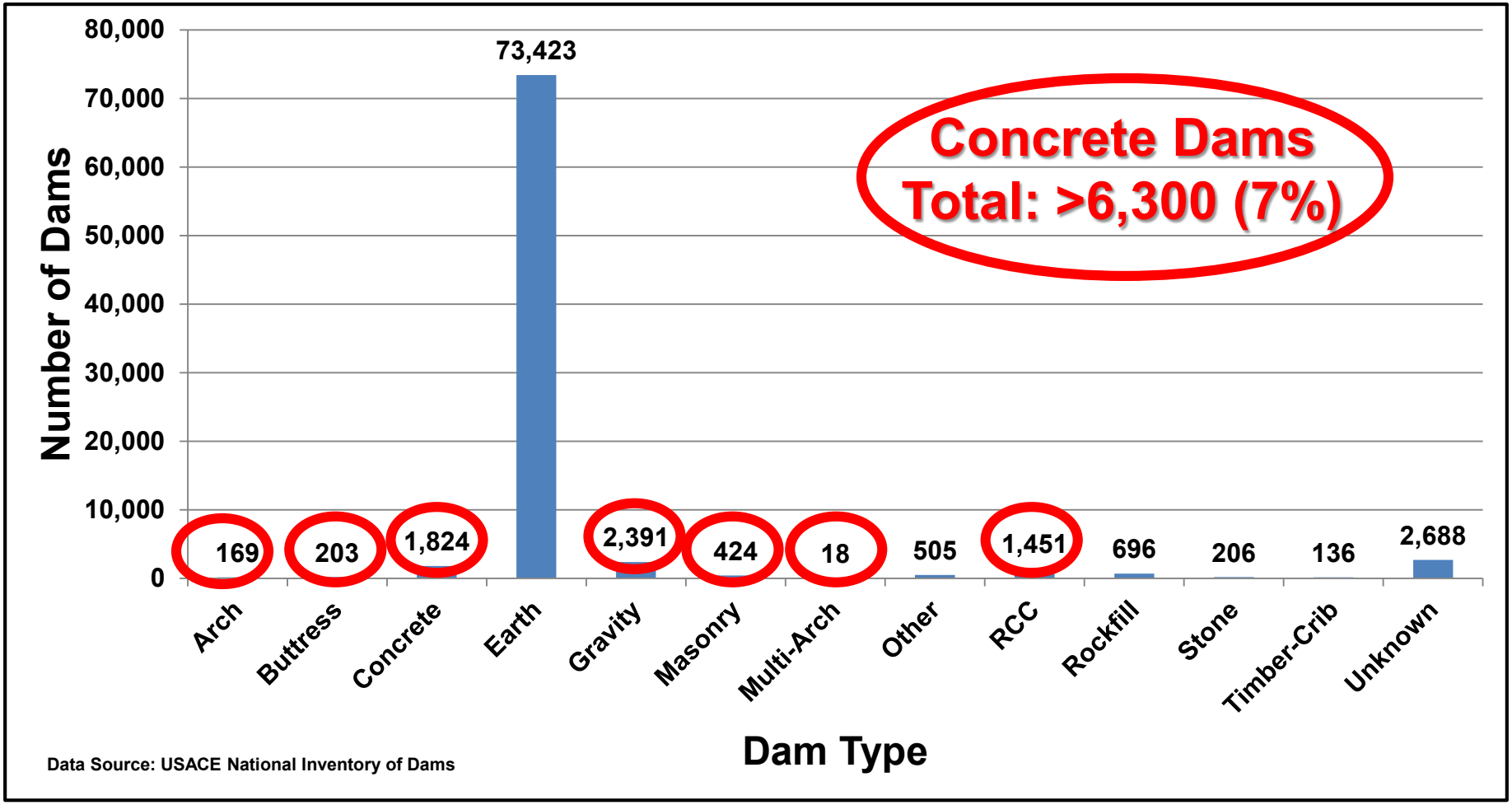
Lessons Learned from Concrete Dam Failures

Gannett Fleming

Maryland Department of the Environment

U.S. Dams by Type



Gravity Spillways

Gravity dams are designed so that each section of the dam is stable, independent of any other dam section

US Deaths From Dam Failures

Dam Failure	Lives Lost
South Fork, PA (1889)	2,209
St. Francis, CA (1928)	450
Walnut Grove, AZ (1890)	150
Mill River, MA (1874)	143
Buffalo Creek, WV (1972)	125
Austin, PA (1911)	80
Laurel Run, PA (1977)	40
Kelly Barnes, GA (1977)	39
Canyon Lake, SD (1972)	33
Teton, ID (1976)	14
Swift, MT (1964)	19
Ka Loko, HI (2006)	8

US Deaths From Dam Failures

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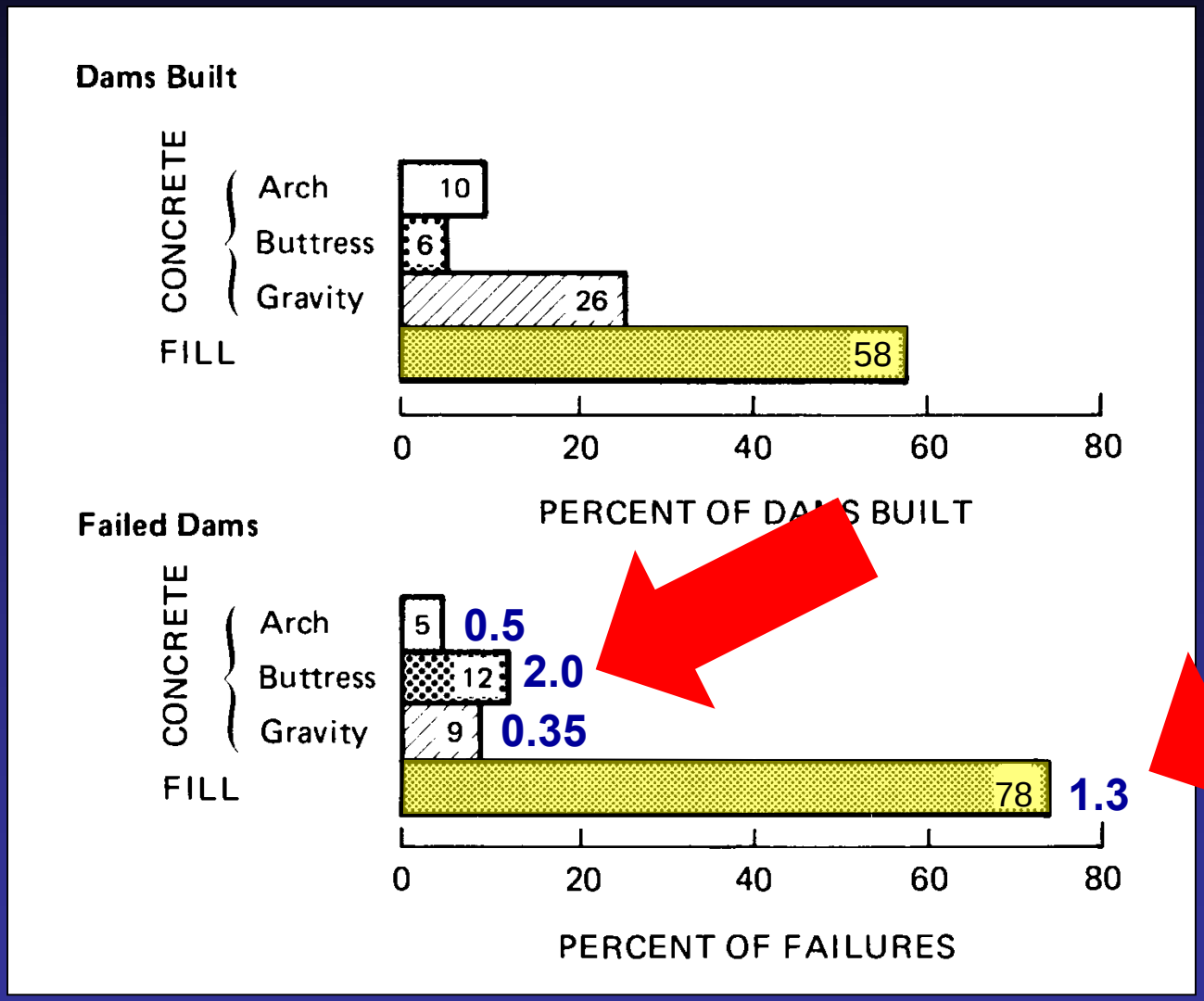
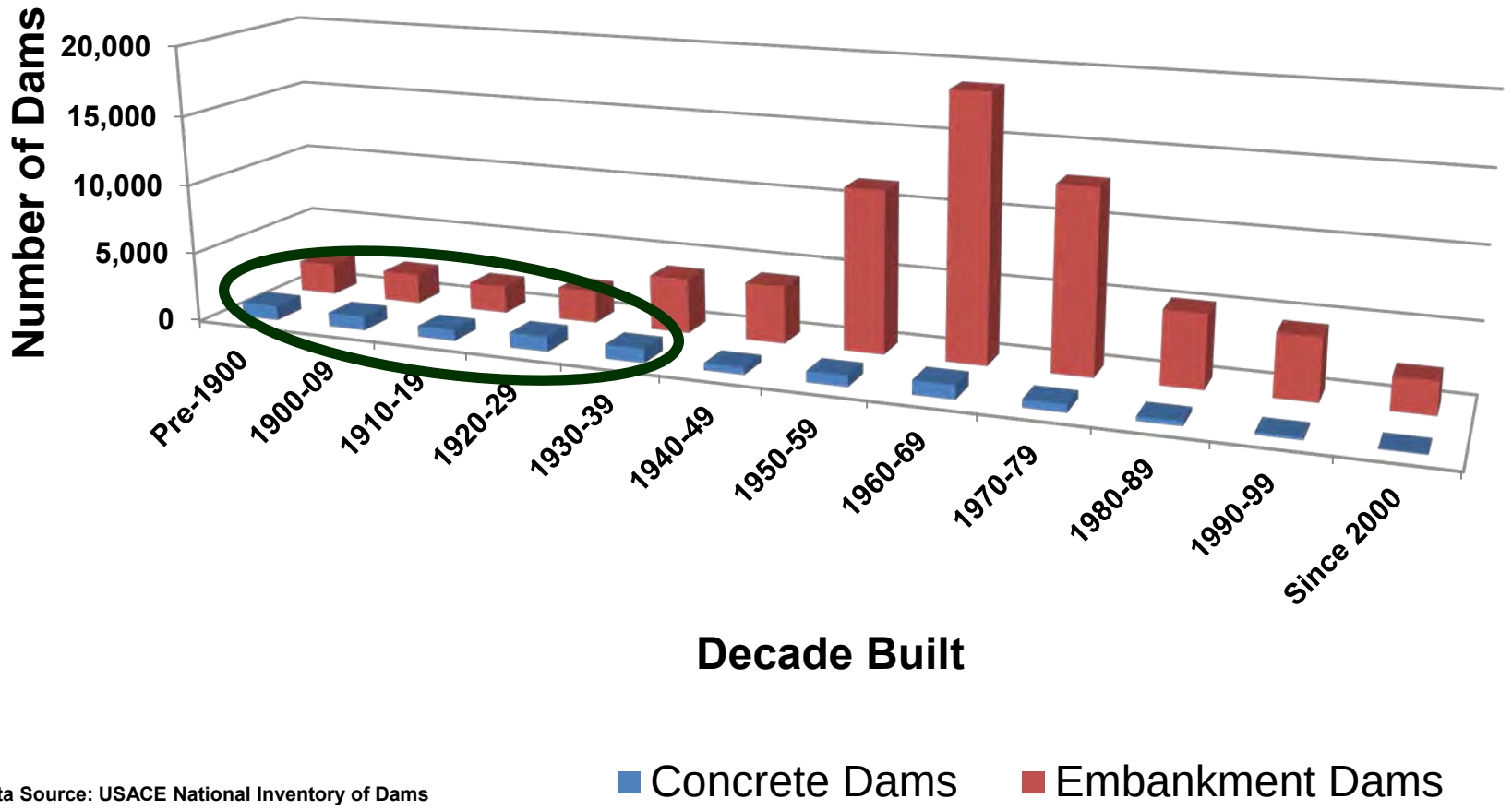
Failures By Dam Type



Source: NRC, Safety of Existing Dams, 1983

U.S. Dams by Decade Built

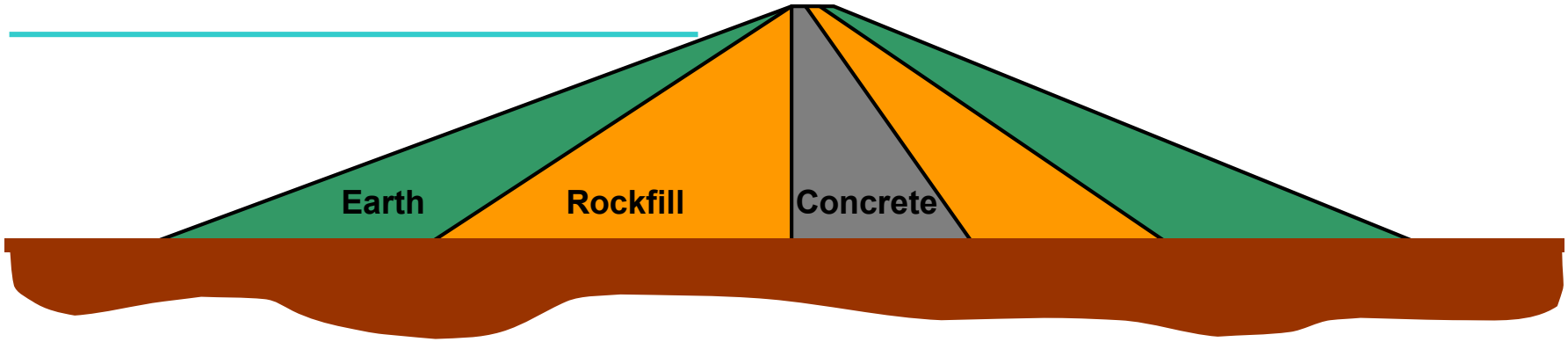


Data Source: USACE National Inventory of Dams

Dam Type Comparison

Concrete Gravity Dam Limitations:

1. High Seepage Gradient
2. Best on Shallow/Sound Rock Foundations



Concrete Gravity Dam Advantages:

1) Smaller Material Volume
2) Smaller Foundation Footprint
3) Integrated Spillway / Outlet Works
4) Better Withstands Overtopping
5) More Easily Facilitates Future Raise

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Furens Dam
St. Etienne, France
Built 1858-66

Image Source: The Design and Construction of Dams, E. Wegmann

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Stone Masonry

Furens Dam
St. Etienne, France
Built 1858-66

Image Source: The Design and Construction of Dams, E. Wegmann

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Stone Masonry

Sodom Dam
New York, NY
Built 1888-93

Image Source: The Design and Construction of Dams, E. Wegmann

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

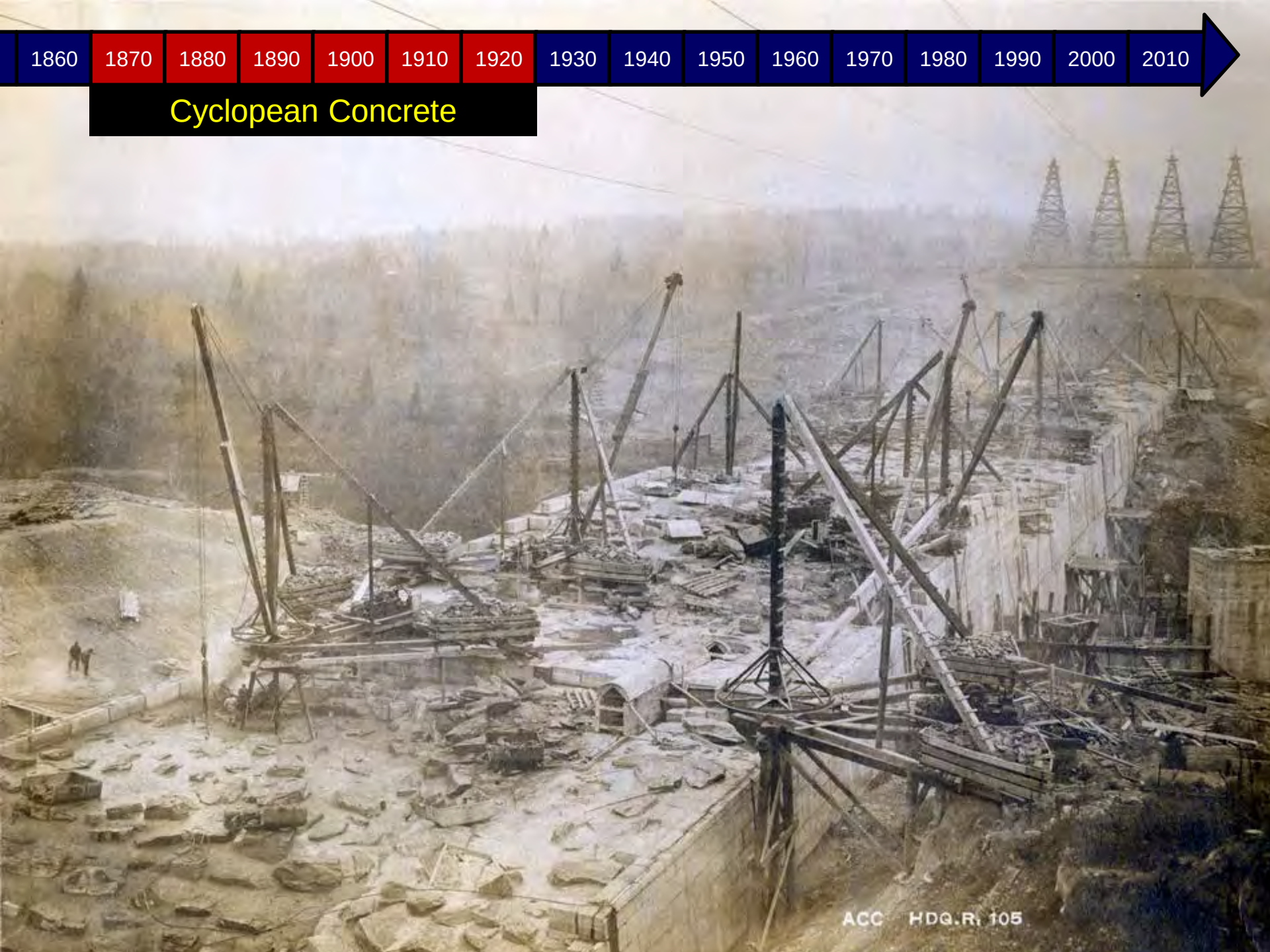
Stone Masonry

Sodom Dam
New York, NY
Built 1888-93

Image Source: The Design and Construction of Dams, E. Wegmann

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Cyclopean Concrete

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Cyclopean Concrete

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Cyclopean Concrete

ACC HDQ. R. 123

CONTRACT 3. MAY, 11, 1910.

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Reinforced Concrete

Big Bear Valley Dam
San Bernardino, CA
Built 1911

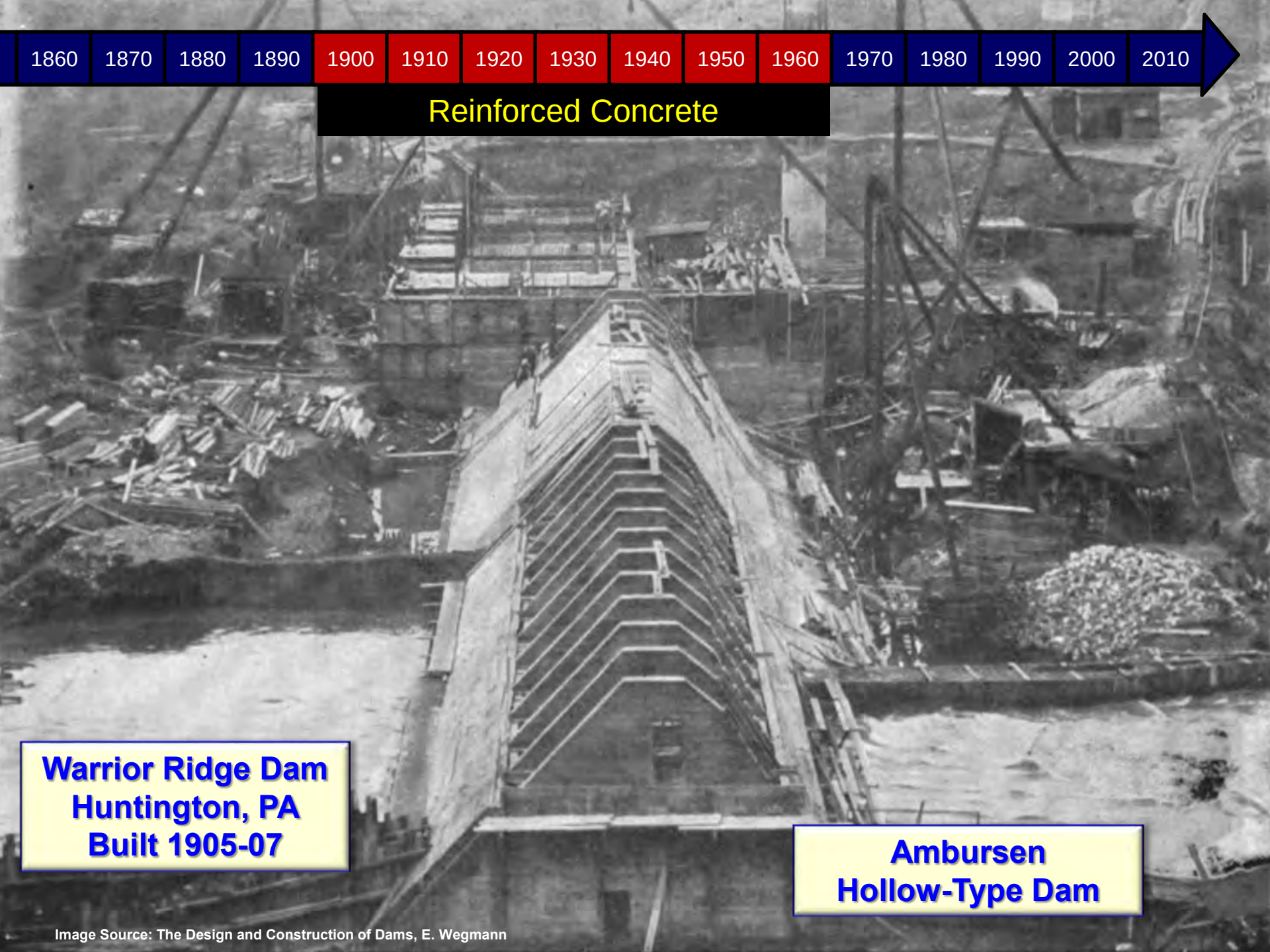

Image Source: The Design and Construction of Dams, E. Wegmann

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Reinforced Concrete

Gem Lake Dam
Bishop, CA
Built 1915-16

Max. Height: 80 feet

Image Source: Southern California Edison

1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Conventional Mass Concrete

Shasta Dam
Shasta Lake City, CA
Built 1938-45


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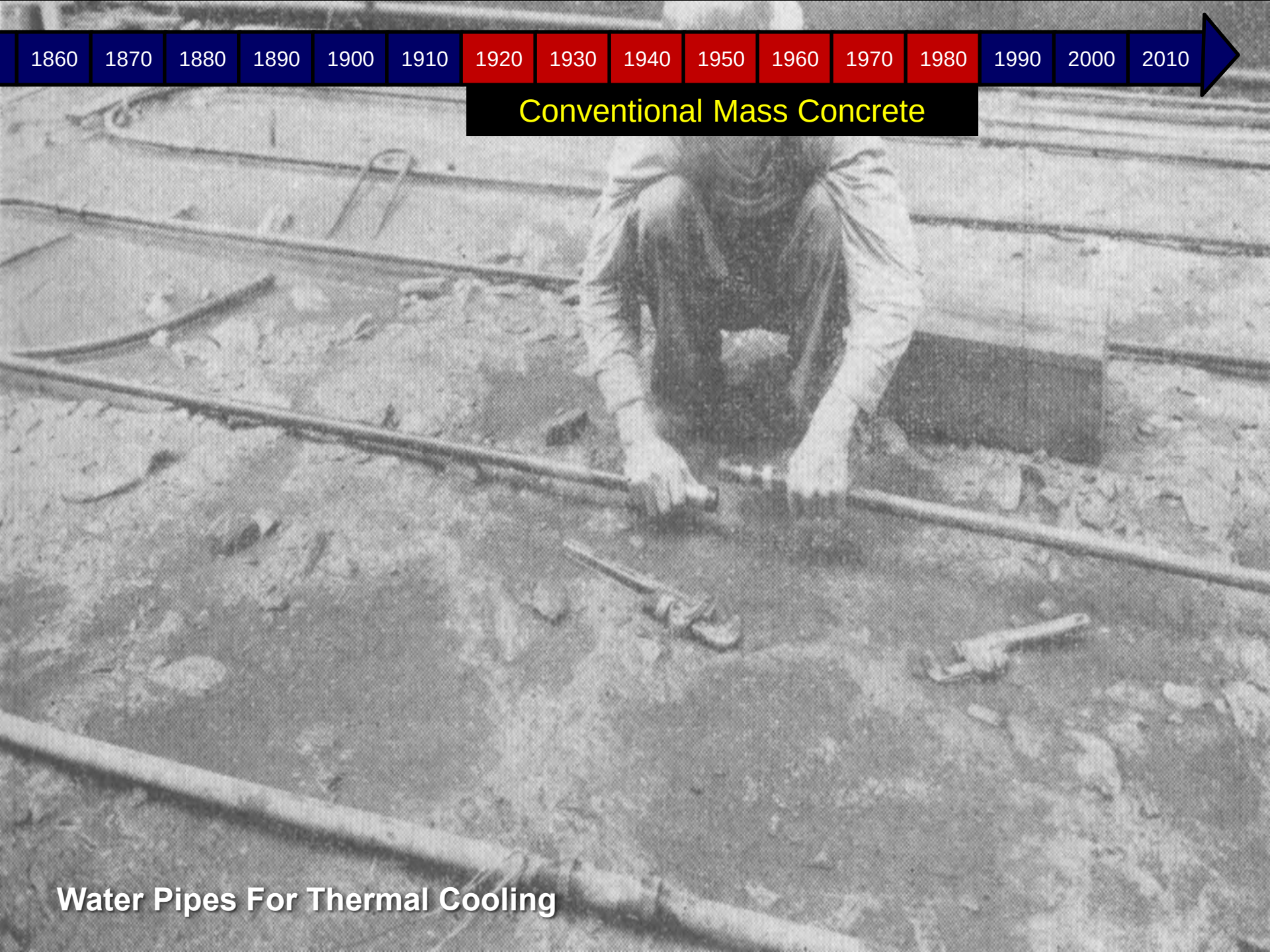
Conventional Mass Concrete
Shasta Dam
Shasta Lake City, CA
Built 1938-45
Image Source: US Bureau of Reclamation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Conventional Mass Concrete
Water Pipes For Thermal Cooling


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Roller-Compacted Concrete (RCC)
Willow Creek Dam
Heppner, OR
Built 1981-83
Image Source: US Army Corps of Engineers


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Roller-Compacted Concrete (RCC)
Spreading


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Roller-Compacted Concrete (RCC)
Compaction


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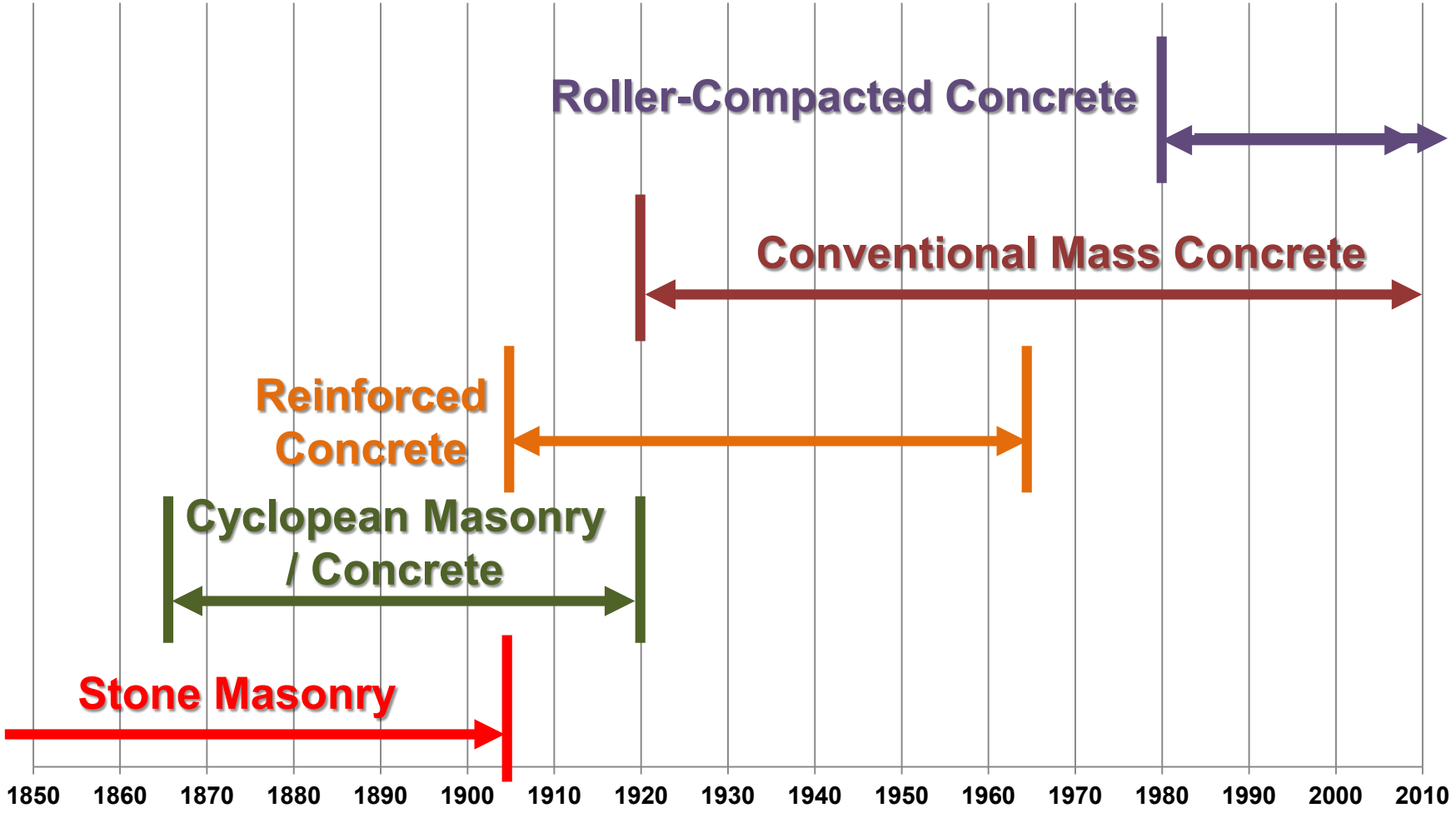
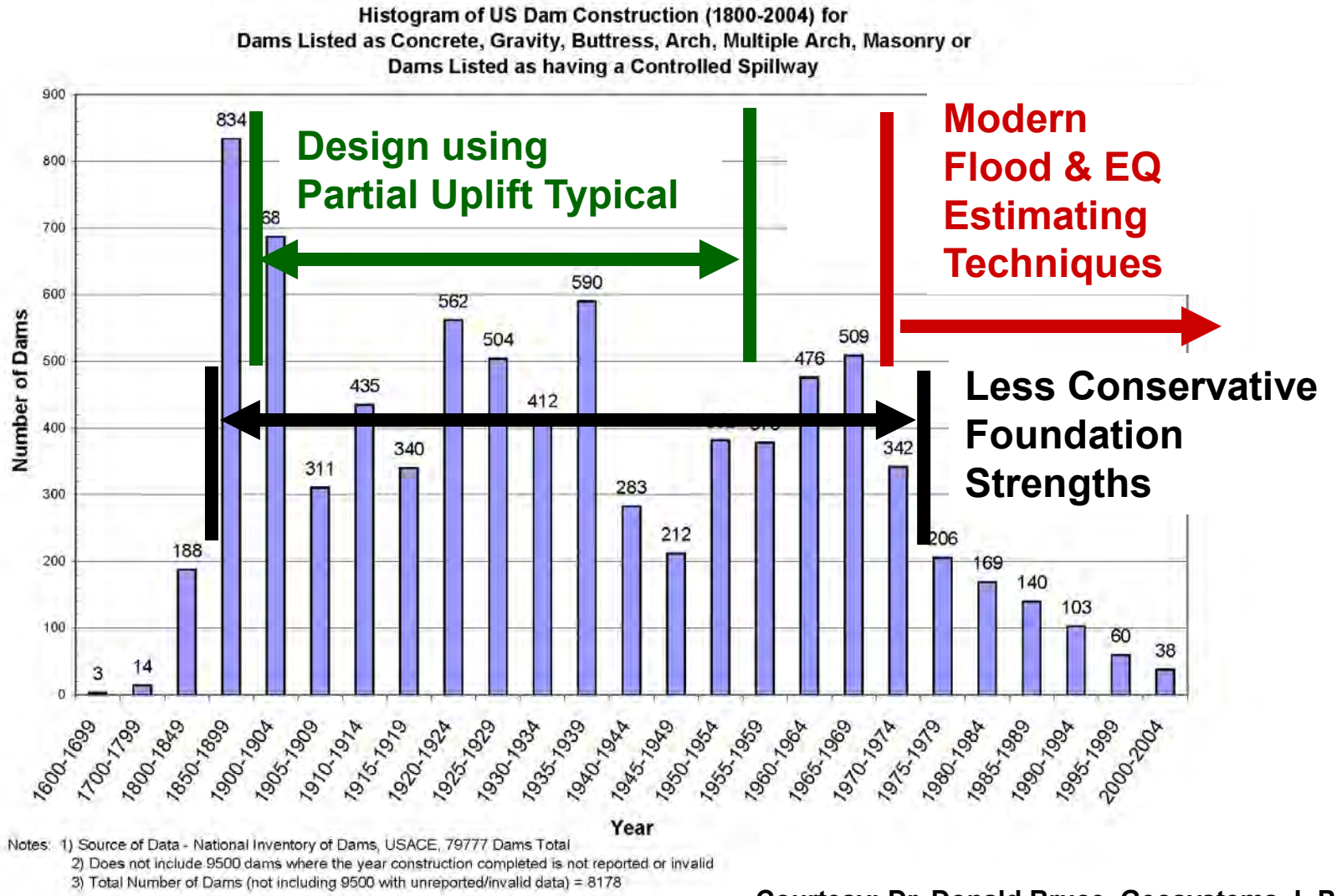
2010
Roller-Compacted Concrete (RCC)
Olivenhain Dam, CA

Construction Practice Timeline





Notes: 1) Source of Data - National Inventory of Dams, USACE, 79777 Dams Total
2) Does not include 9500 dams where the year construction completed is not reported or invalid
3) Total Number of Dams (not including 9500 with unreported/invalid data) = 8178

Courtesy: Dr. Donald Bruce, Geosystems, L.P.

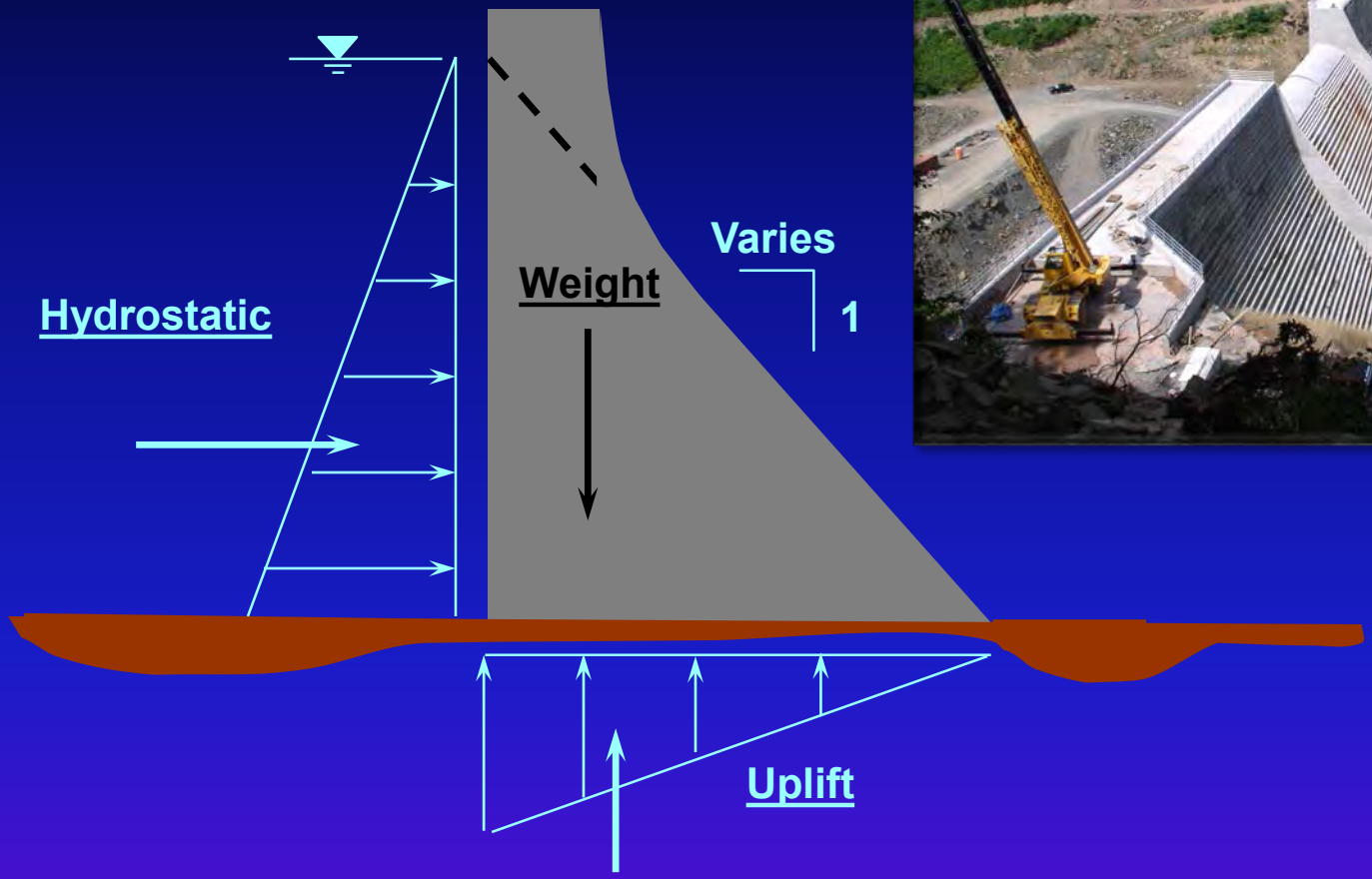
Spillway Capacity

Occoquan Dam, VA

Spillway Capacity

Occoquan Dam, VA

Typical Cross-Section



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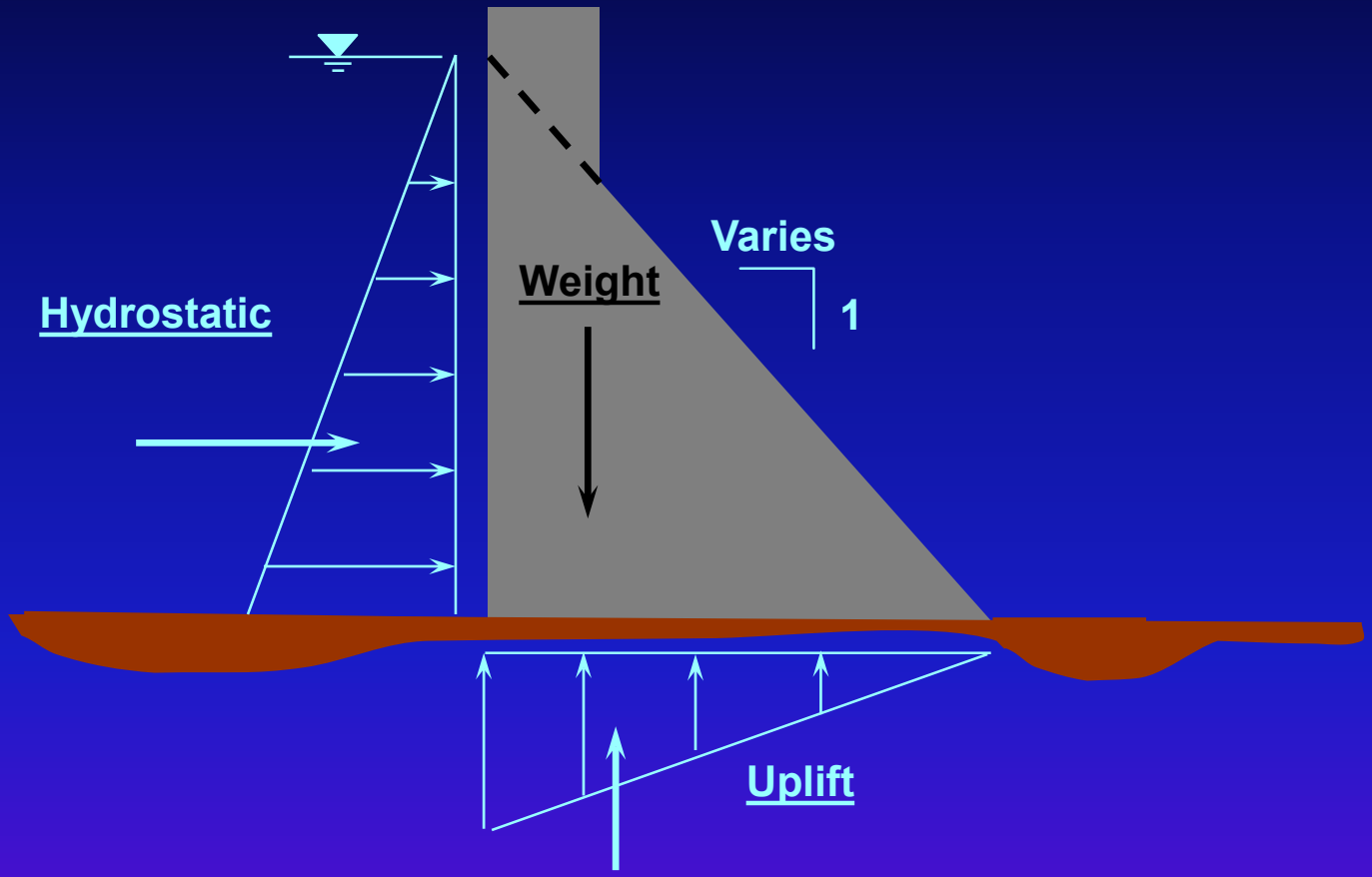
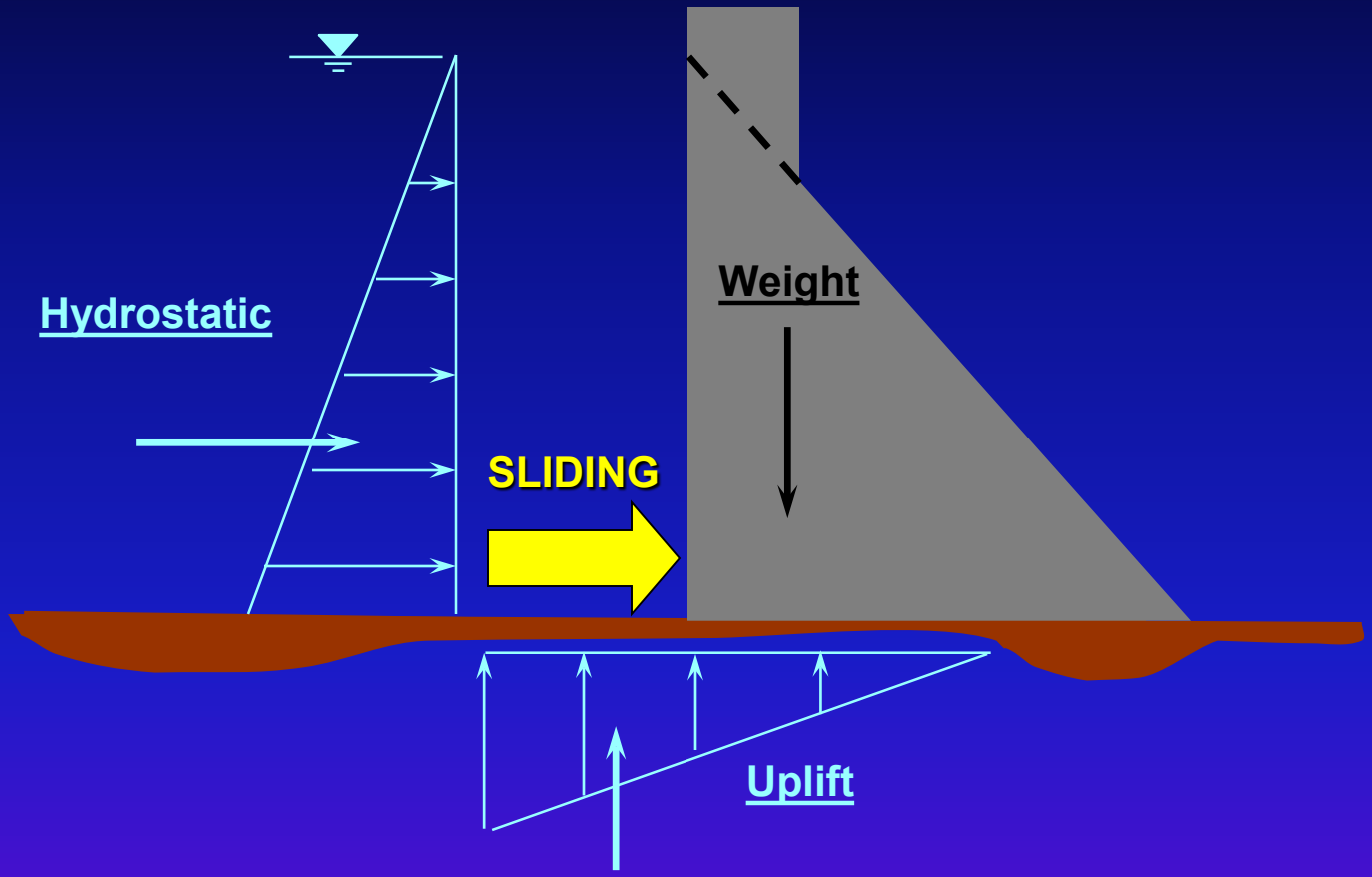
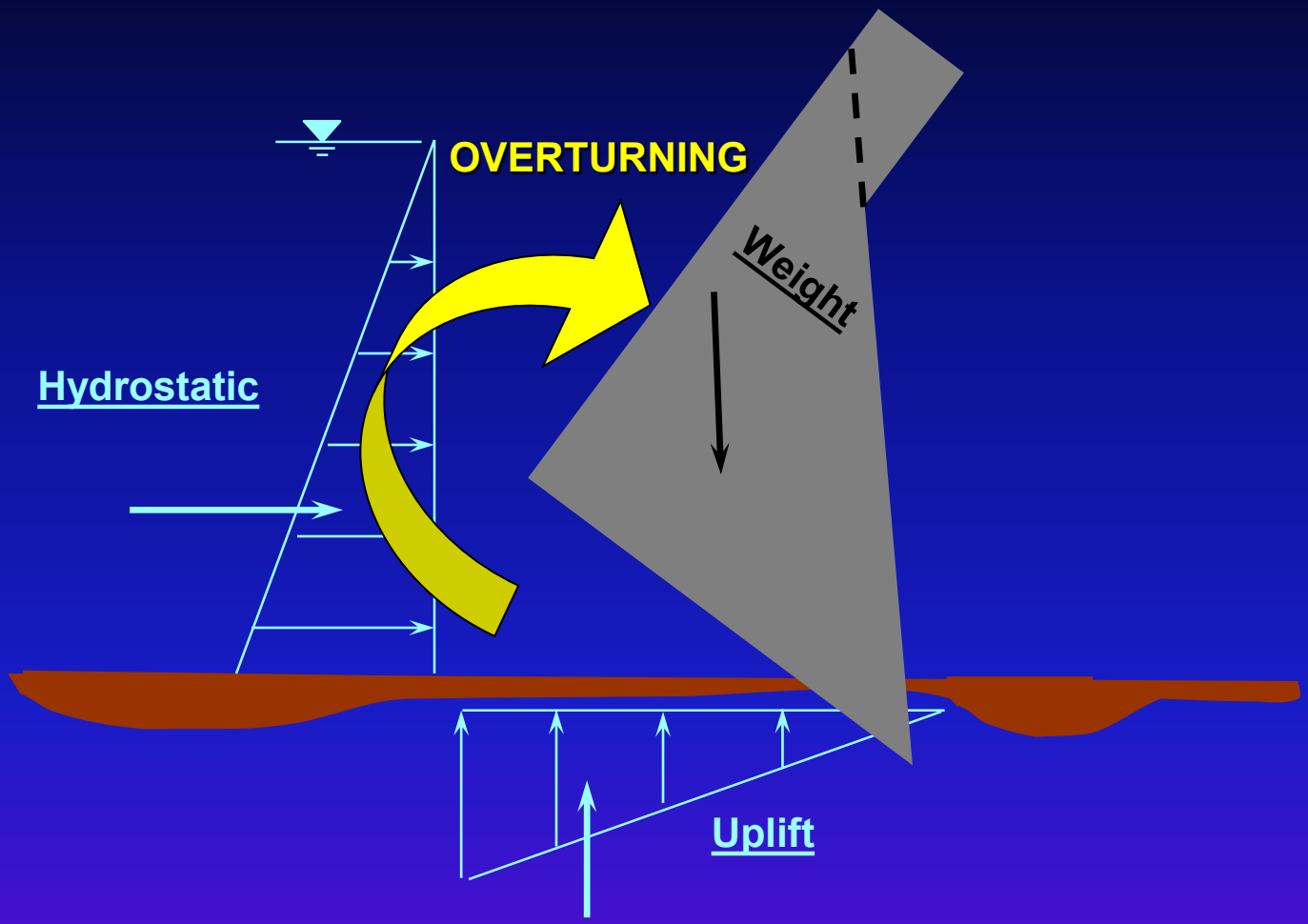


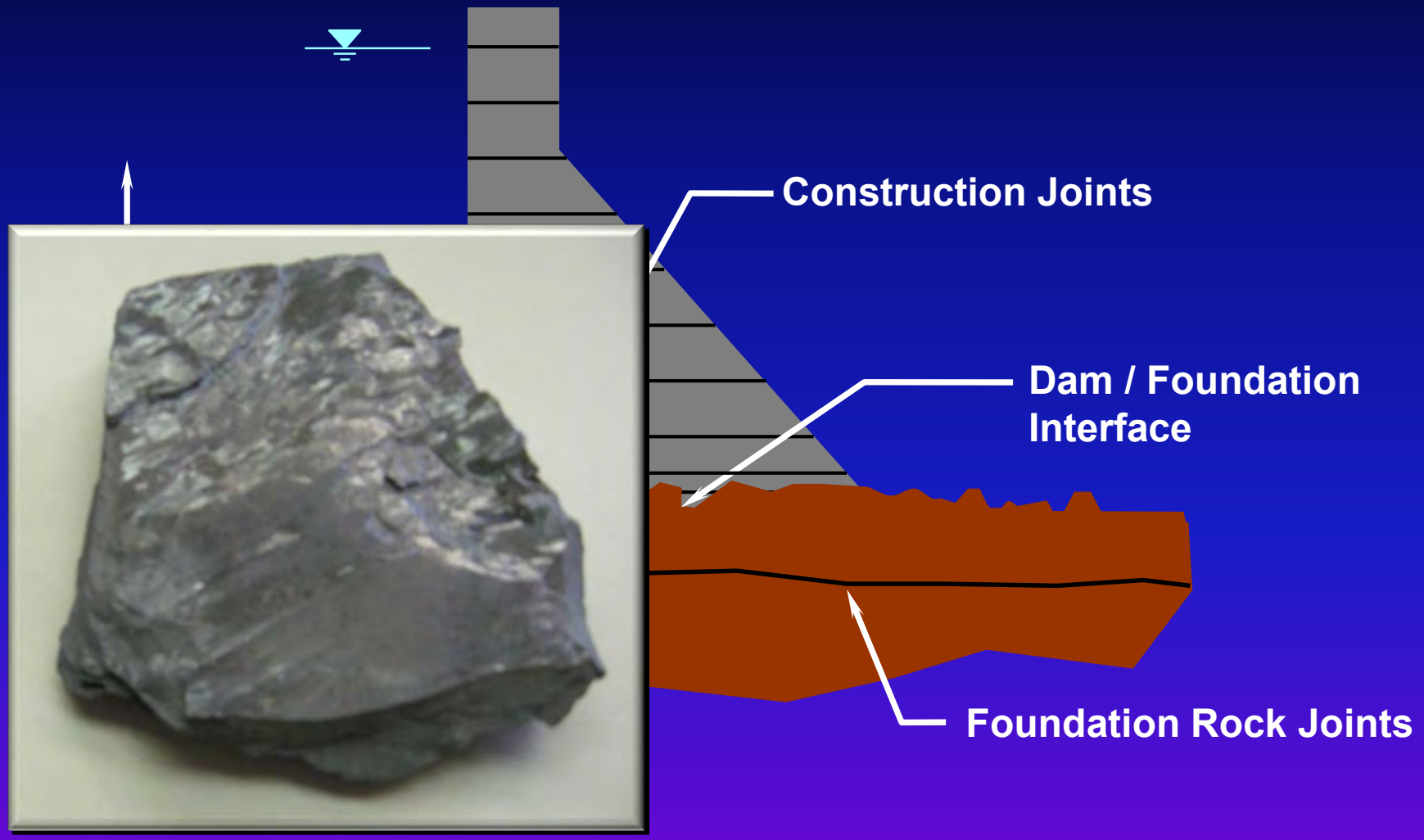
Sliding Failure Mode



Overturning Failure Mode



Critical Potential Failure Planes



“When a big project has troubles, they may well be big troubles.”

John Lowe III
Consulting Engineer
(Referring to Tarbella Dam - 1982)

NOTEWORTHY GRAVITY DAM FAILURES

Stone Masonry Gravity Dam

Built:	1878-1880
Partial Failure:	12:00 PM, March 14, 1884
Complete Failure:	5:45 AM, April 27, 1895
Fatalities:	85

BOUZEY DAM
EPINAL, FRANCE

Bouzey Dam
Epinal, France

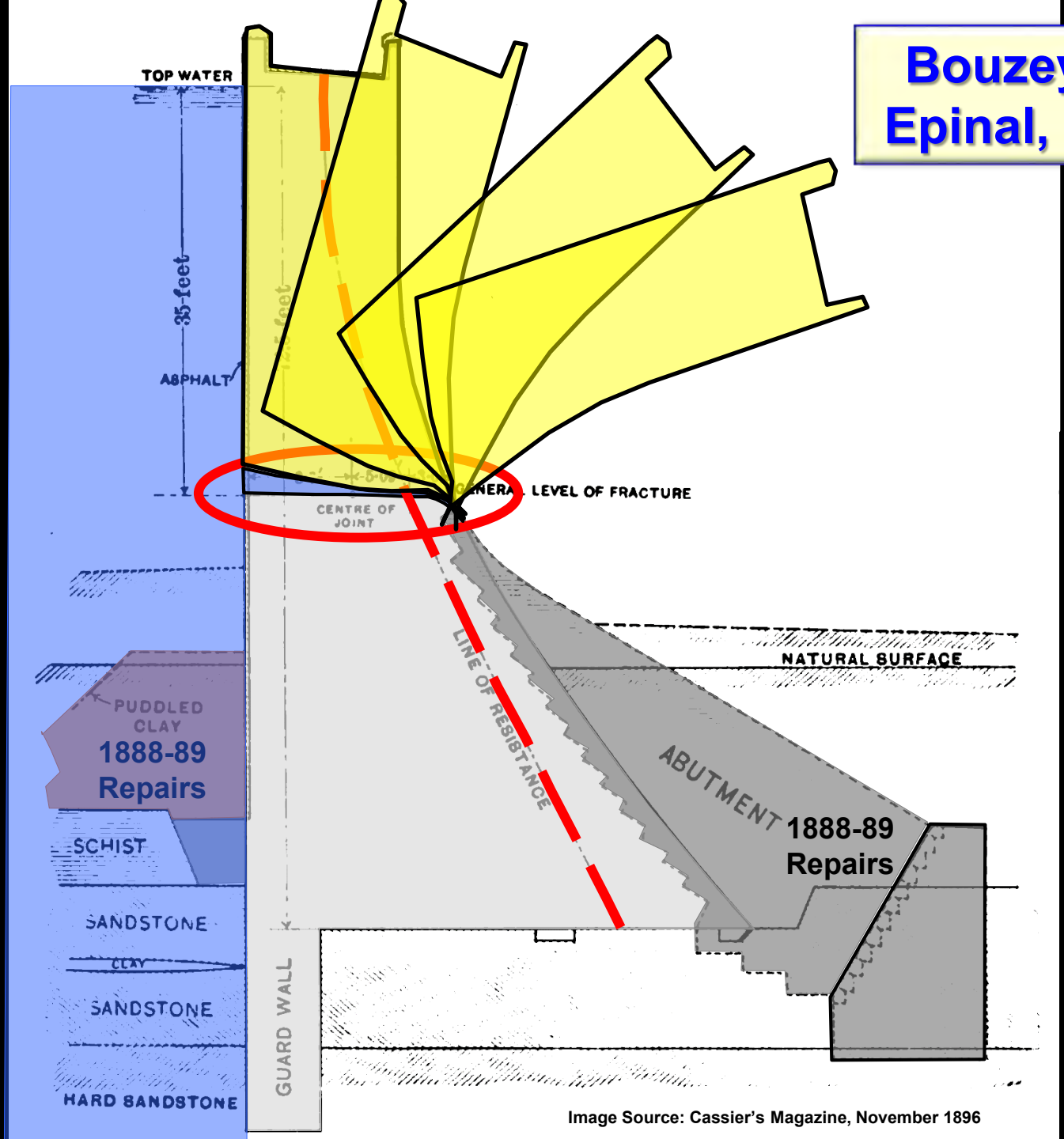
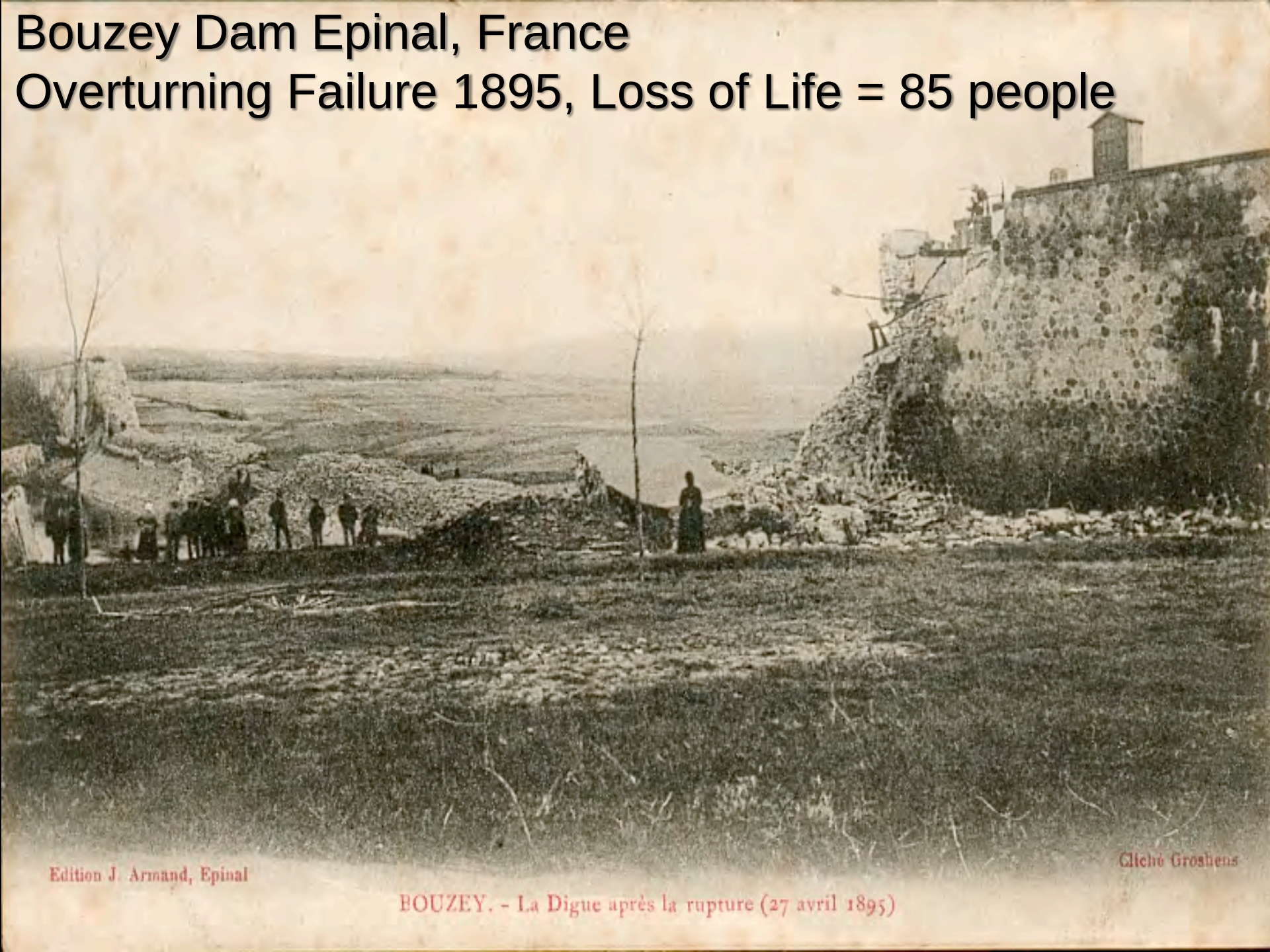


Image Source: Cassier's Magazine, November 1896

Bouzey Dam Epinal, France
Overturning Failure 1895, Loss of Life = 85 people



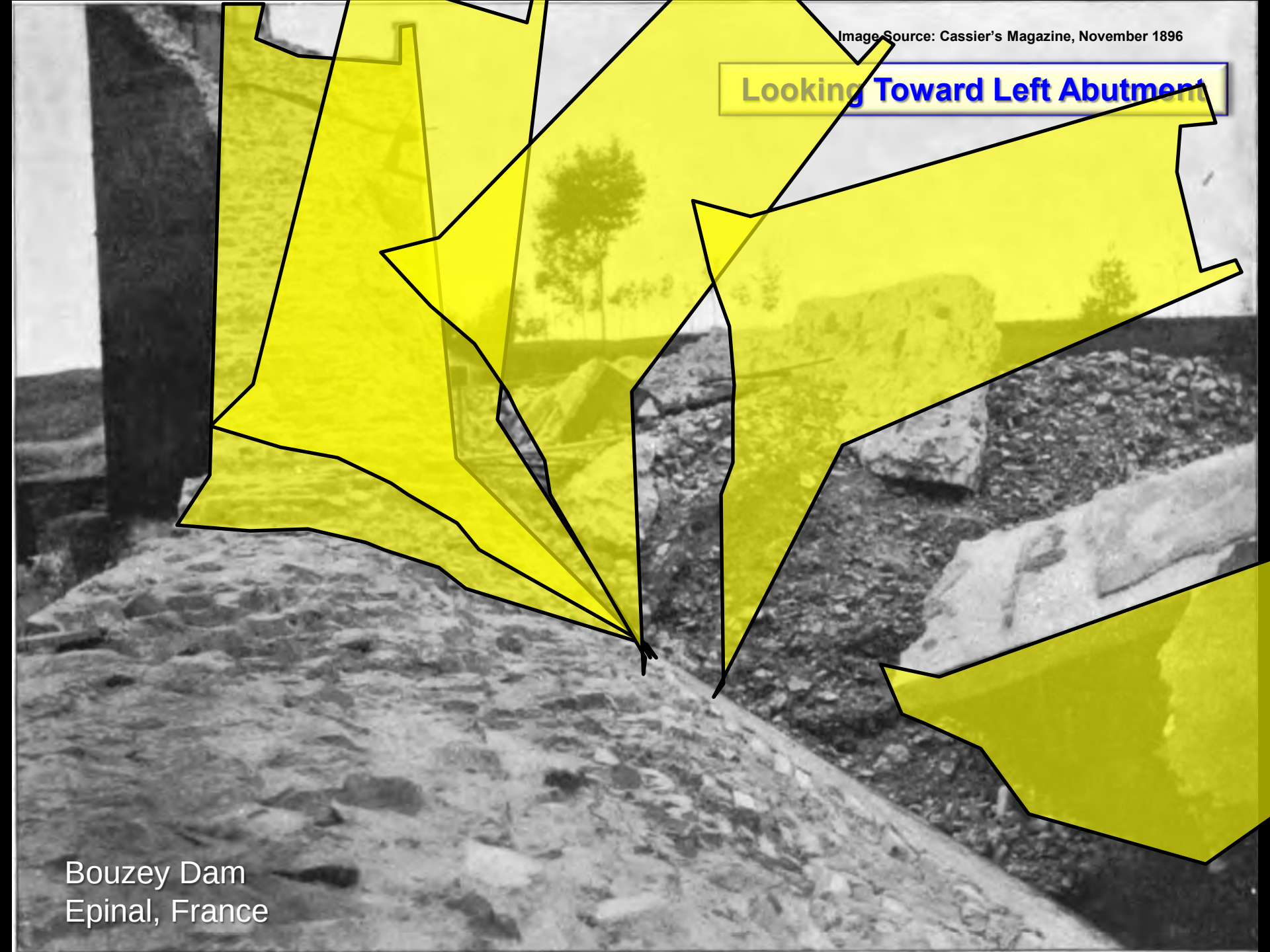
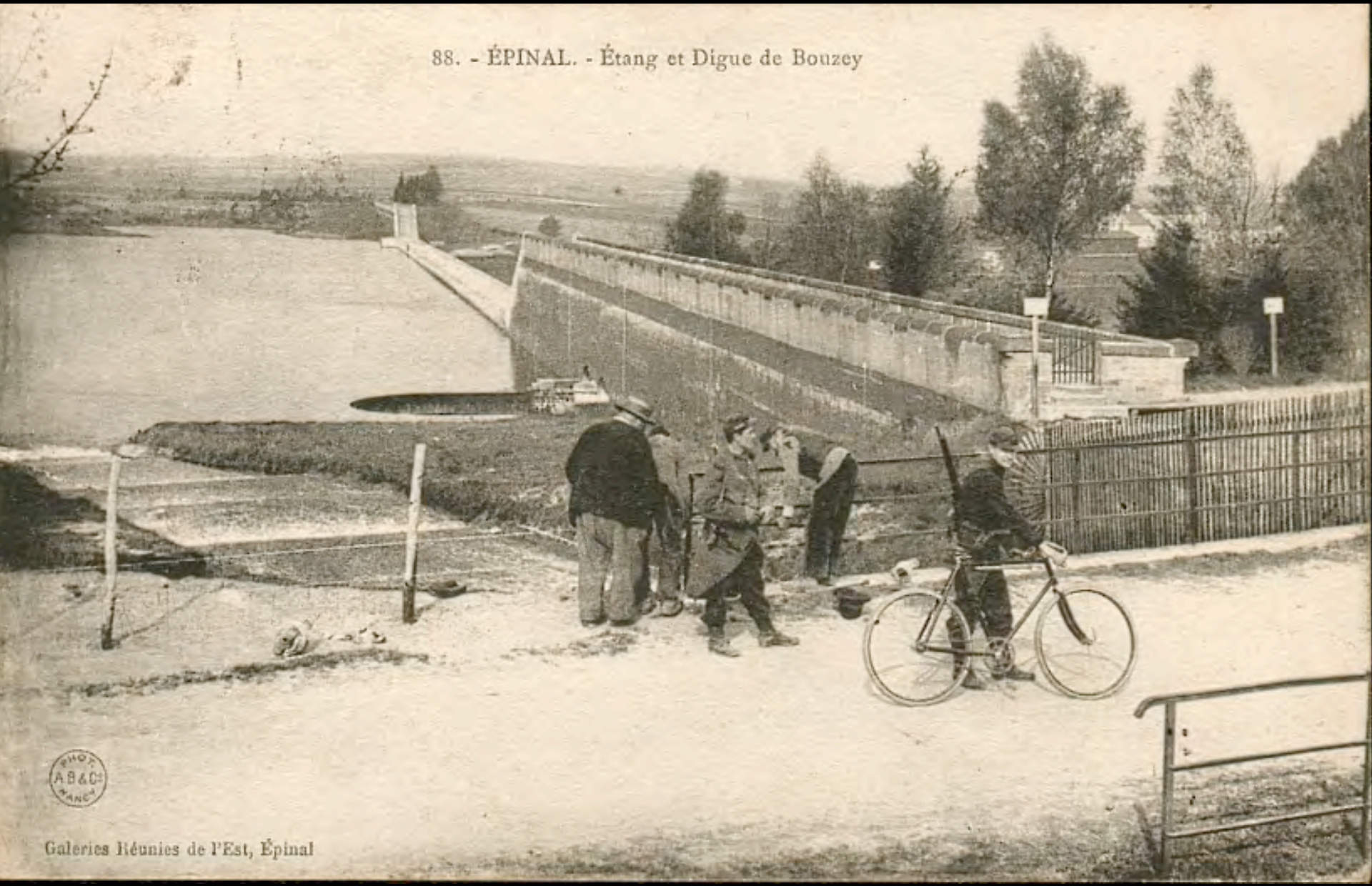


Image Source: Cassier's Magazine, November 1896
Looking Toward Left Abutment
Bouzey Dam
Epinal, France



Postcard Image Courtesy: Anne Rouillon

Stone Masonry Gravity Dam
Built: 1890-93
Failed: 11:20 AM, April 7, 1900
Fatalities: 8 (At Powerhouse)

AUSTIN DAM
AUSTIN, TX

Image Source: USGS Paper No. 40, 1900

February 1893


Max. Height: 66 feet
Image Source: University of Texas Libraries

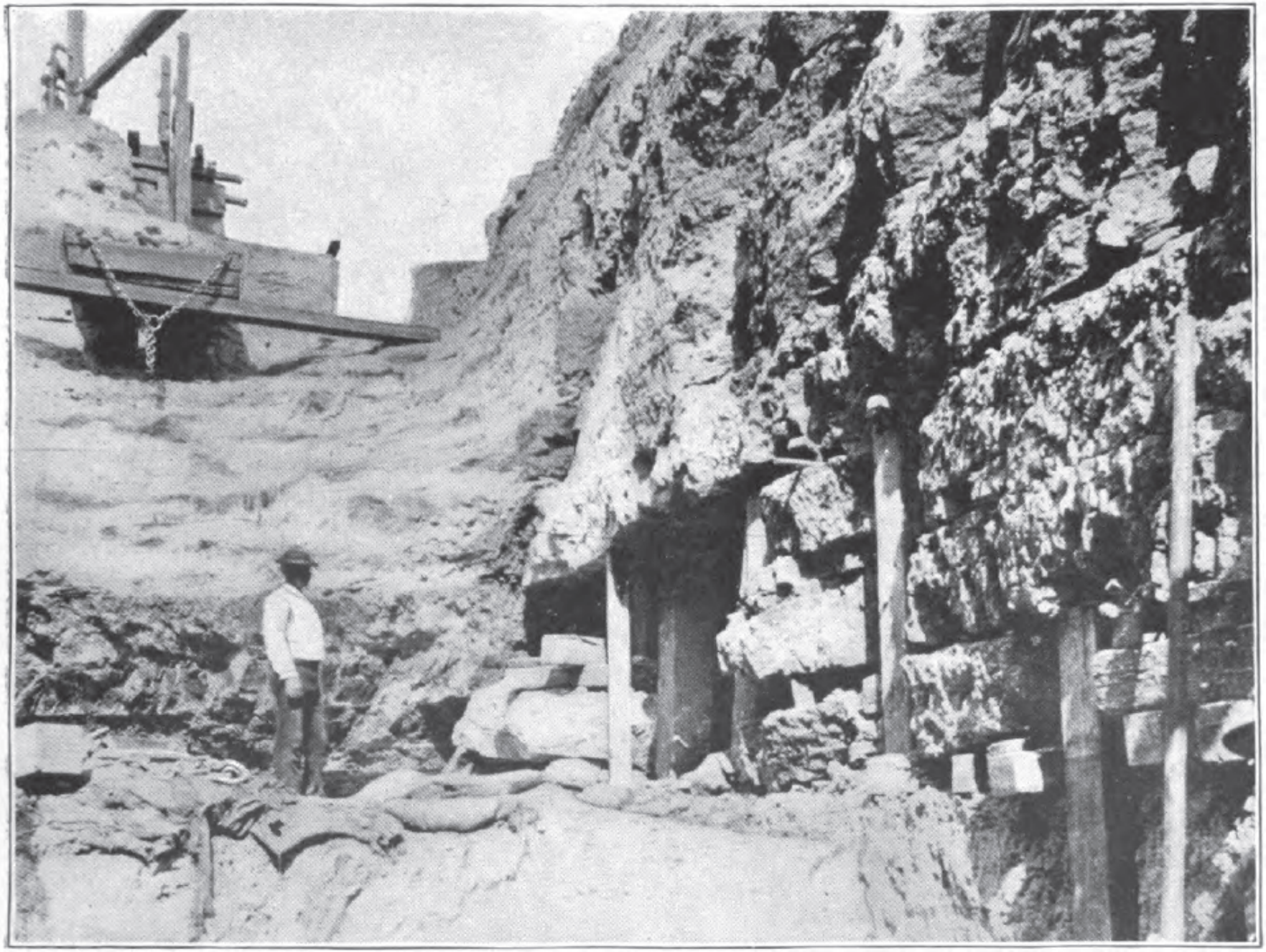
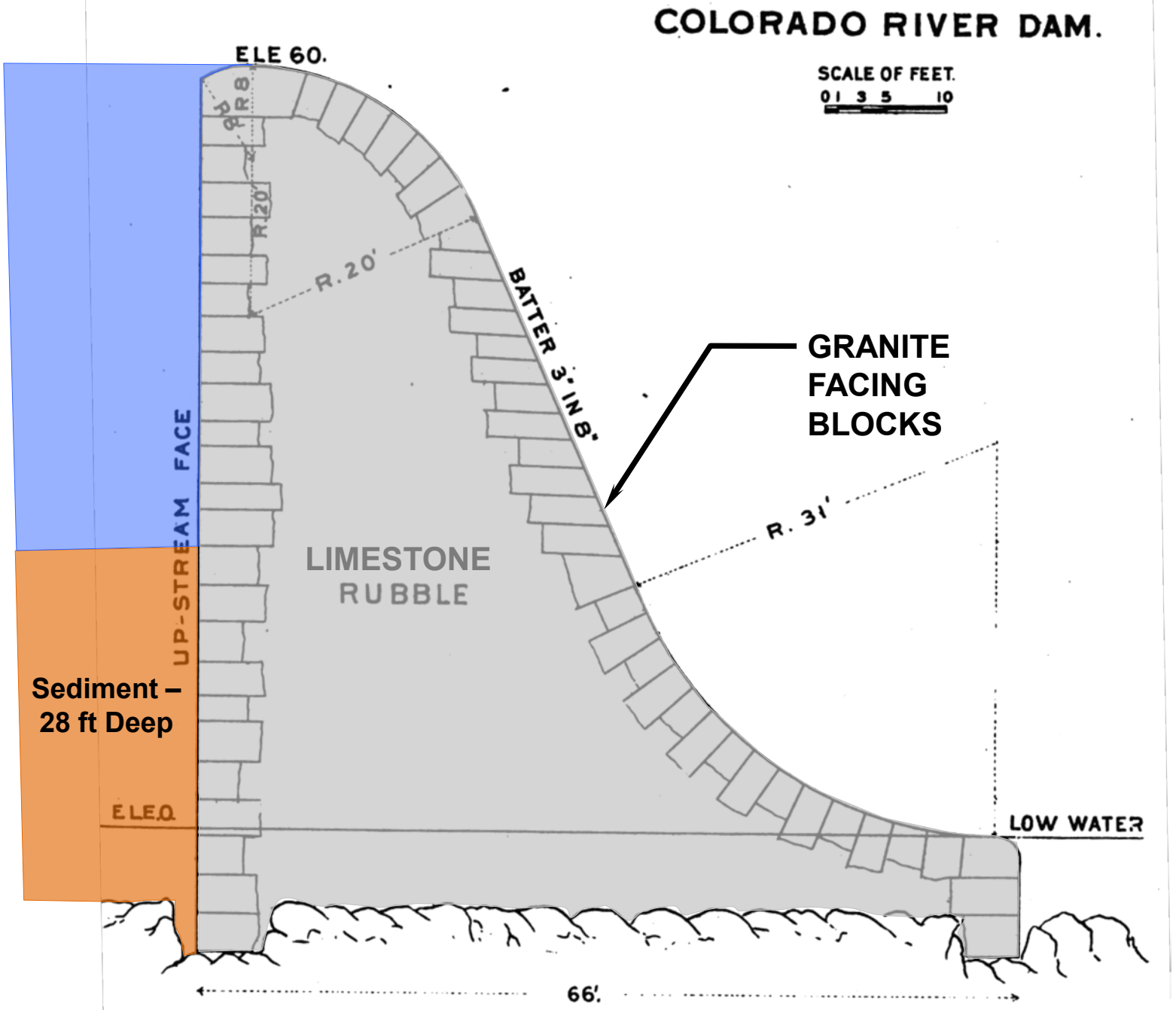
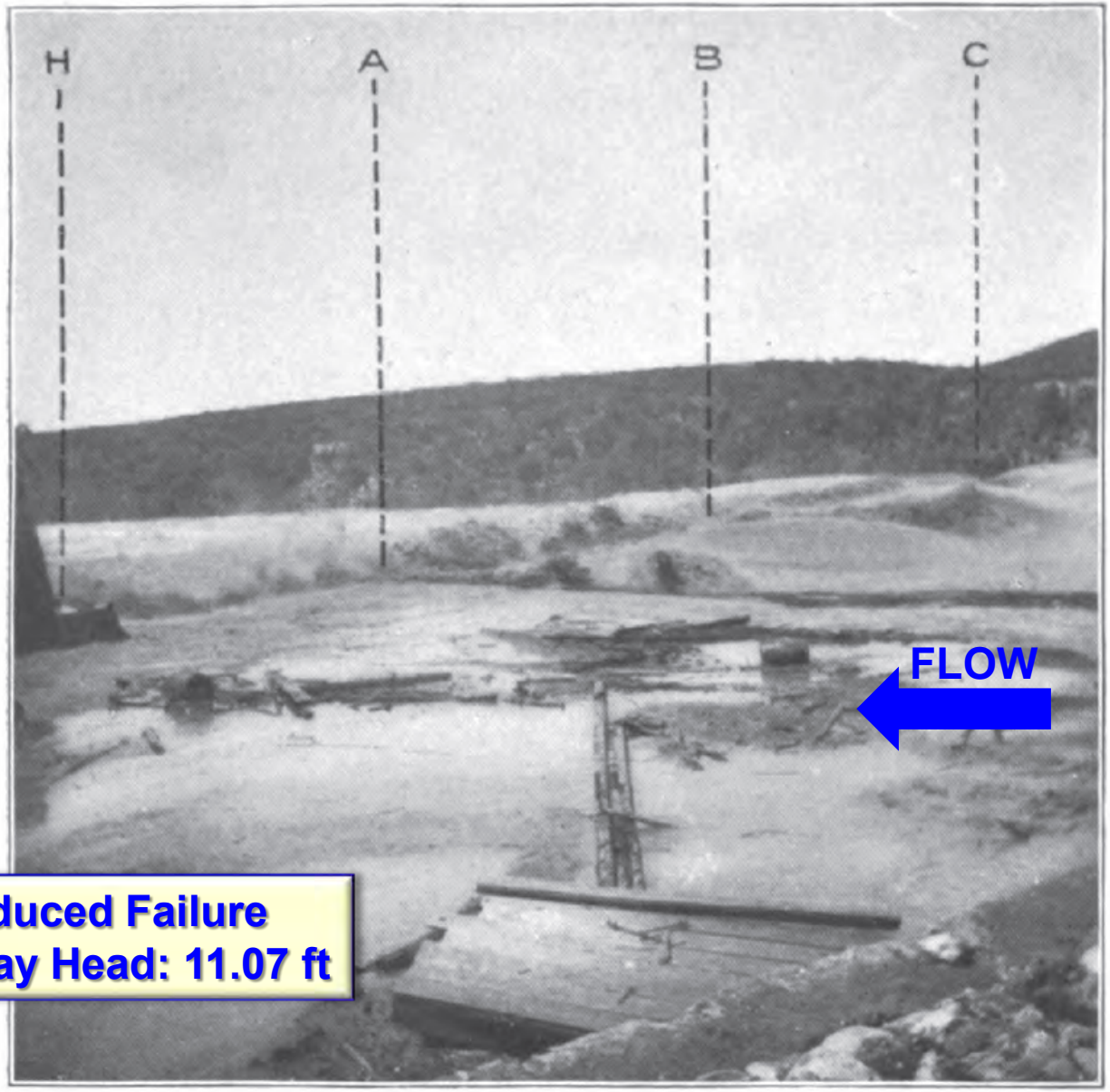


Image Source: USGS Paper No. 40, 1900

B. LIMESTONE STRATA AT HEAD GATE.

Image Source: The Design and Construction of Dams, E. Wegmann



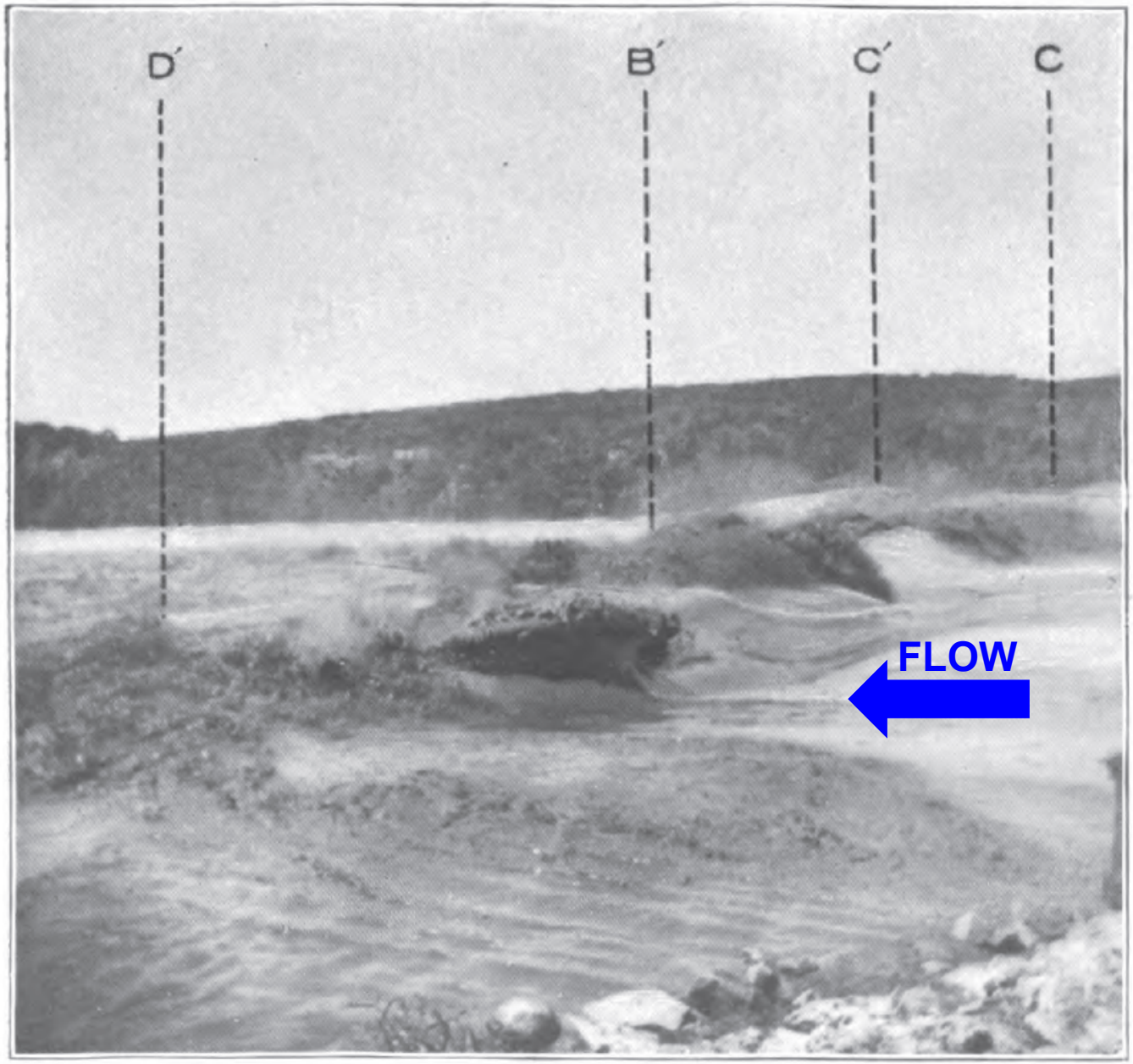


Flood-Induced Failure
Peak Spillway Head: 11.07 ft

A. VIEW THREE MINUTES AFTER FAILURE OF DAM.

A—B and B—C are portions of dam first broken; H—A is eastern part of dam (83 feet long on crest) left standing.

Image Source:
USGS Paper No. 40, 1900



B. VIEW TEN MINUTES AFTER FAILURE OF DAM.

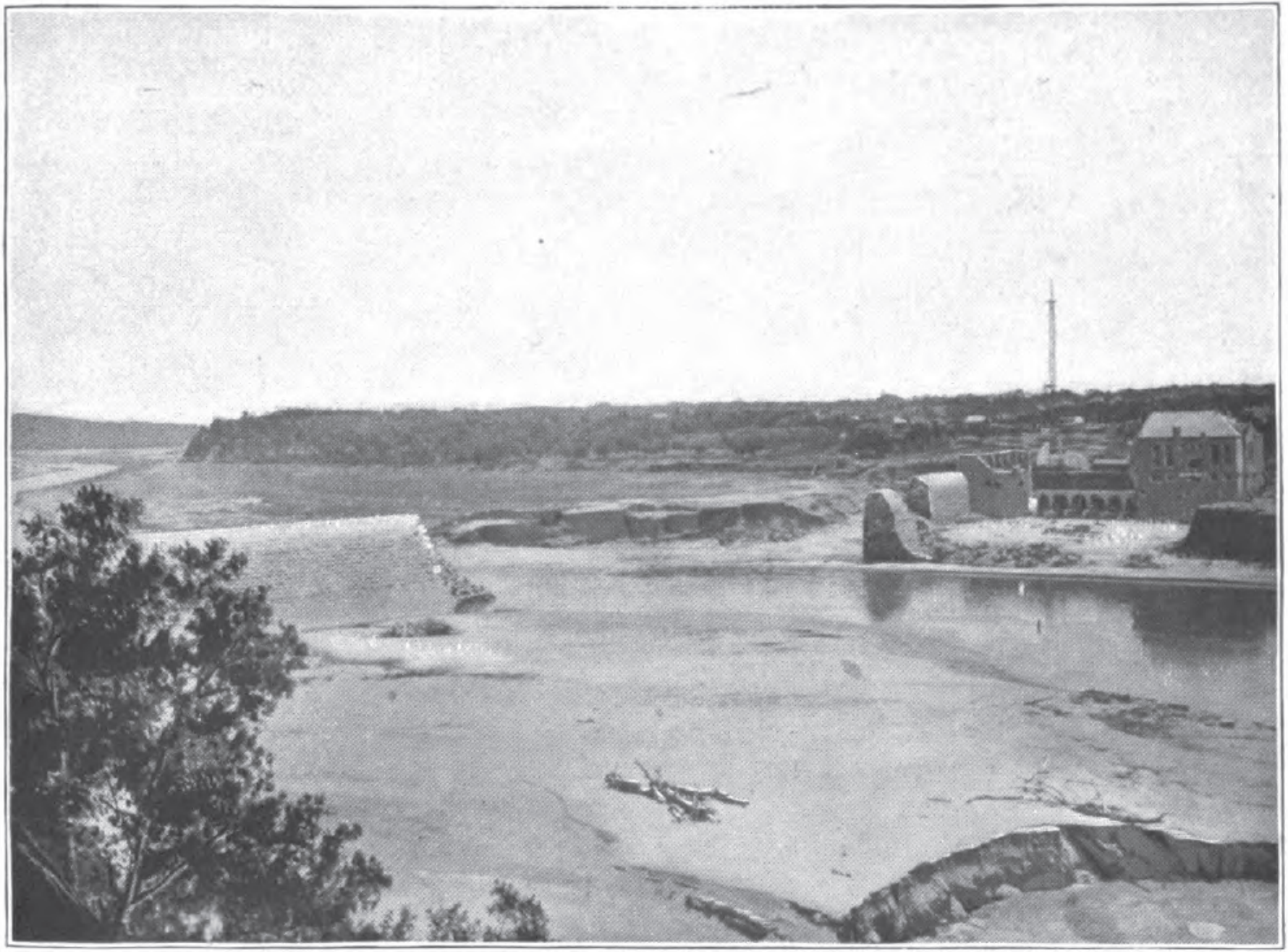
D′—B′ is broken portion of dam still standing; B′—C′ is western portion of break; C is end of western part of dam (456 feet long on crest) left standing.

Image Source:
USGS Paper No. 40, 1900

Austin Dam
Austin, TX

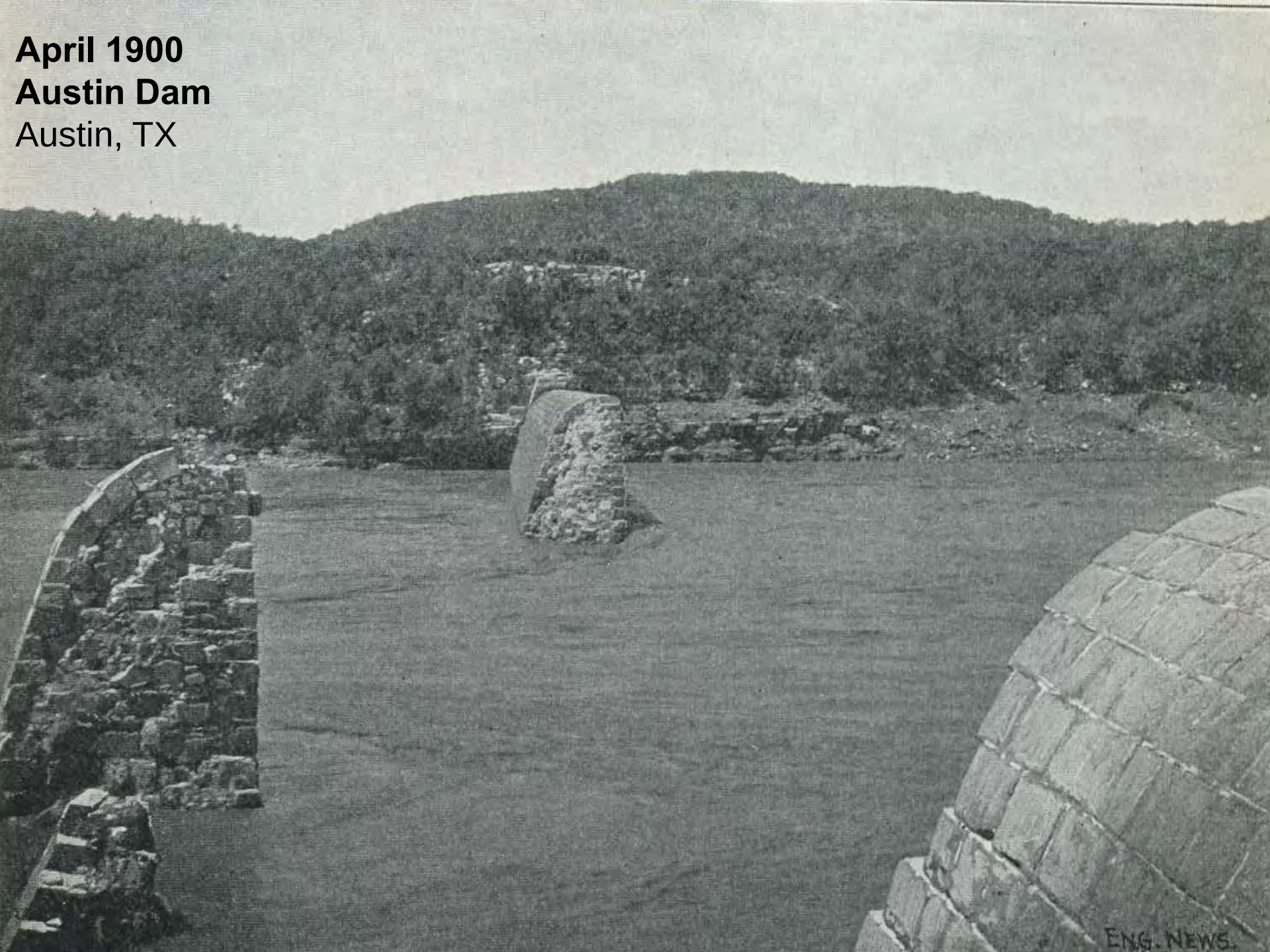
One hour after failure

Image Source: USGS Paper No. 40, 1900



A. BROKEN DAM, SHOWING IN FOREGROUND SAND BAR LEFT IN MAIN CHANNEL.

April 1900
Austin Dam
Austin, TX



Concrete Slab and Buttress Dam

Built: 1907-08

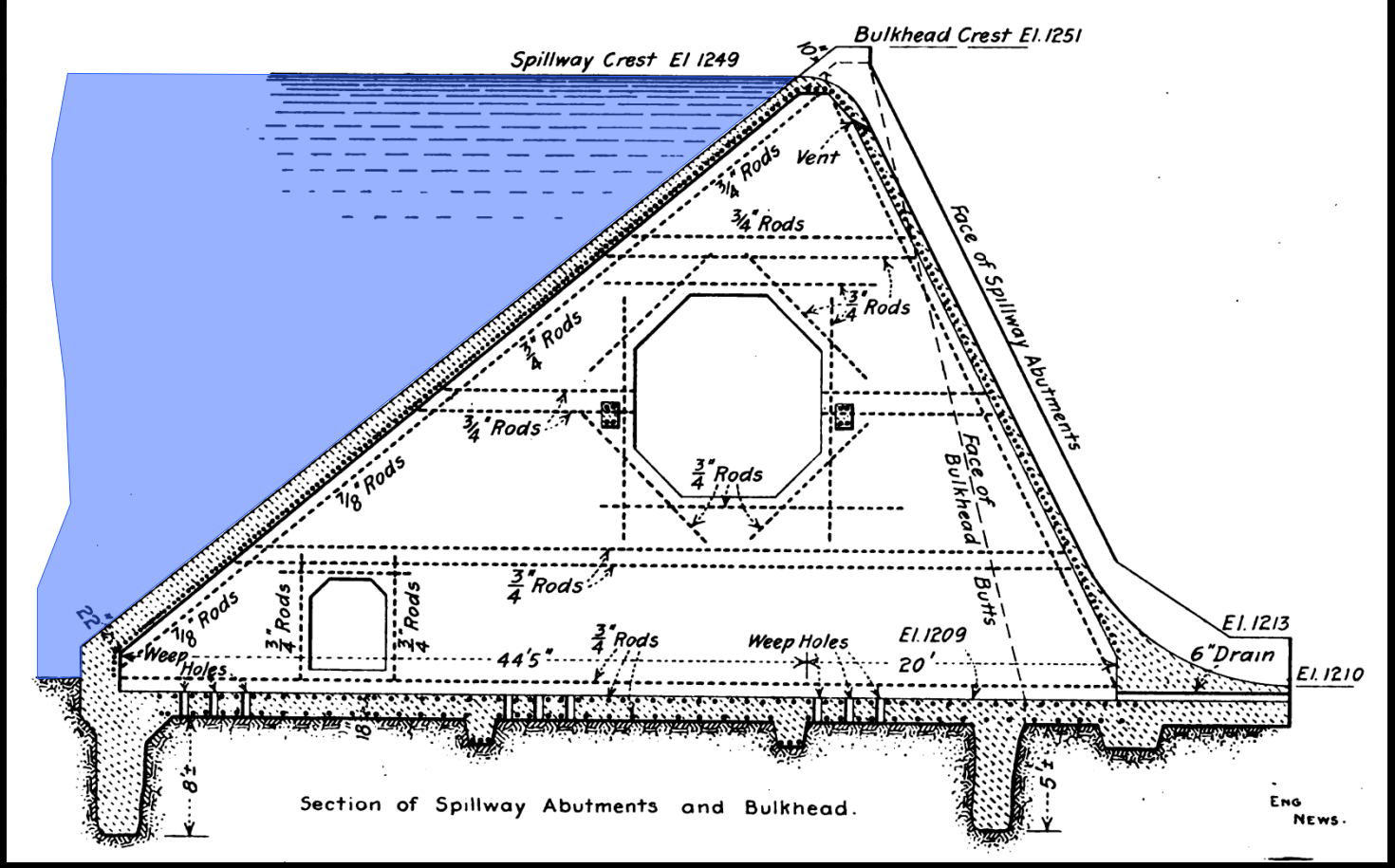
Piping Incident: January 7, 1909

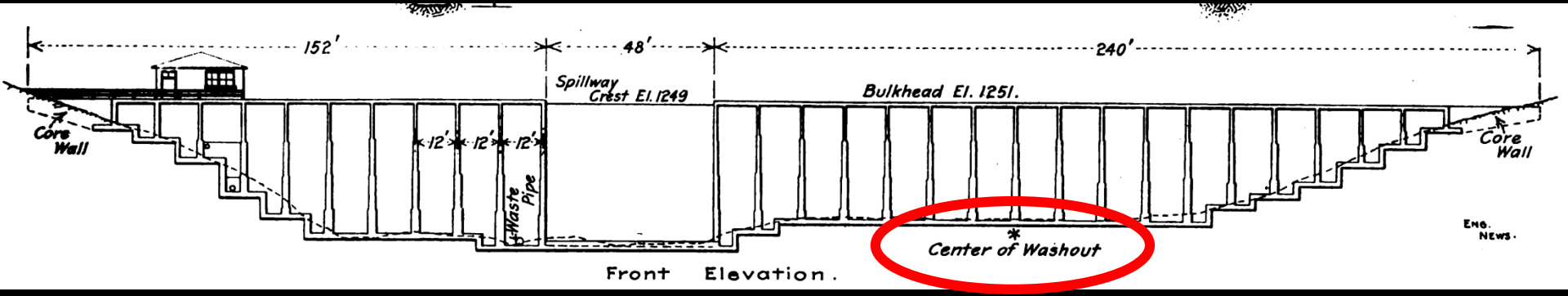
Fatalities: 0

ASHLEY DAM
PITTSFIELD, MA

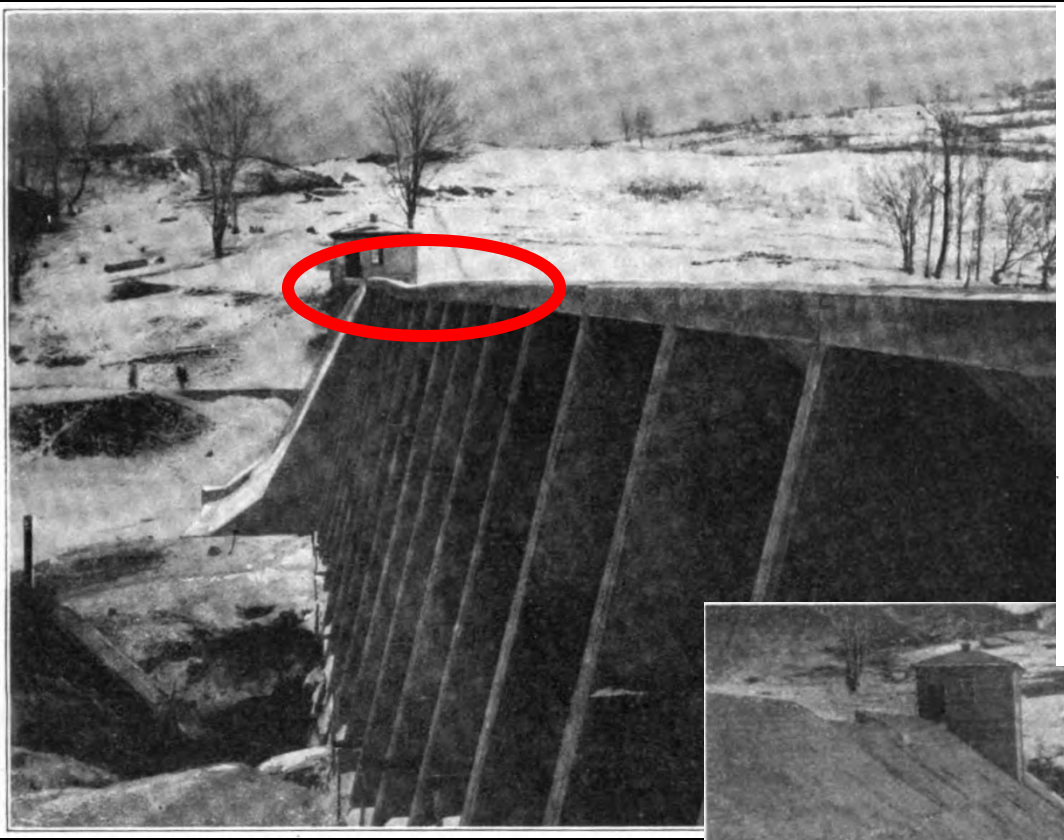
Ashley Dam
Pittsfield, MA - 1909

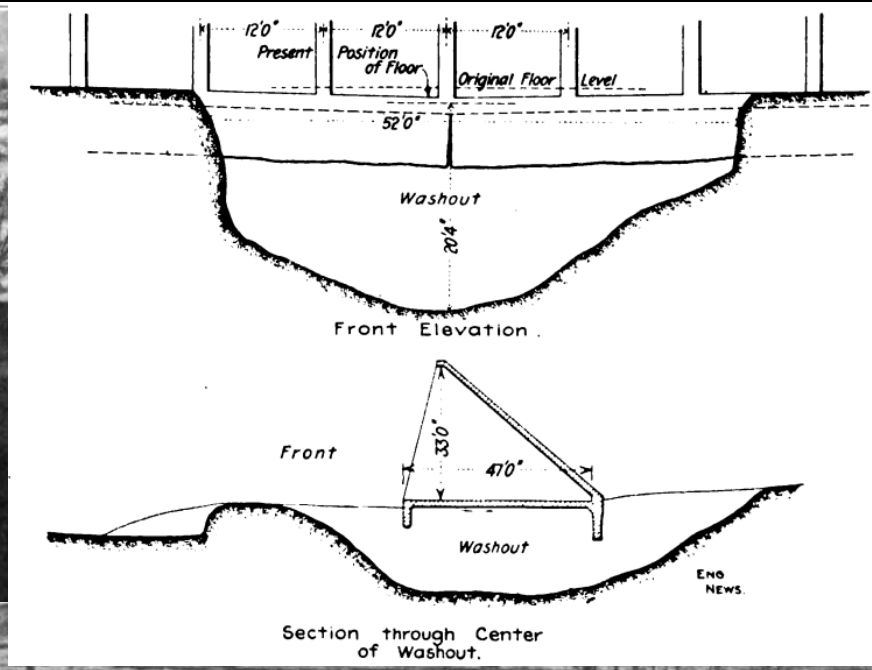
Image Source: Reservoirs for Irrigation, Water-Power, and Domestic Water-Supply, 1909





Images Source: Engineering News April 1, 1909





Ashley Dam
Pittsfield, MA - 1909

Images Source: Engineering News April 1, 1909

Cyclopean Concrete Gravity Dam

Constructed:	May - December 1, 1909
Partial Failure:	January 23, 1910
Complete Failure:	2:20 PM, September 30, 1911
Fatalities:	78

BAYLESS DAM
AUSTIN, PA

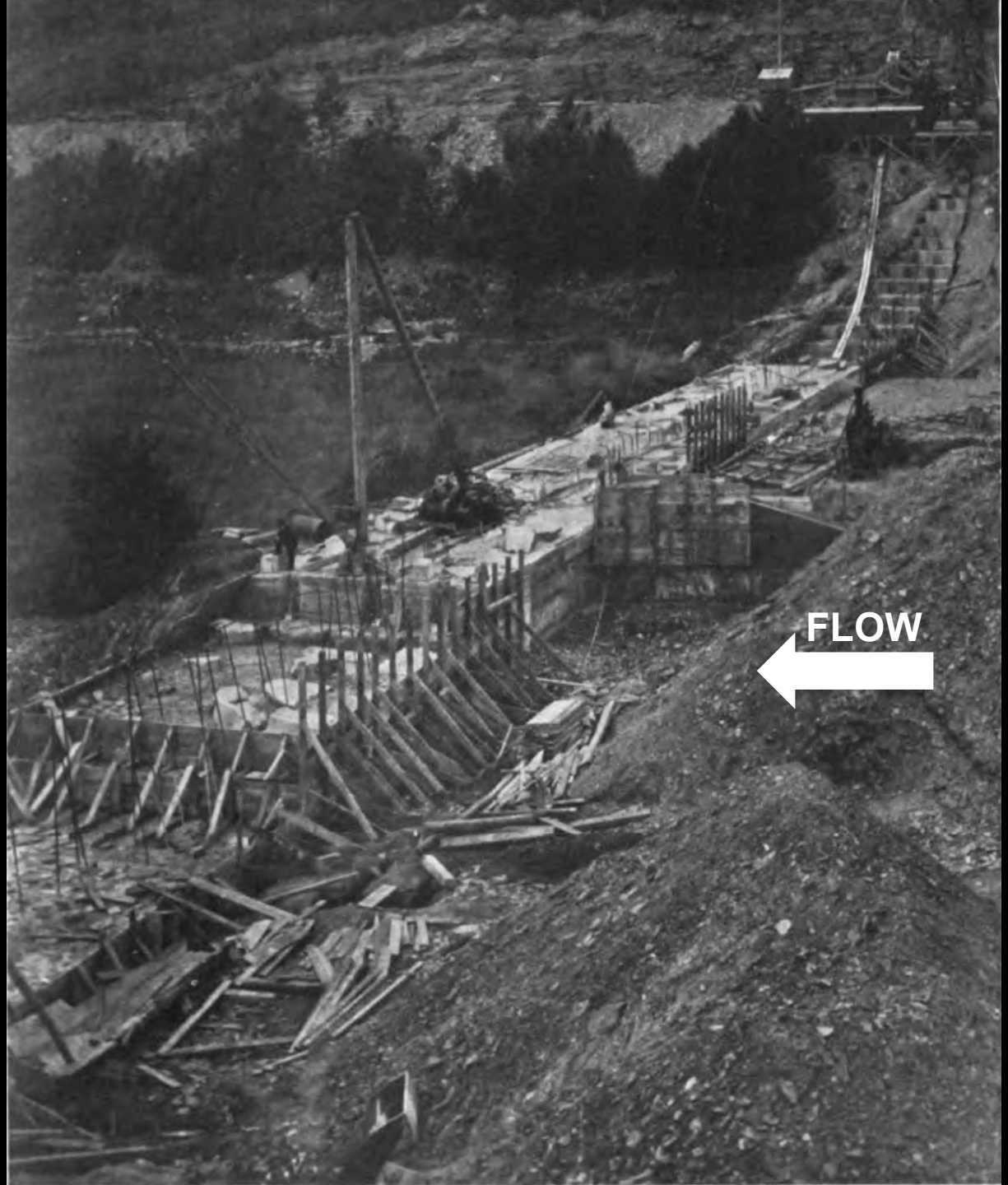


Image Source:
Some Features of the Construction and Failure of the Austin, PA, Dam
T. Chalkley Hatton, Sep 19, 1912

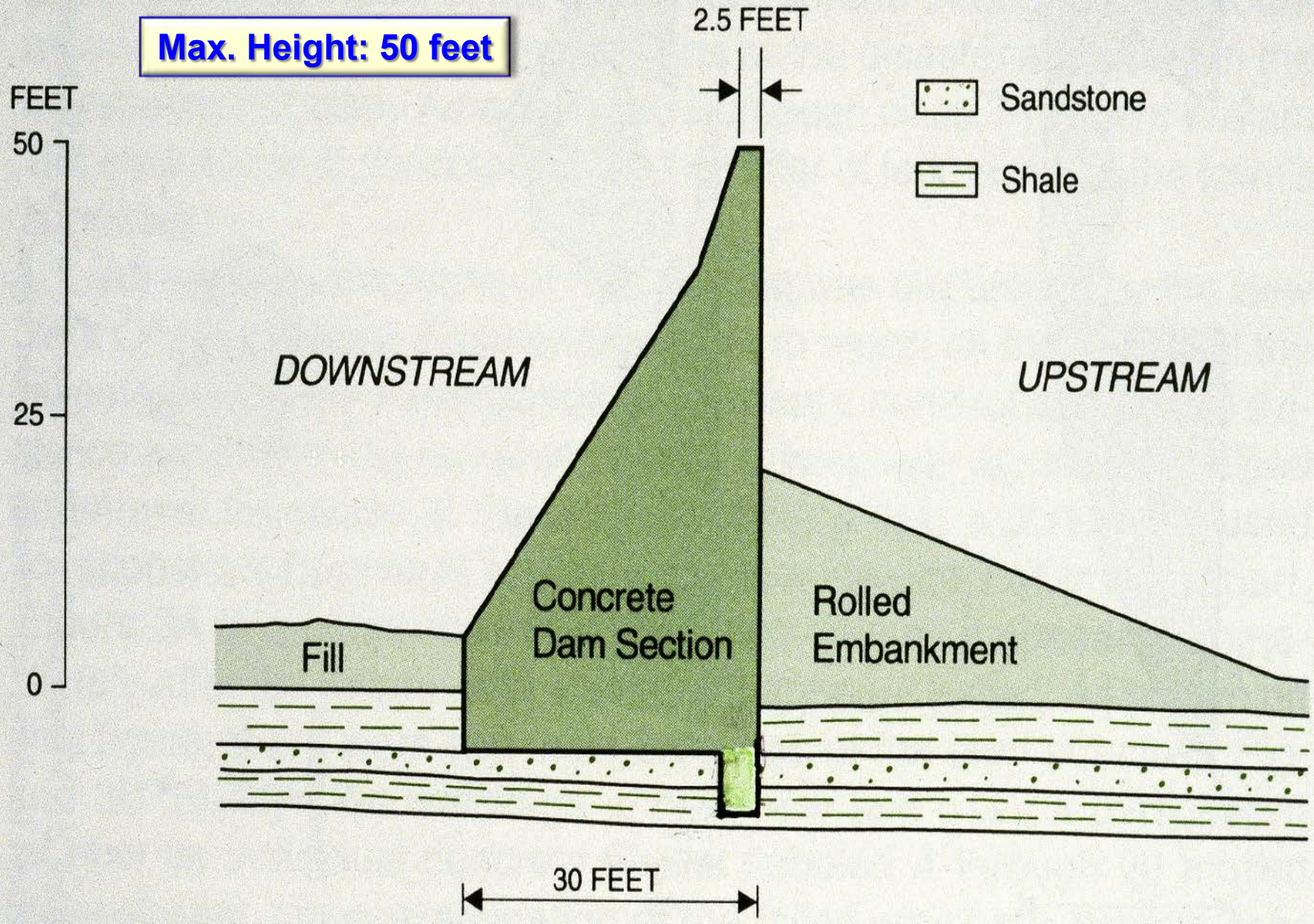
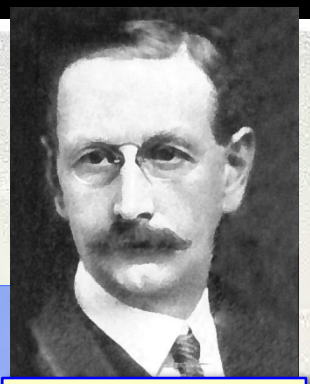


Figure 4. Prefailure cross section of Austin Dam at Block "D."

Key Design Features

1. Neglected Uplift Pressure
2. Embankment to Reduce Hydrostatic Load
3. Vertical Rods for Overturning Stability
4. Key Wall for Sliding Stability
5. 2-in. Dia. Boreholes on 15-20-foot Centers
6. 25-45-foot Monoliths with Keyways
7. Concrete Mix – 1.25 Barrels Cement per CY
8. Each Cement Delivery Tested
9. Outlet Works – 36-inch dia. Pipe
10. Spillway Crest Raised 2 feet



Design Engr.
T. Chalkley Hatton

Project Objectives

1. 200,000,000 Gallon Reservoir
2. $85,000 Budget

Image Source: USACE, Brian H. Greene, Ph.D., P.G.

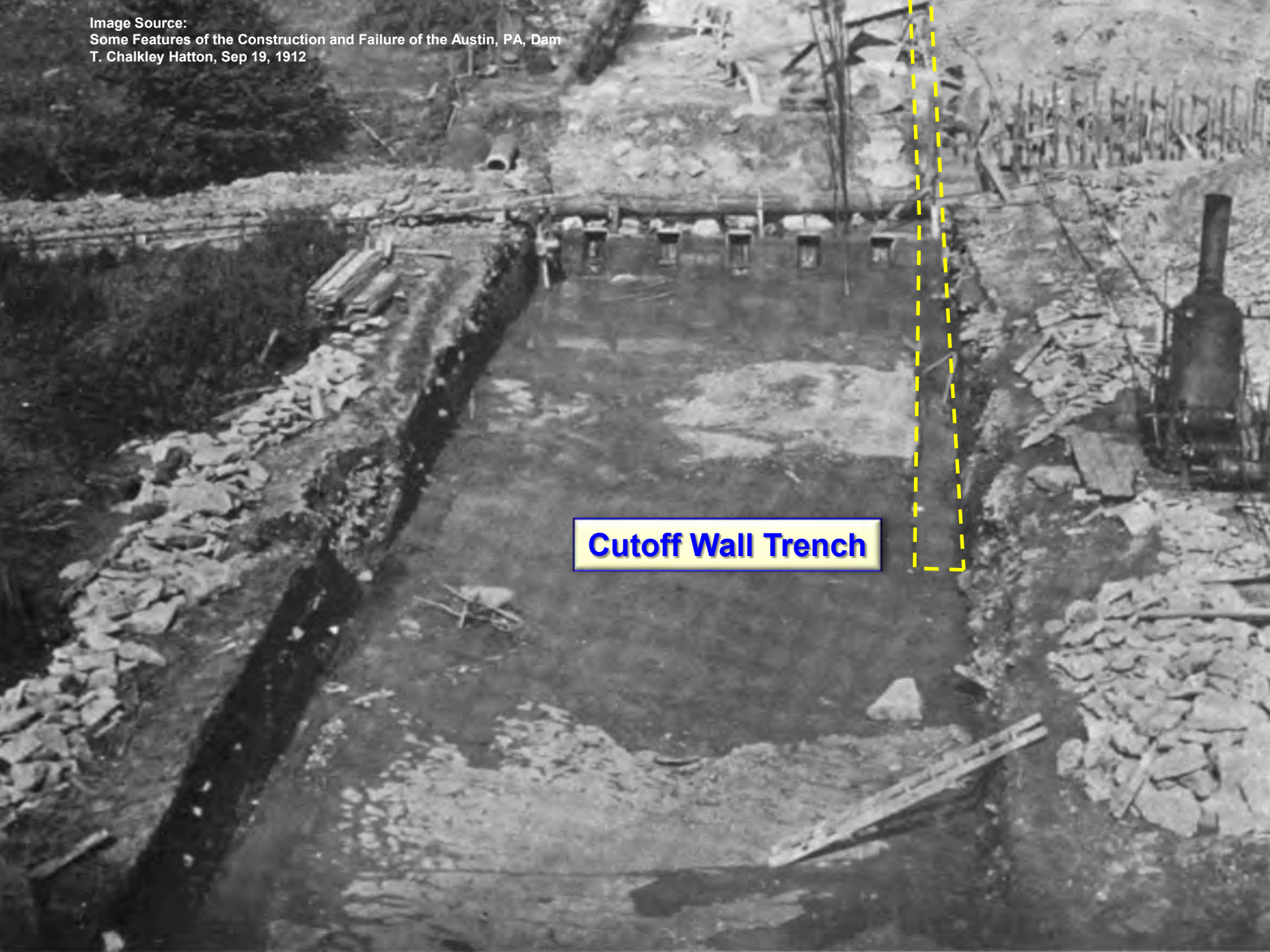


Image Source:
Some Features of the Construction and Failure of the Austin, PA, Dam
T. Chalkley Hatton, Sep 19, 1912

Image Source: Potter County Historical Society

Bayless Dam, Austin, PA
January 23, 1910
Max. Horizontal Displacement:
Crest: 31 inches
Base: 18 inches

Image Source:
Potter County Historical Society

Image Source: The Concrete Dam in Freeman's Run, Austin, PA., Frank P. McKibben, January 1912

Image Source: Potter County Historical Society

Why Re-fill Reservoir?

- Bayless Paper Mill major employer.
- Belief – No severe consequences from failure.
- No active independent governing influence.

Bayless Paper Mill

BAYLESS PAPER MILL

Sunny Day Failure

Image Source: Potter County Historical Society

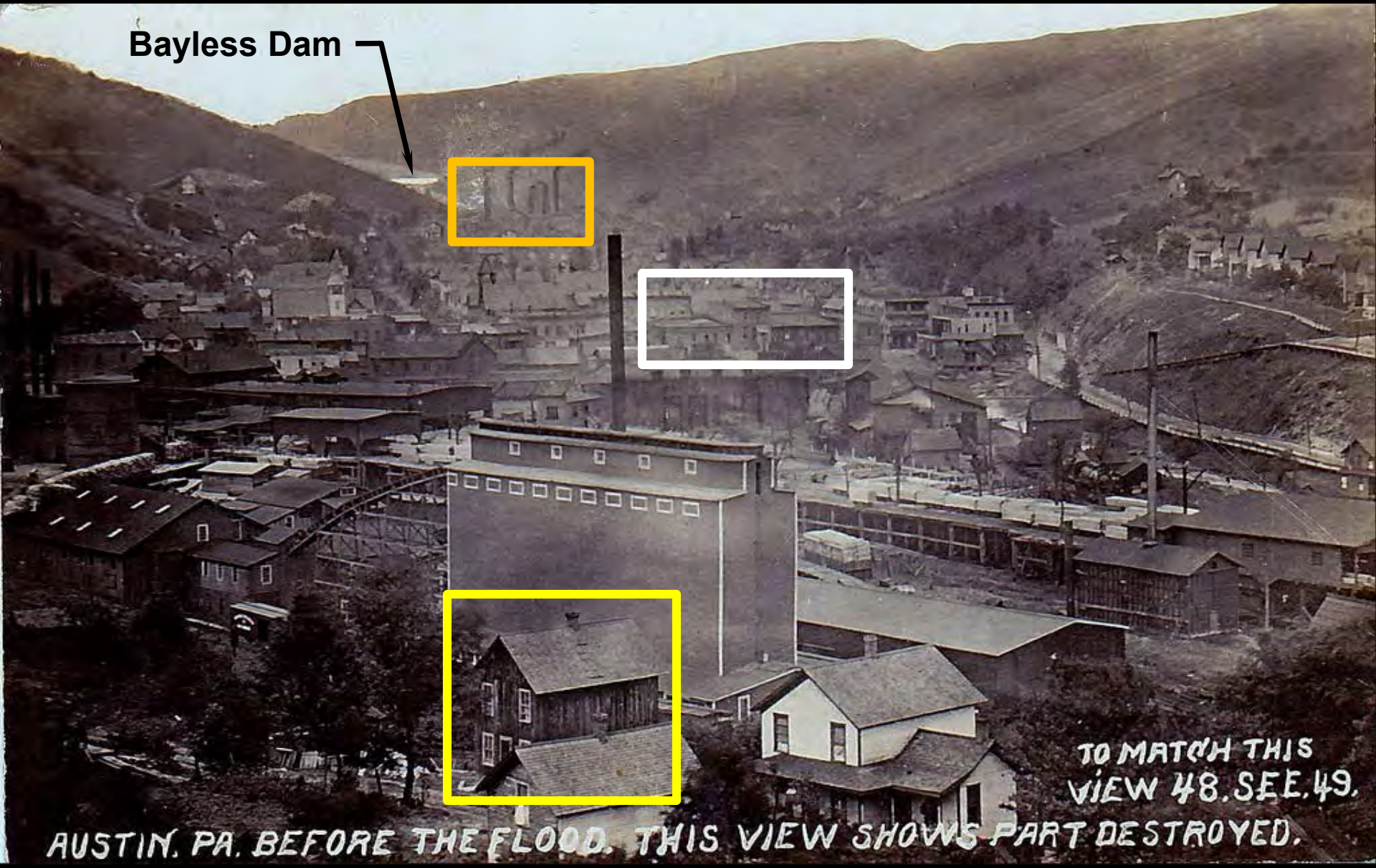


Image Source: Potter County Historical Society

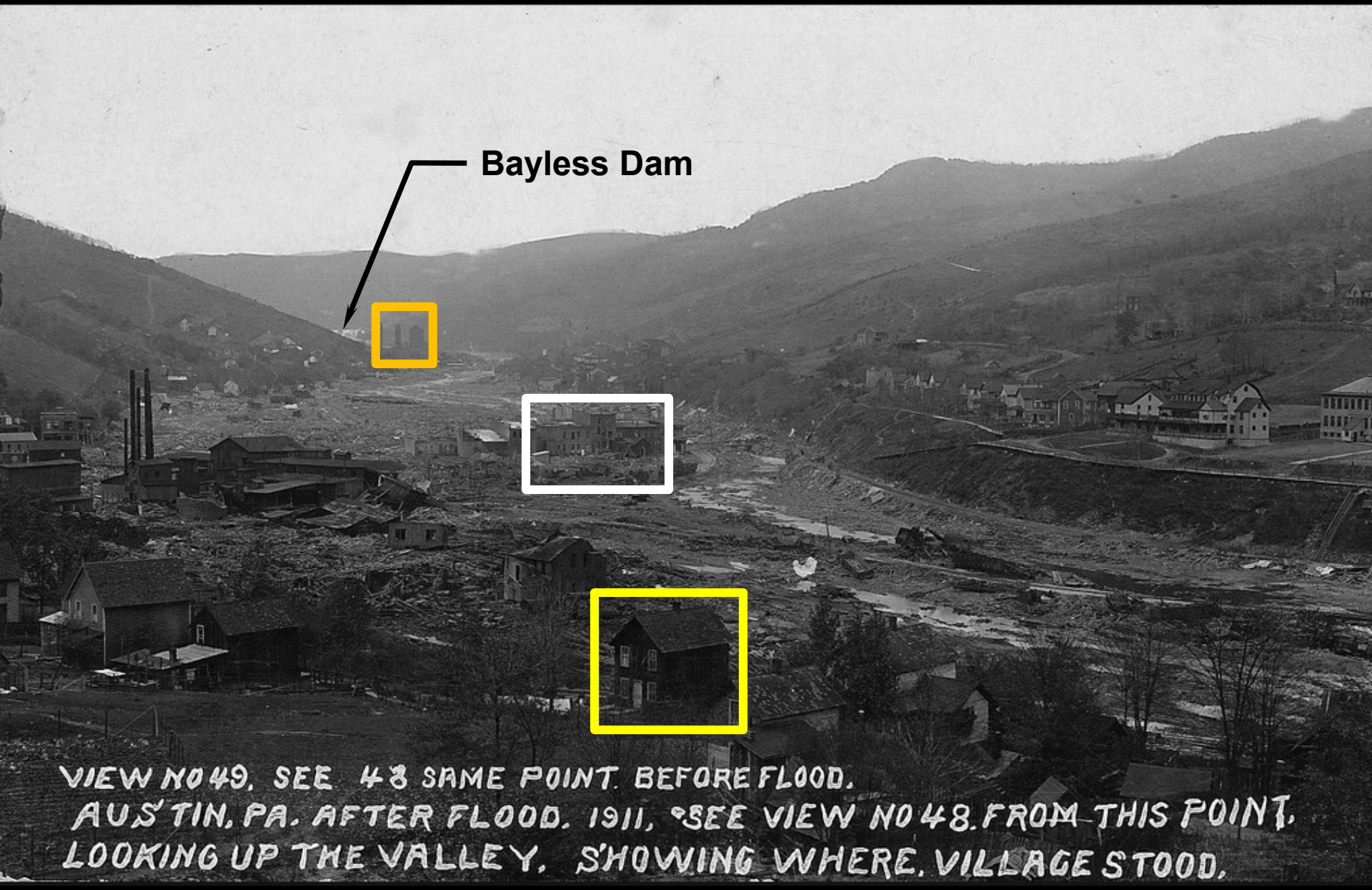


Image Source: Potter County Historical Society

Loss of Life = 78 people

September 1911
Bayless Dam
Austin, PA

Design Engr.
T. Chalkley Hatton

"The failure of this dam was not the result of poor workmanship, but poor judgment upon my part. I should have sought the advice of a man more skilled than I in determining foundations for dams. Had there been such a state officer it might have resulted in saving this dam and my reputation."

Design Engr.
T. Chalkley Hatton

“I was also influenced in my judgment by the necessity for keeping the expenditure within certain limits. I have since felt that a very grave responsibility for my failure to advise the client early in my engagement that no paring down of this work should be countenanced. Had I done so, either the dam would not have been built, or it would have been built in accordance with my first design. The owner had not intention at any time of building a dam the safety of which he doubted, and nn blame can be attached to him for its failure. He depended upon my judgment entirely, even though he may have tried to influence me to keep the expenditures down to the lowest possible limit”

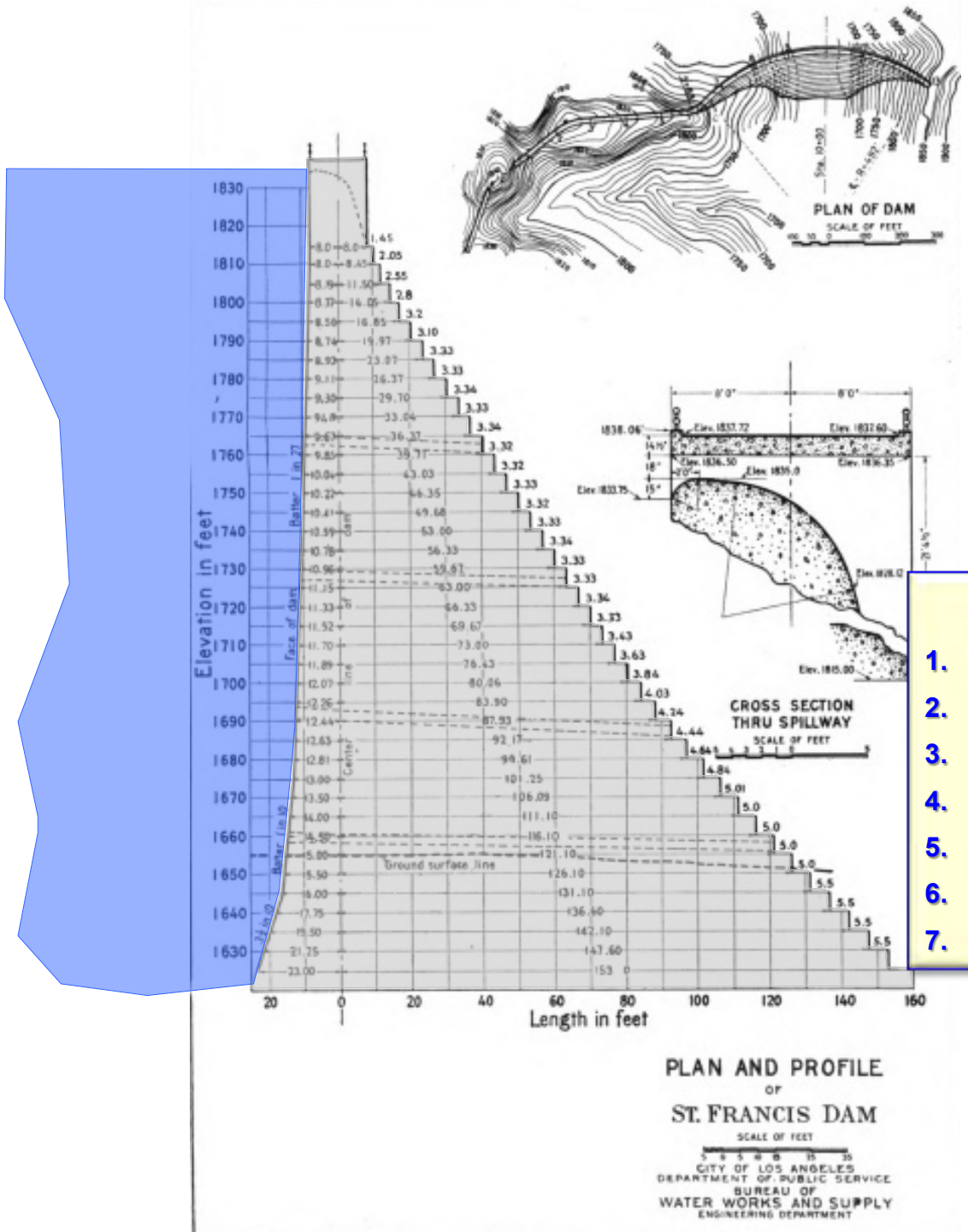
Design Engr.
T. Chalkley Hatton

"To the young engineer who is called upon to design an important structure, the safety or sufficiency of which he is not entirely satisfied with, I would strongly urge the wisdom of calling to his help the advice of an older engineer skilled in that particular line. Never sacrifice for cost, no matter how urgent your client may become. He does not realize the danger, and you should. If you cannot agree with him, resign your engagement, for sooner or later the reckoning will come"

Source: Chalkley Hatton, Journal of New England Waterworks Assn., 1912

Conventional Mass Concrete Gravity Dam
Built: 1924-26
Failed: 11:57:30 PM, March 12, 1928
Fatalities: 400-450

ST. FRANCIS DAM
LOS ANGELES, CA



Chief Engr.
William Mulholland

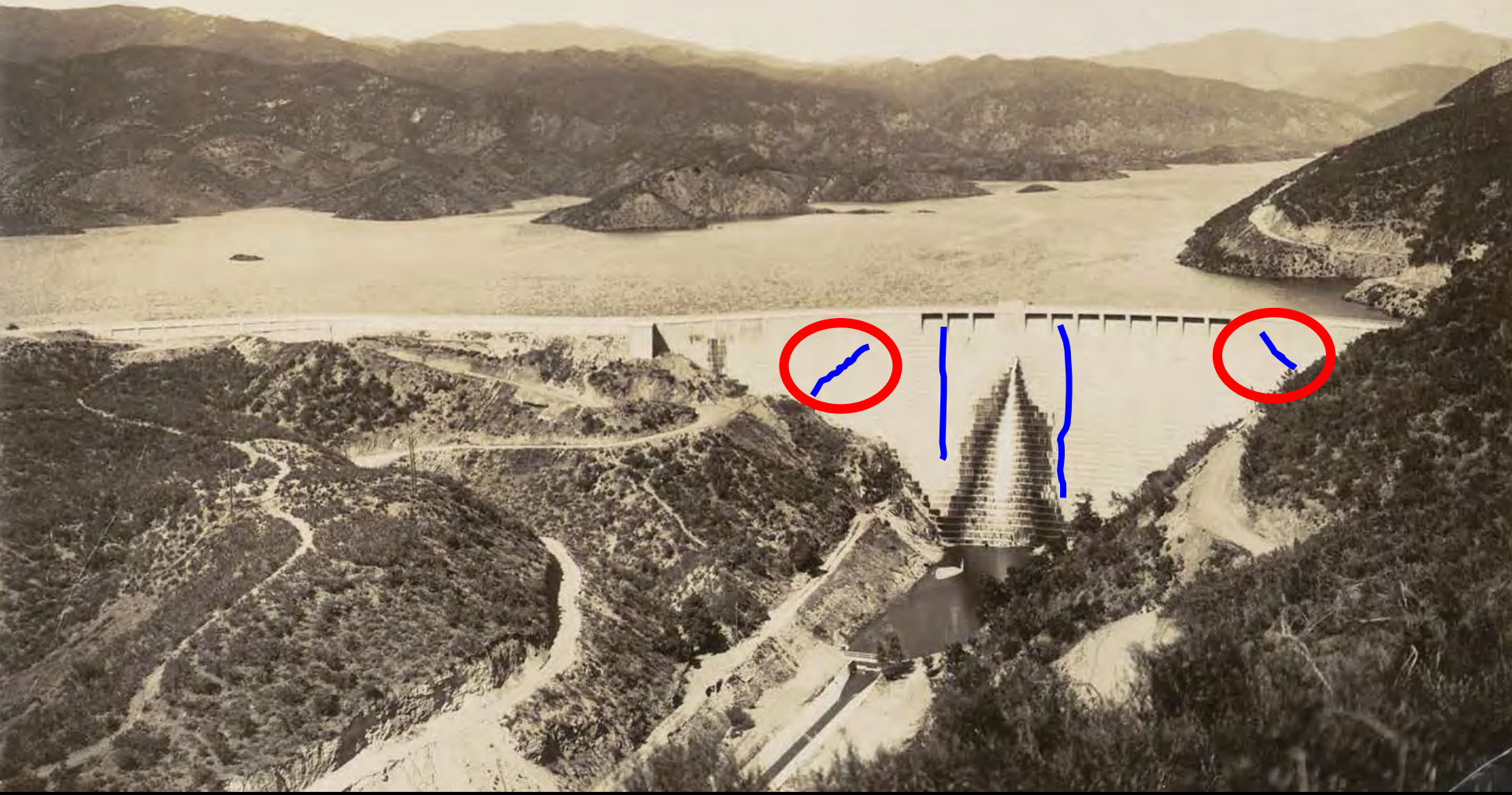
Key Design Features

1. Neglected Uplift Pressure
2. Curved Alignment Gravity Dam
3. Original Height – 180 feet
4. Reservoir Volume – 32,000 Acre-feet
5. Largest of 9 Reservoirs Built 1920-26
6. 10 Drainholes within Max. Section
7. Outlet Works – 5 30-inch-dia. Pipes

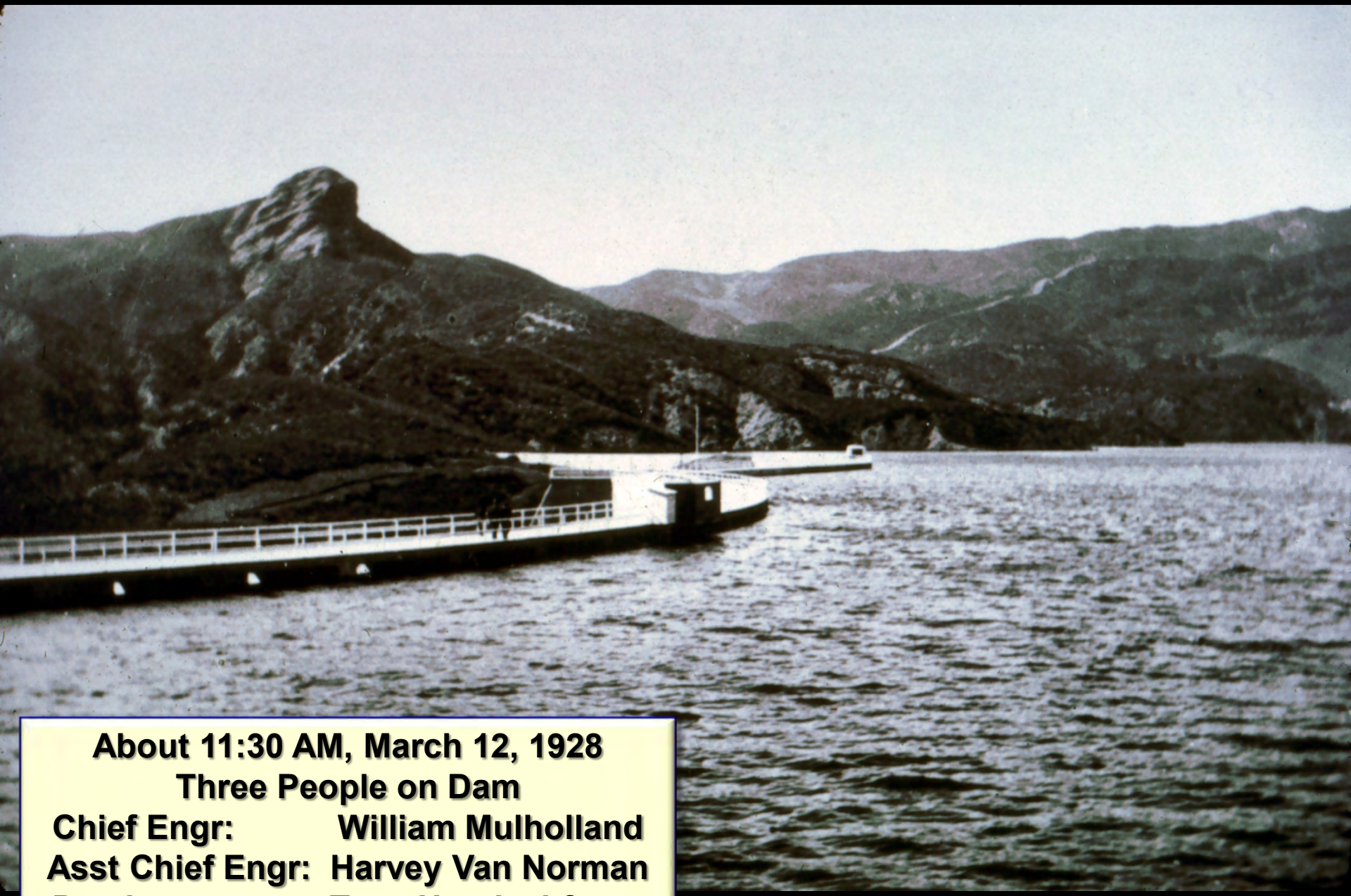
Image Source:
Causes Leading to the Failure of St. Francis Dam, 1928
University of California Library Copy

Saint Francis Dam Failure, CA 1928

Foundation Problems ...



Images Source: University of California Libraries



About 11:30 AM, March 12, 1928
Three People on Dam

Chief Engr:	**William Mulholland**
Asst Chief Engr:	**Harvey Van Norman**
Damkeeper:	**Tony Harnischfeger**

Image Source: California State University, John Spoor Broome Library


Catastrophic Failure:
11:57:30 PM, March 12, 1928
Reservoir Empty:
≈ 40 Minutes
Sunny Day Failure
March 1928
St. Francis Dam
Los Angeles, CA

Image Source: University of California Libraries

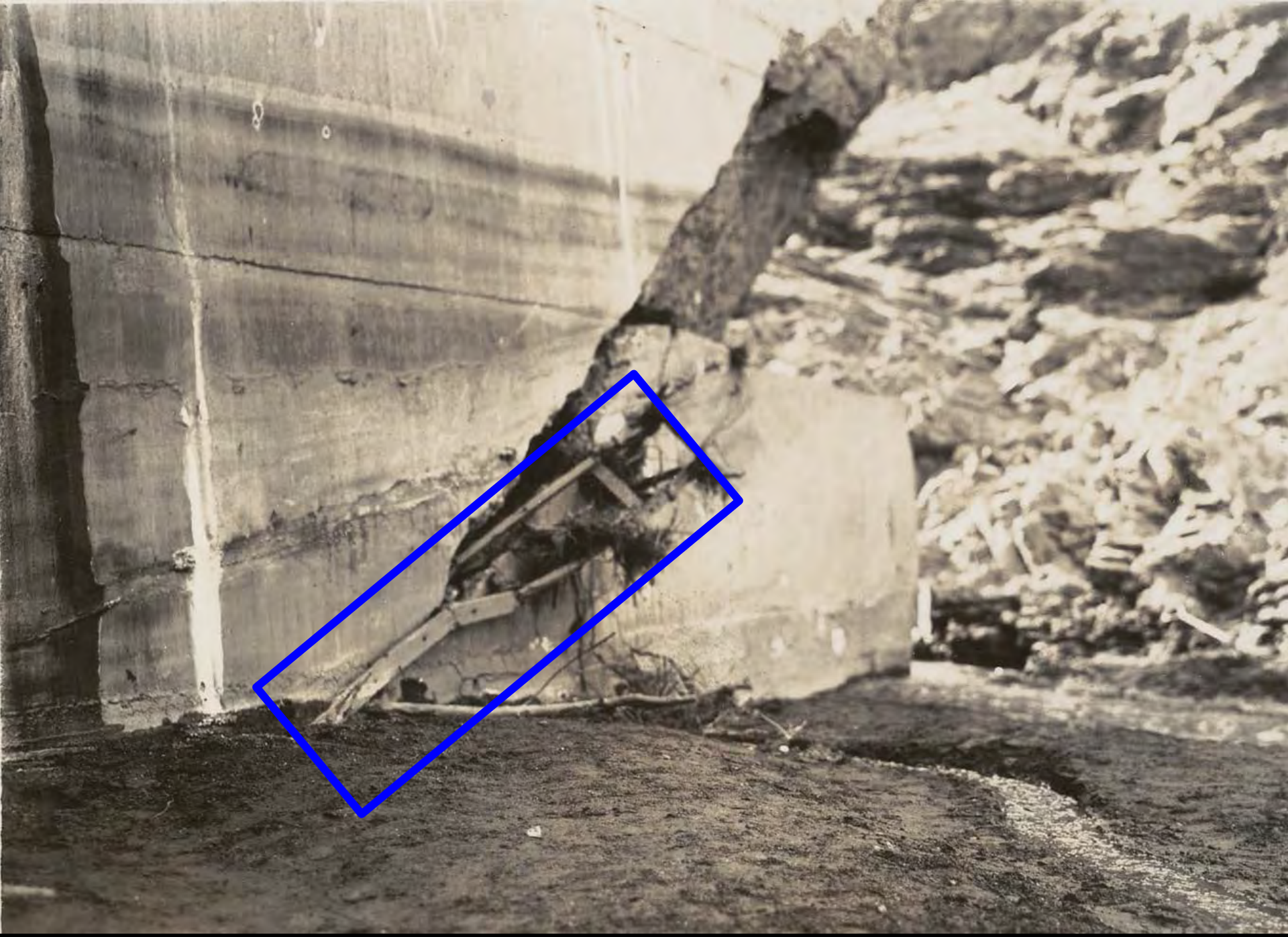


Image Source: University of California Libraries

- 205 Feet High, Foundation Failure
- Collapsed Without Warning, 11:45 p.m.
- 125-foot High Flood Wave

Image Source: University of California Libraries

Image Source: Santa Clarita Valley Historical Society

Powerhouse No. 2
1.5 Miles Downstream of Dam

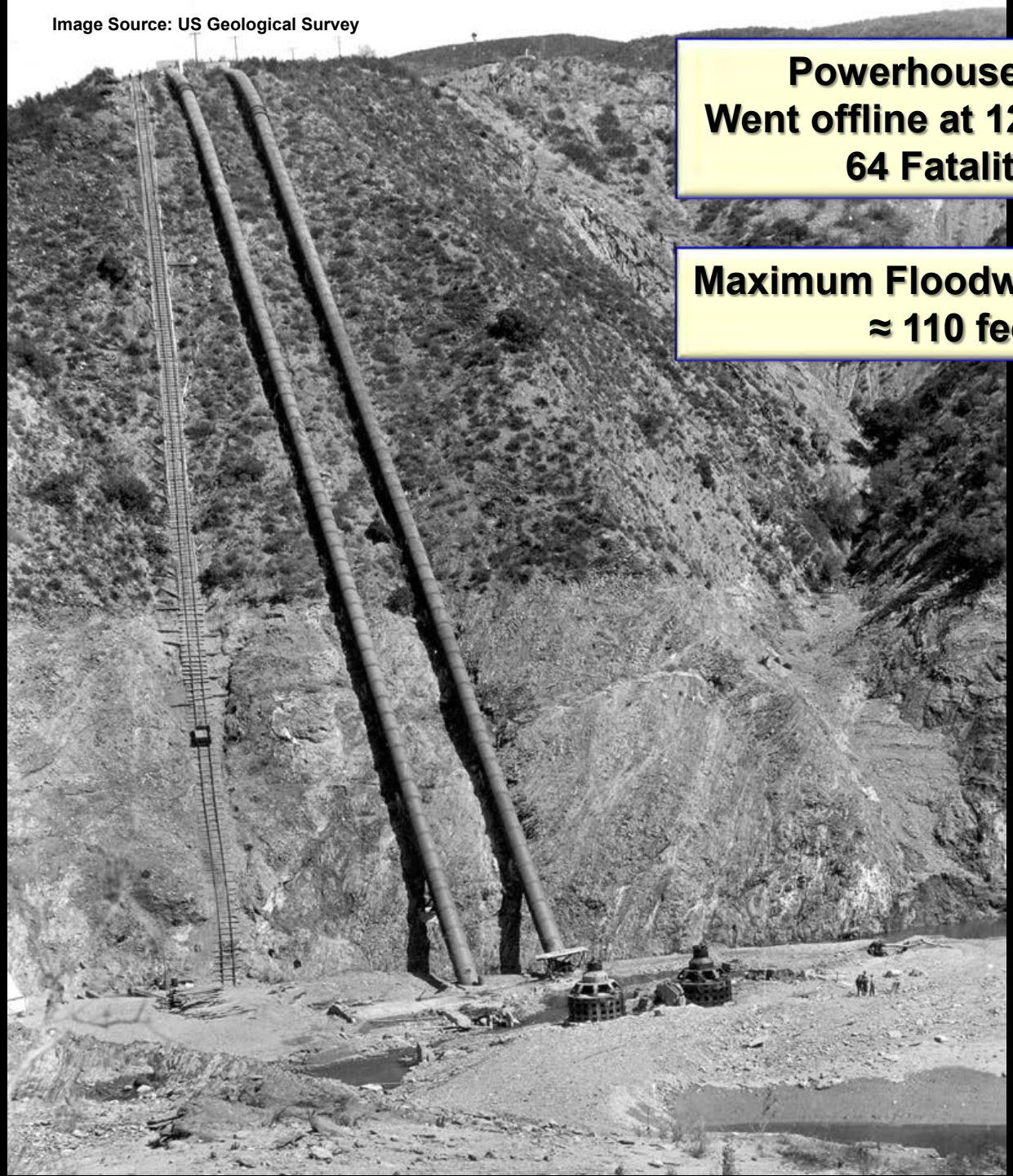
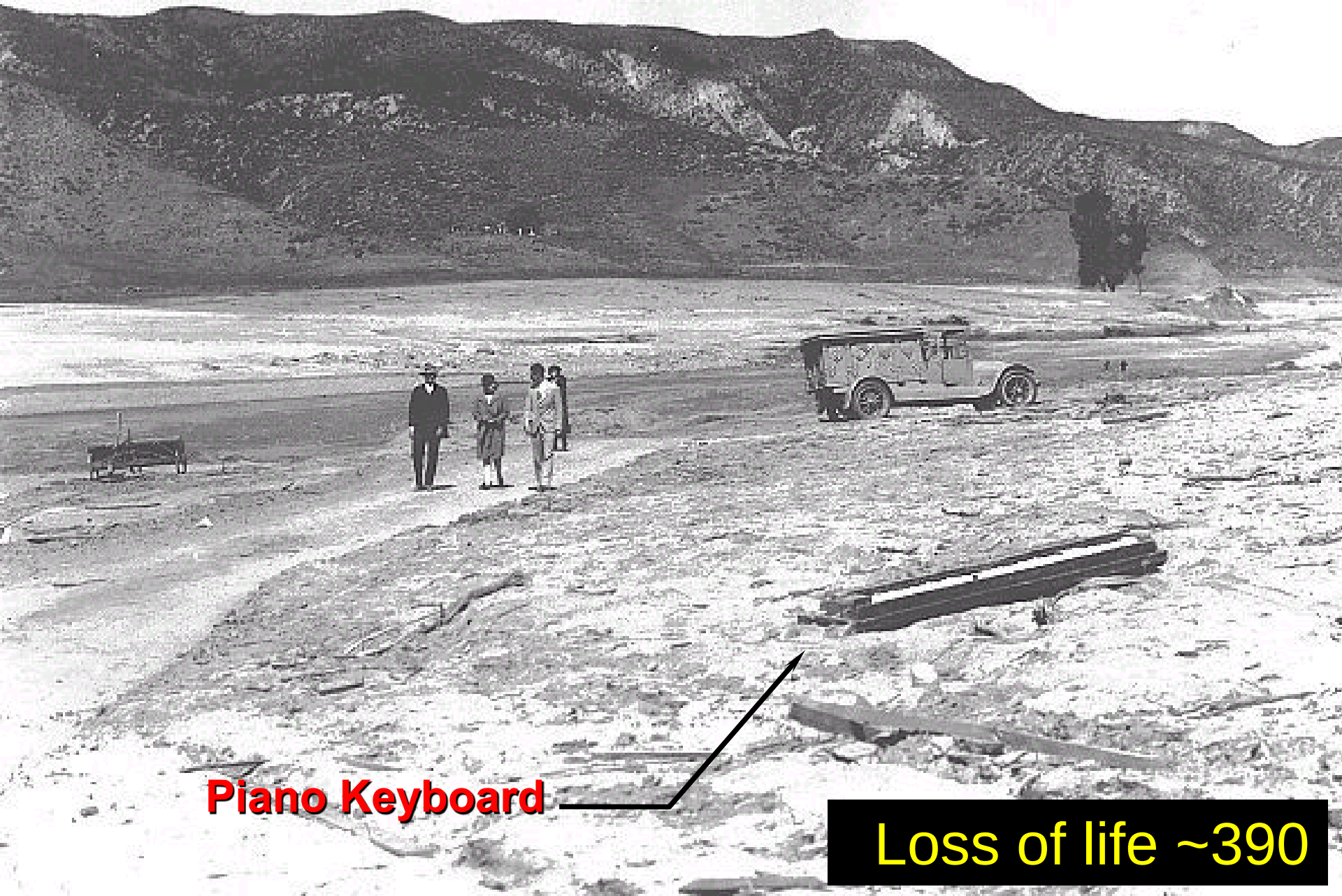


Image Source: US Geological Survey

Powerhouse No. 2
Went offline at 12:02:30 AM
64 Fatalities

Maximum Floodwave Depth:
≈ 110 feet

3 hours after the failure, the wave struck the town of Santa Paula, 38 miles downstream of the dam ...



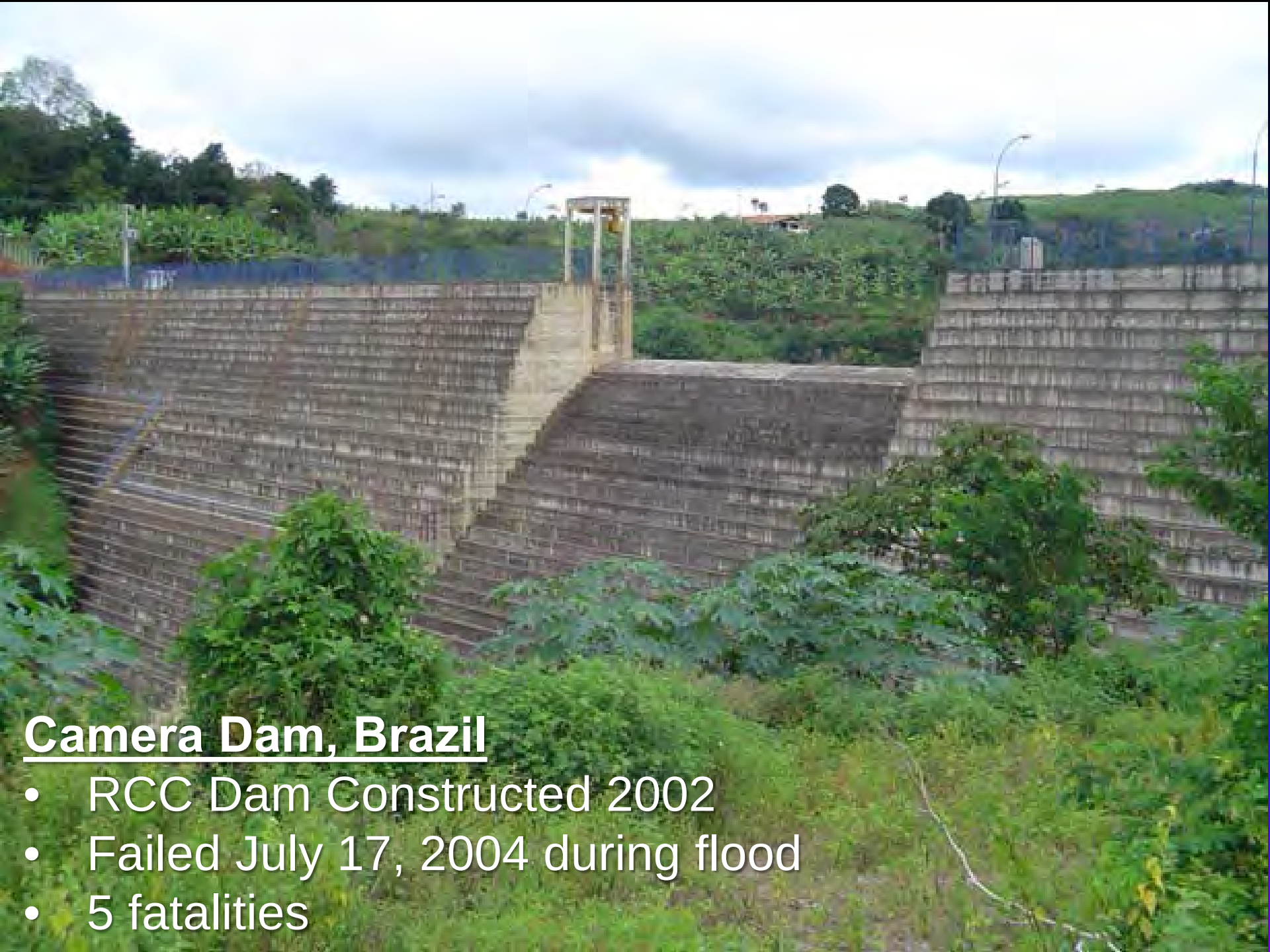
Loss of life ~390


> 50 Miles of Destruction
Loss of life ~450

As the flood approached Santa Paula in the darkness of night, two Santa Paula police officers road motorcycles through the low lying areas of town, warning residents to evacuate. Telephone operators similarly called residents through the night. This sculpture was commissioned by the Santa Paula Historical Society to commemorate these lifesaving efforts.

Roller-Compacted Concrete Gravity Dam
Completed: 2002
Failed: June 17, 2004
Fatalities: 5

CAMARA DAM
PARAIBA, BRAZIL



Camera Dam, Brazil

- RCC Dam Constructed 2002
- Failed July 17, 2004 during flood
- 5 fatalities

Camera Dam, Brazil


Camara Dam, Brazil

Camara Dam, Brazil

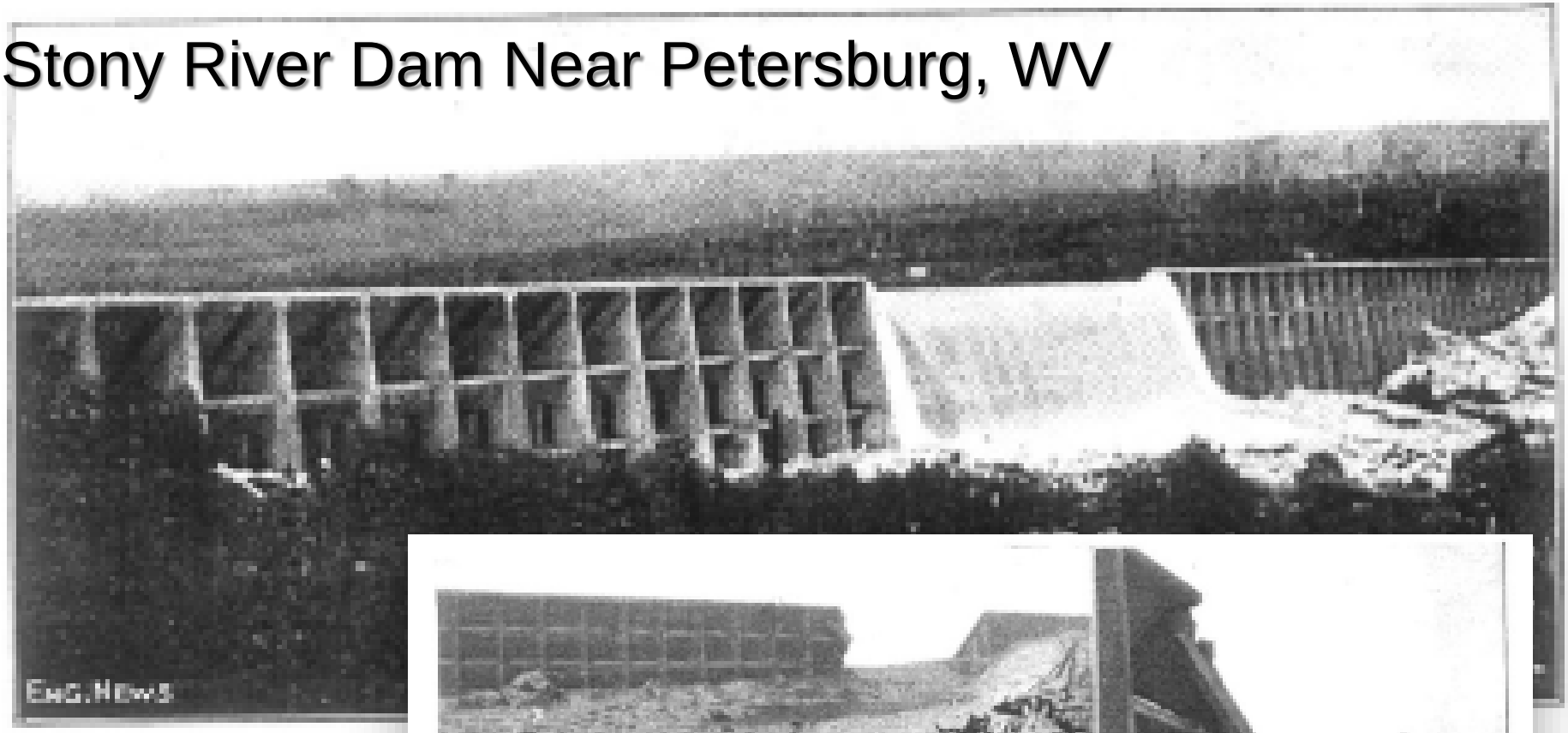
Approximately 70 percent of concrete dam failures can be attributed to geological or geotechnical problems.

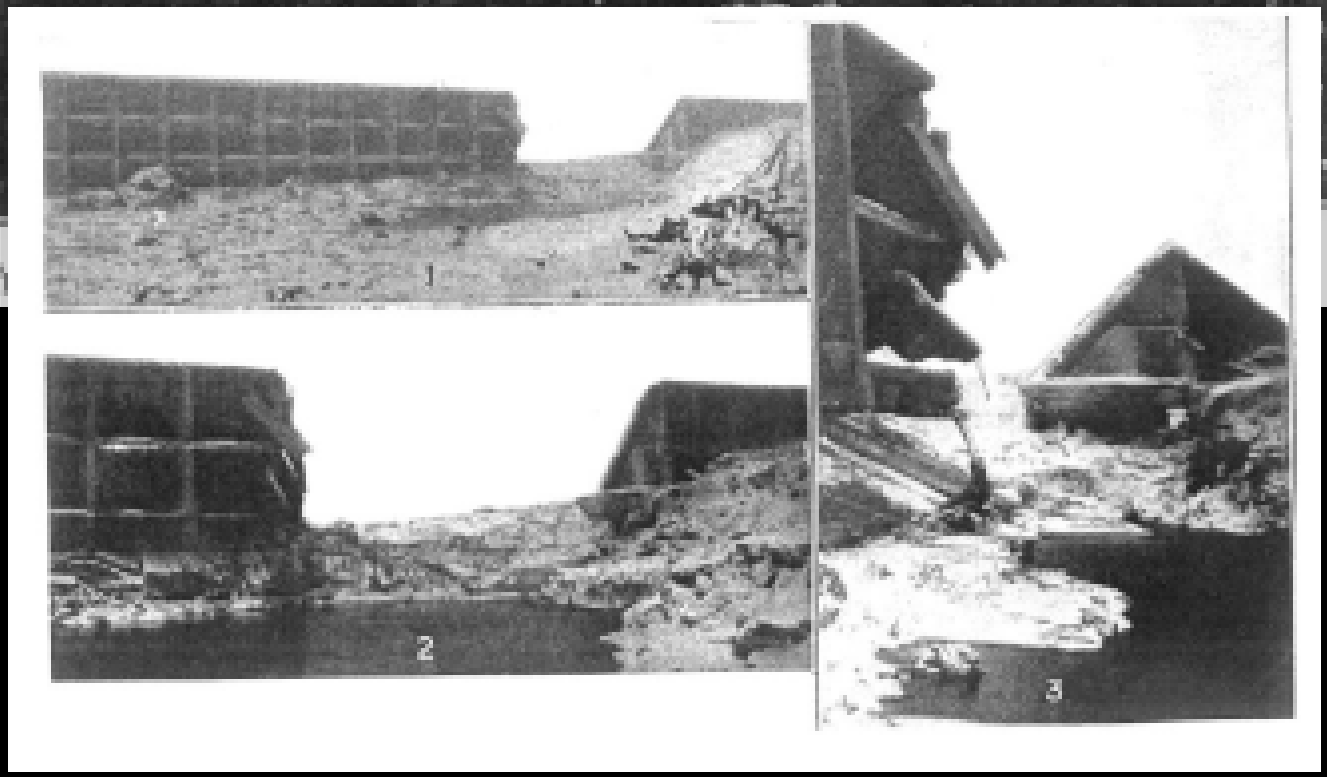
ICOLD, 1974

Ambursen Dam
Constructed: 1913
Failure: 1914, 6 Months After Reservoir Impoundment
Fatalities: 0

STONY RIVER DAM
NEAR PETERSBURG, WV

Stony River Dam Near Petersburg, WV





51 Feet High

Stony River Dam Near Petersburg, WV

Gleno Dam Italy:
Cause: Poor workmanship and construction materials
Failed December 1923 (First filling)
356 Fatalities

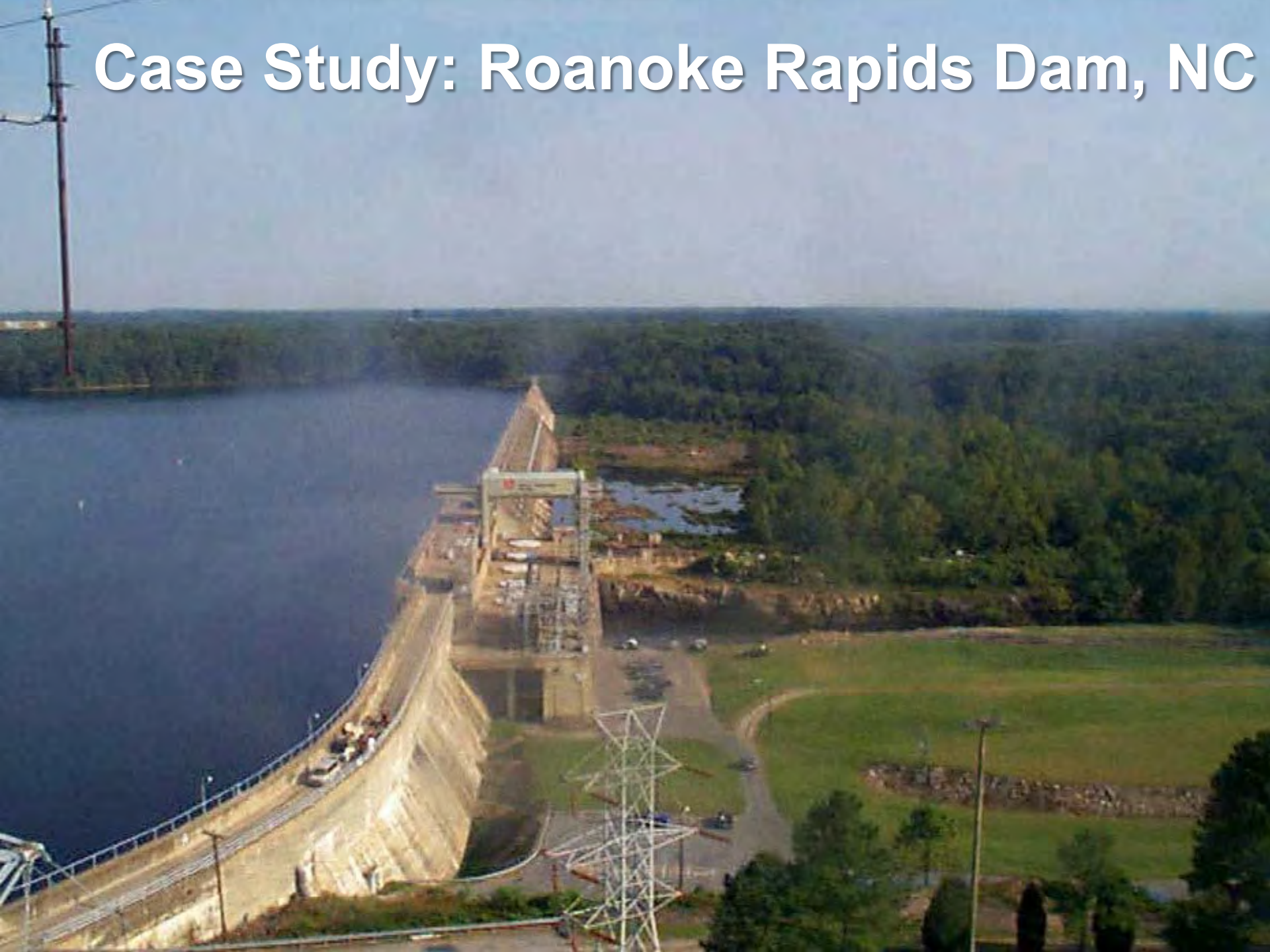
Gleno Dam Italy: Cause: Poor workmanship and construction materials
Failed December 1923 (First filling)
356 Fatalities

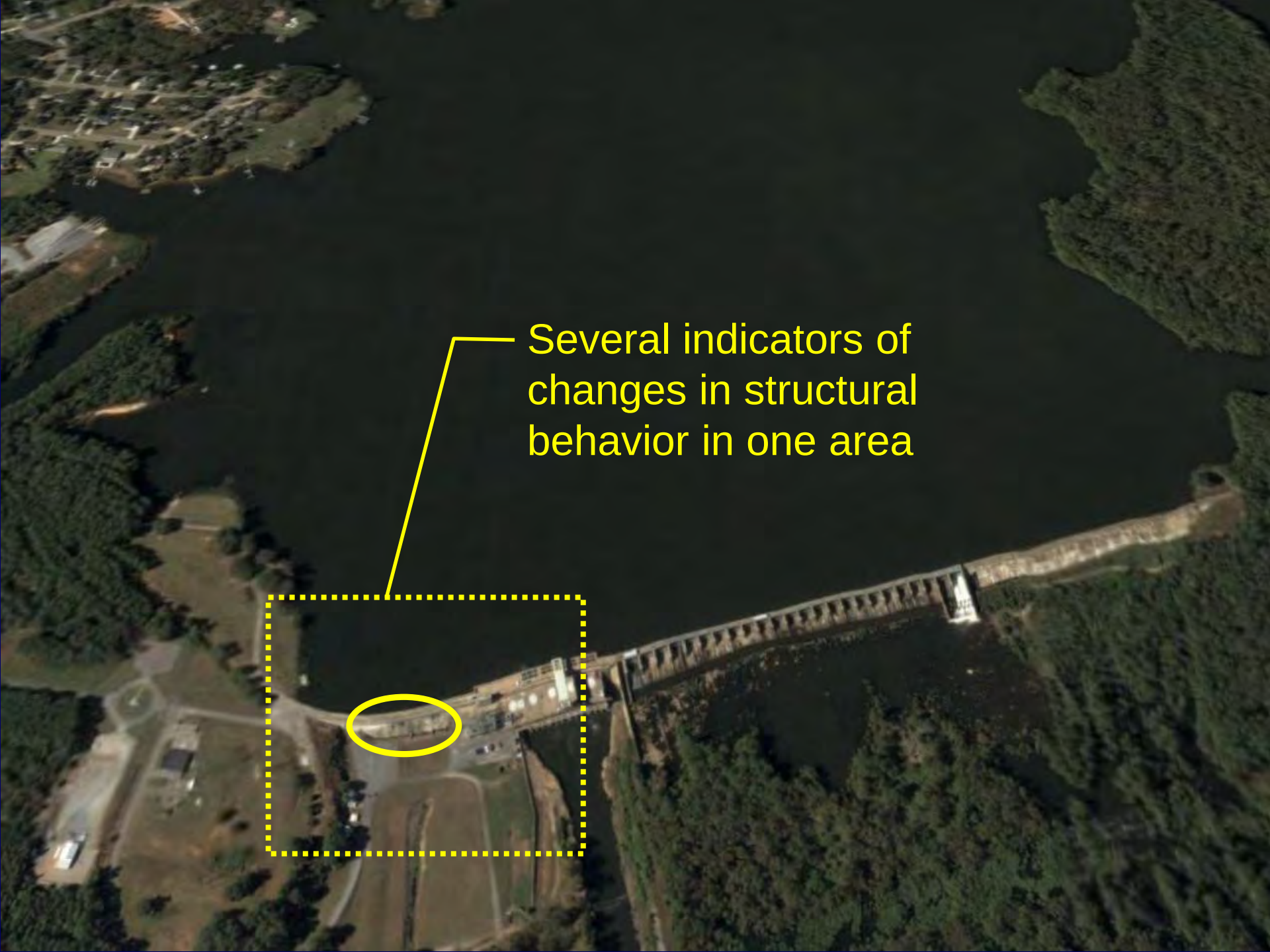
The concrete in the arches was of a poor quality and it was reinforced with anti-grenade scrap netting that had been used during World War I. There were also indications that the dam was poorly joined with its foundation. Additionally, the concrete was believed to not be completely cured when the reservoir was filling. Reportedly, workers who complained about the construction techniques were fired.

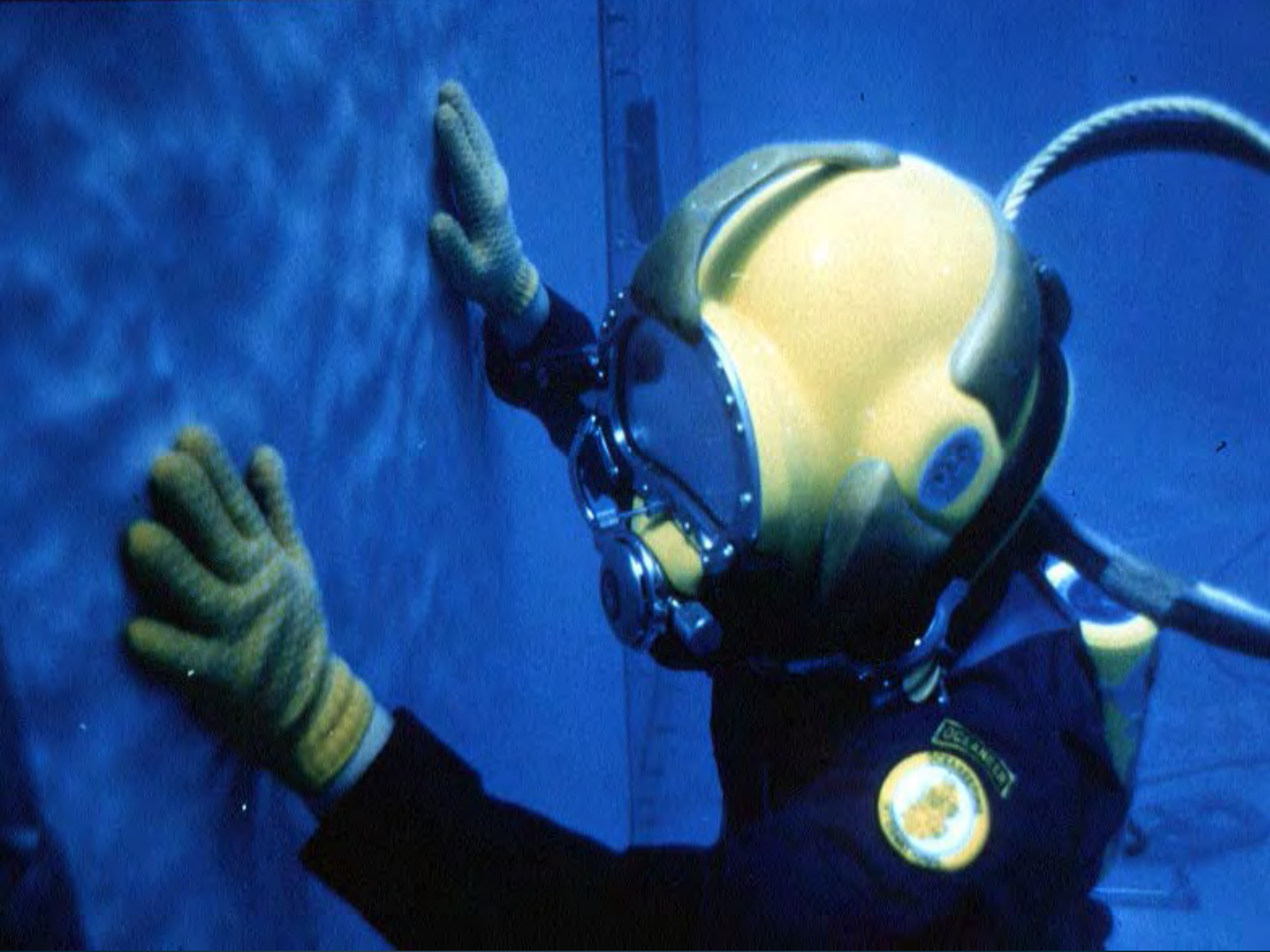
Decommissioning Lower Lake Gerard Dam

Decommissioning Lower Lake Gerard Dam

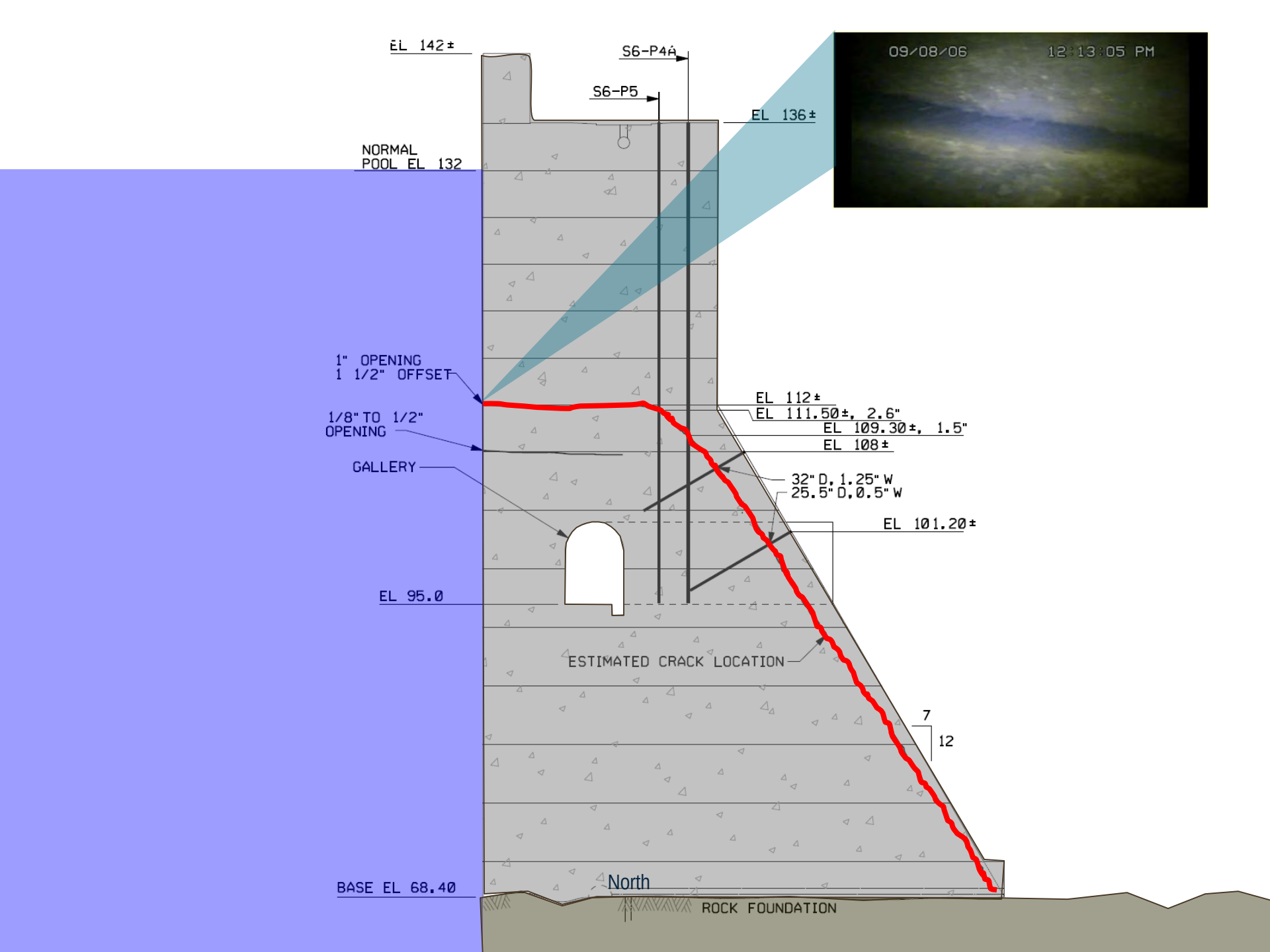
Case Study: Roanoke Rapids Dam, NC

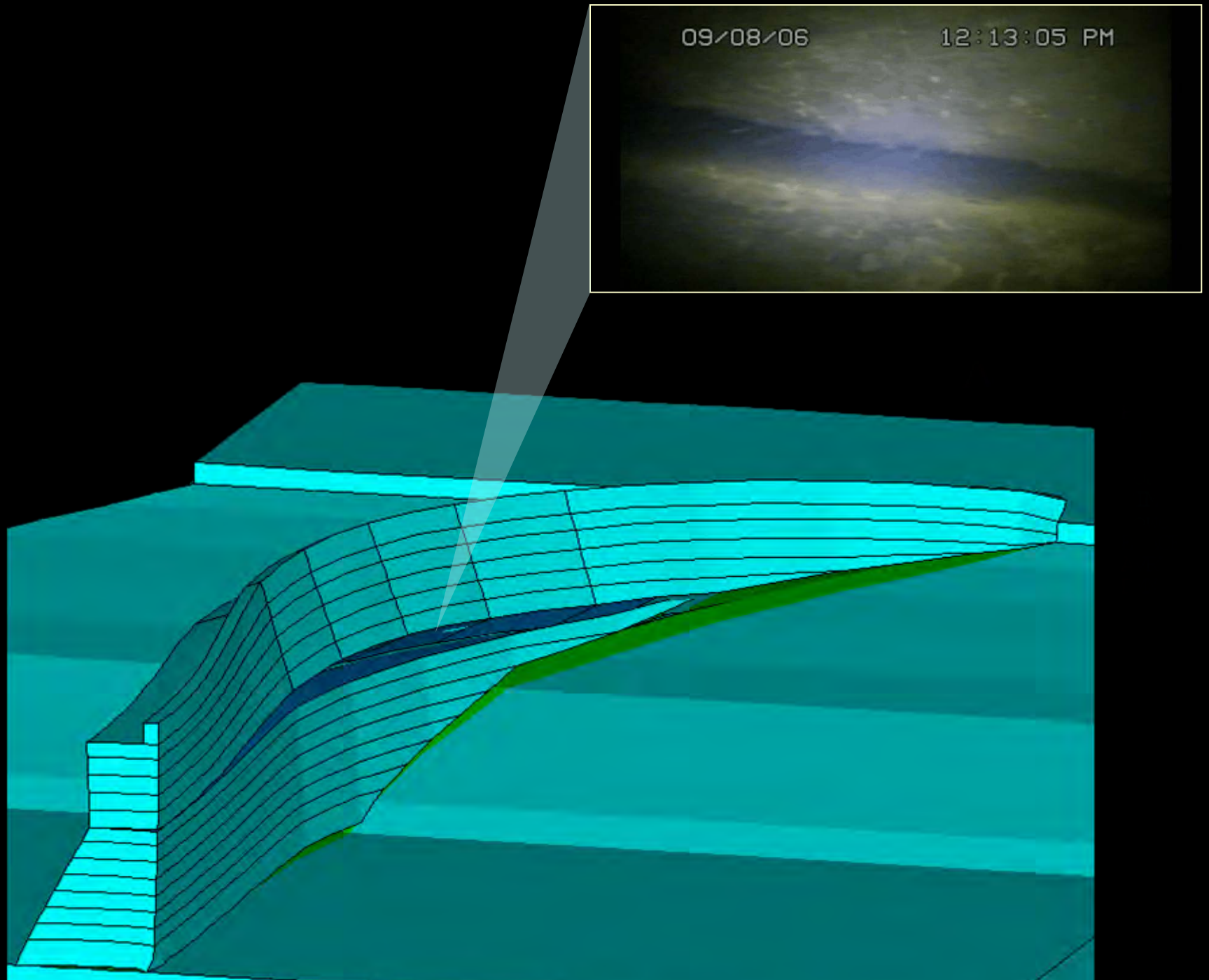



Several indicators of changes in structural behavior in one area



Underwater Inspection and Video


EL 142±
S6-P4A
S6-P5
EL 136±
NORMAL
POOL EL 132
09/08/06
12:13:05 PM
1" OPENING
1 1/2" OFFSET
1/8" TO 1/2"
OPENING
GALLERY
EL 112±
EL 111.50±, 2.6"
EL 109.30±, 1.5"
EL 108±
32" D, 1.25" W
25.5" D, 0.5" W
EL 101.20±
EL 95.0
ESTIMATED CRACK LOCATION
7
12
BASE EL 68.40
North
ROCK FOUNDATION


09/08/06
12:13:05 PM

Alkali-Silica Reaction (ASR) Gel

ASR Gel

Ettringite

Movement

Engineers were tipped to a possible problem Tuesday when they noticed a slight bowing of a concrete curb on the dam deck. They also noticed that the affected

The heightened alert at the dam comes after divers Thursday discovered a crack in one of the dam's concrete support piers that measures 2 inches wide by 65 feet long.

The PUD will draw the reservoir behind the dam down another 14 feet by Tuesday for a total expected drawdown of 20 feet, Stredwick said.

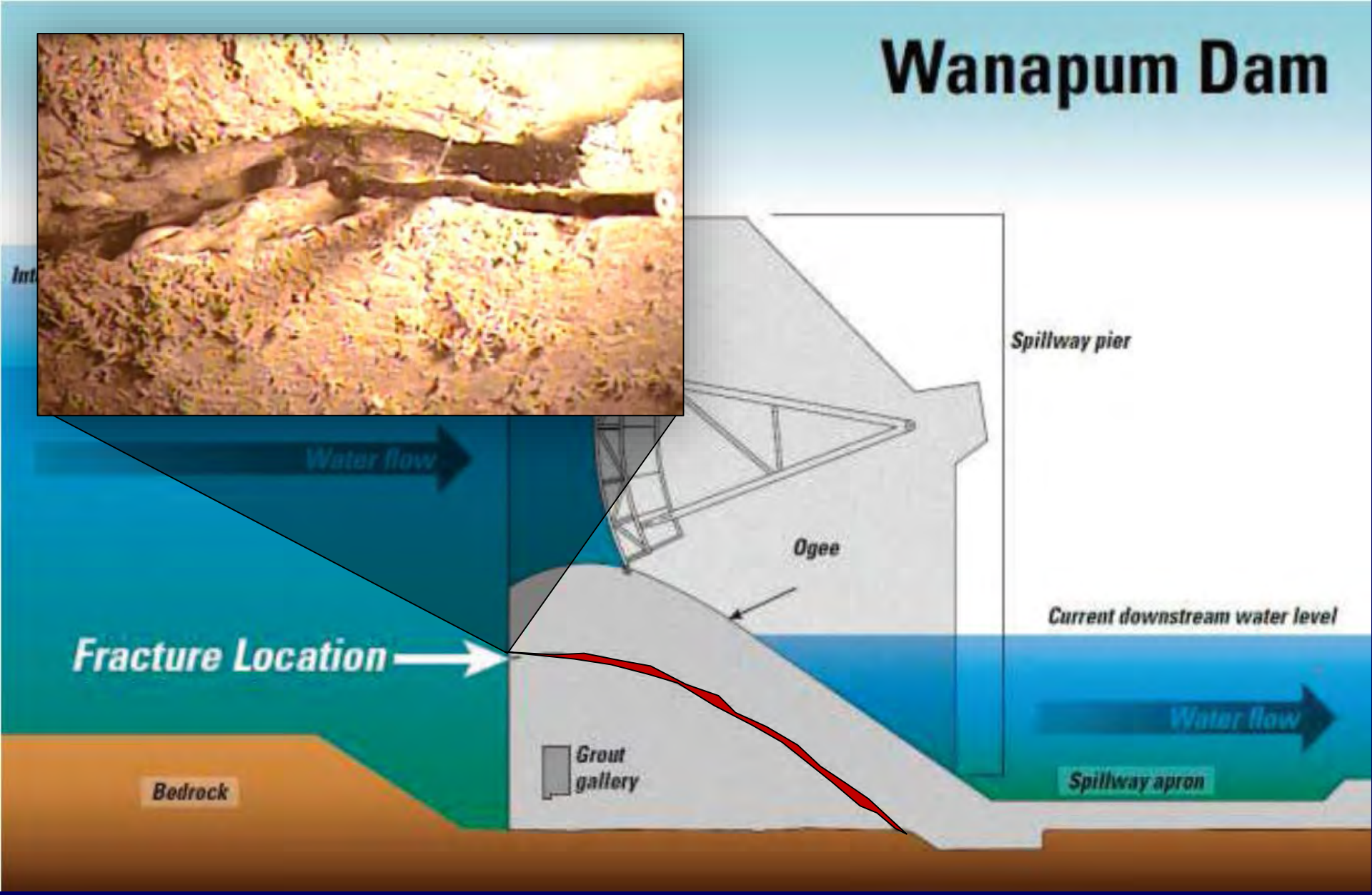
by Christine Pratt | Feb. 28, 2014, 4:47 p.m. | Comment


Wanapum Dam,
Columbia River near Vantage, Washington


Wanapum Dam,
Columbia River near Vantage, Washington
Incident occurred after 50 years of service!


Wanapum Dam,
Columbia River near Vantage, Washington

Source: Wanapum Dam Crack Development Root Cause Analysis, HDR Engineering, Inc.

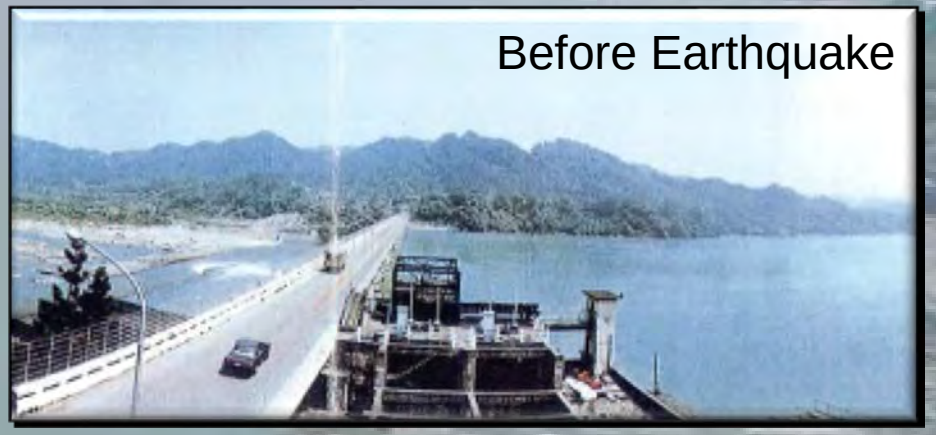


Source: Wanapum Dam Crack Development Root Cause Analysis, HDR Engineering, Inc.

Reinforced Concrete Dam
Completed: 1977
Failed: September 21, 1999
Fatalities: 0

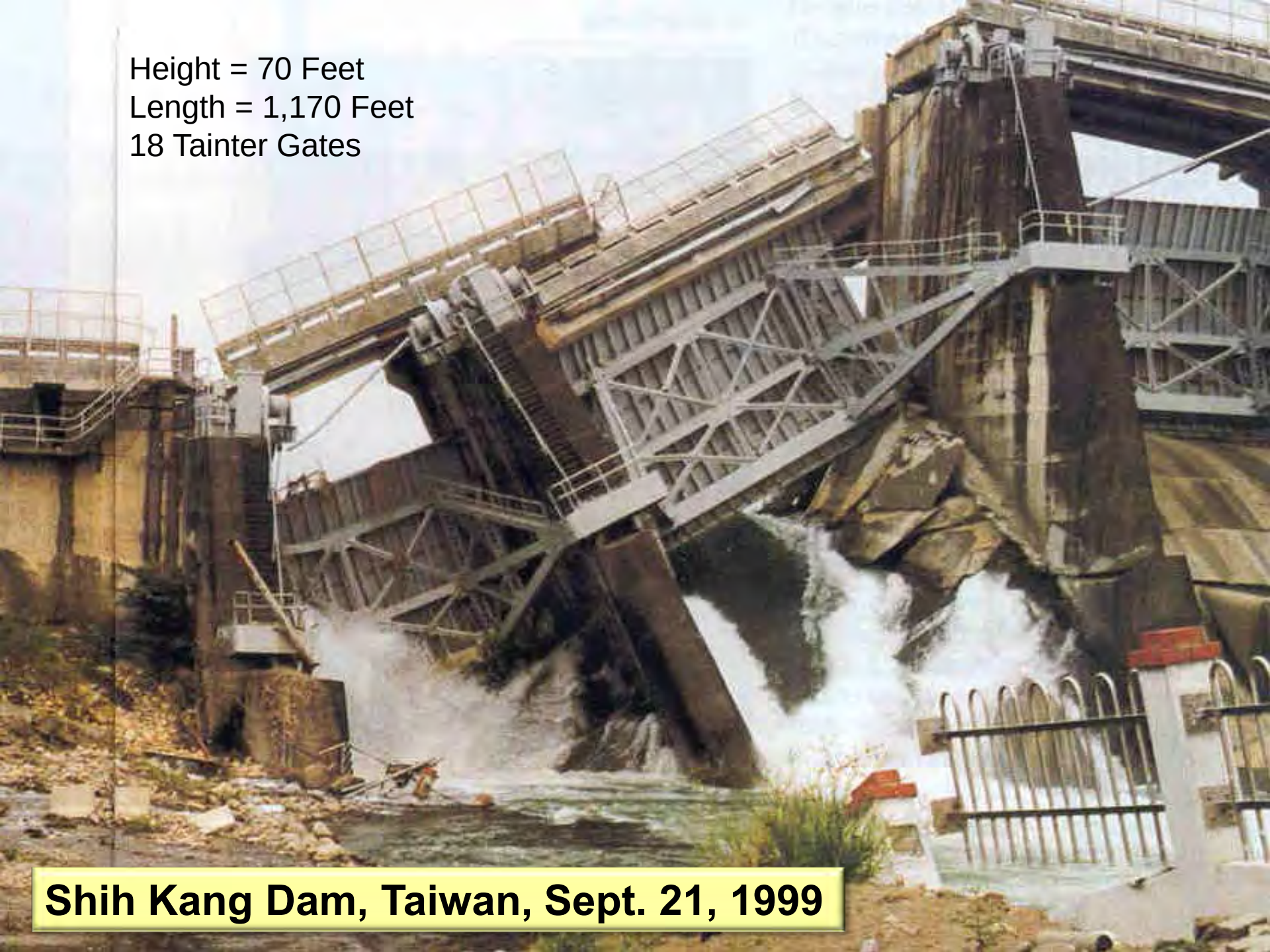
SHIH KANG DAM, TAIWAN

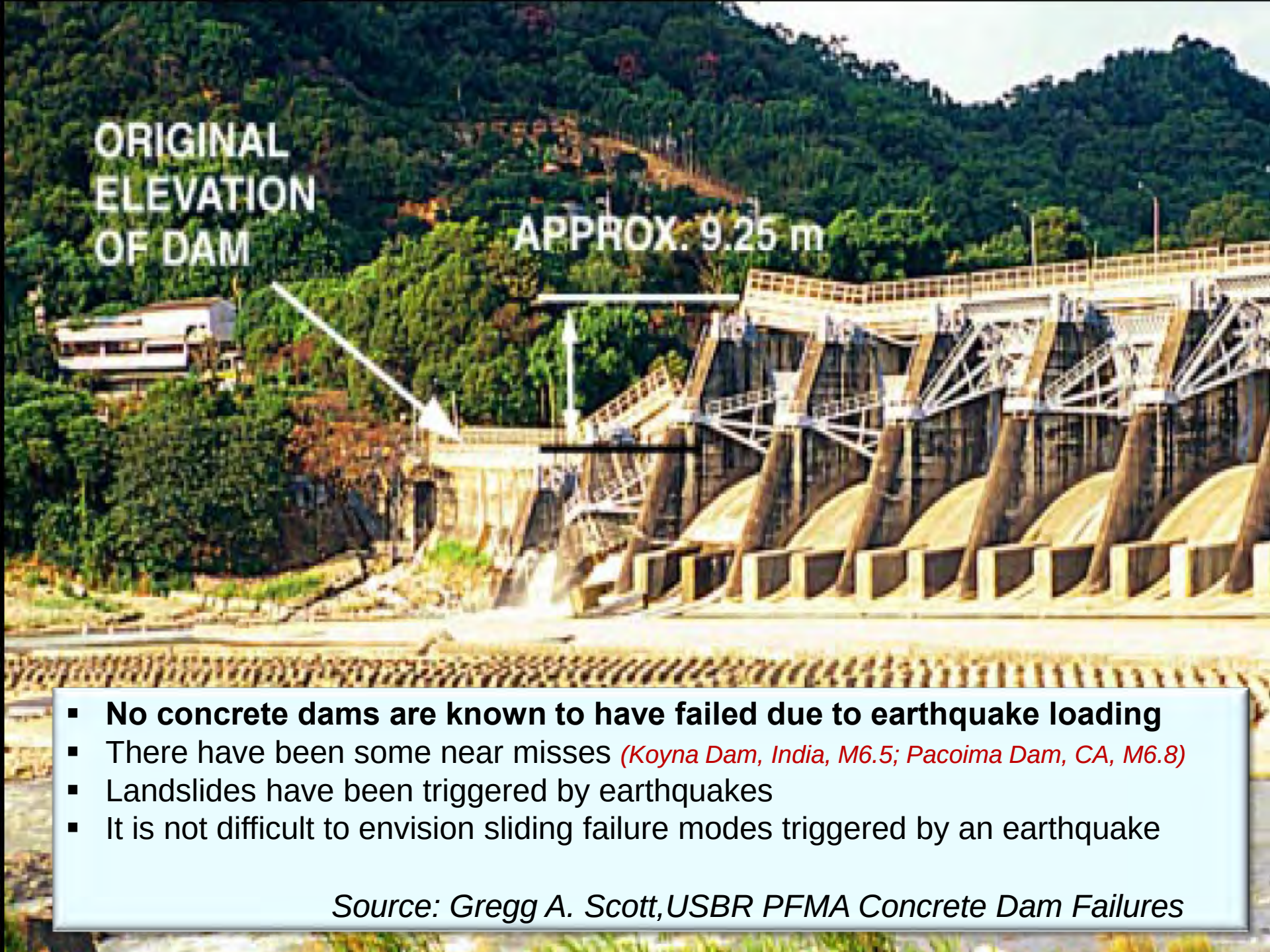
75’ High, 1100’ long, 18 gates



No known concrete gravity dam failures related to earthquakes!

Shih Kang Dam, Taiwan, Sept. 21, 1999

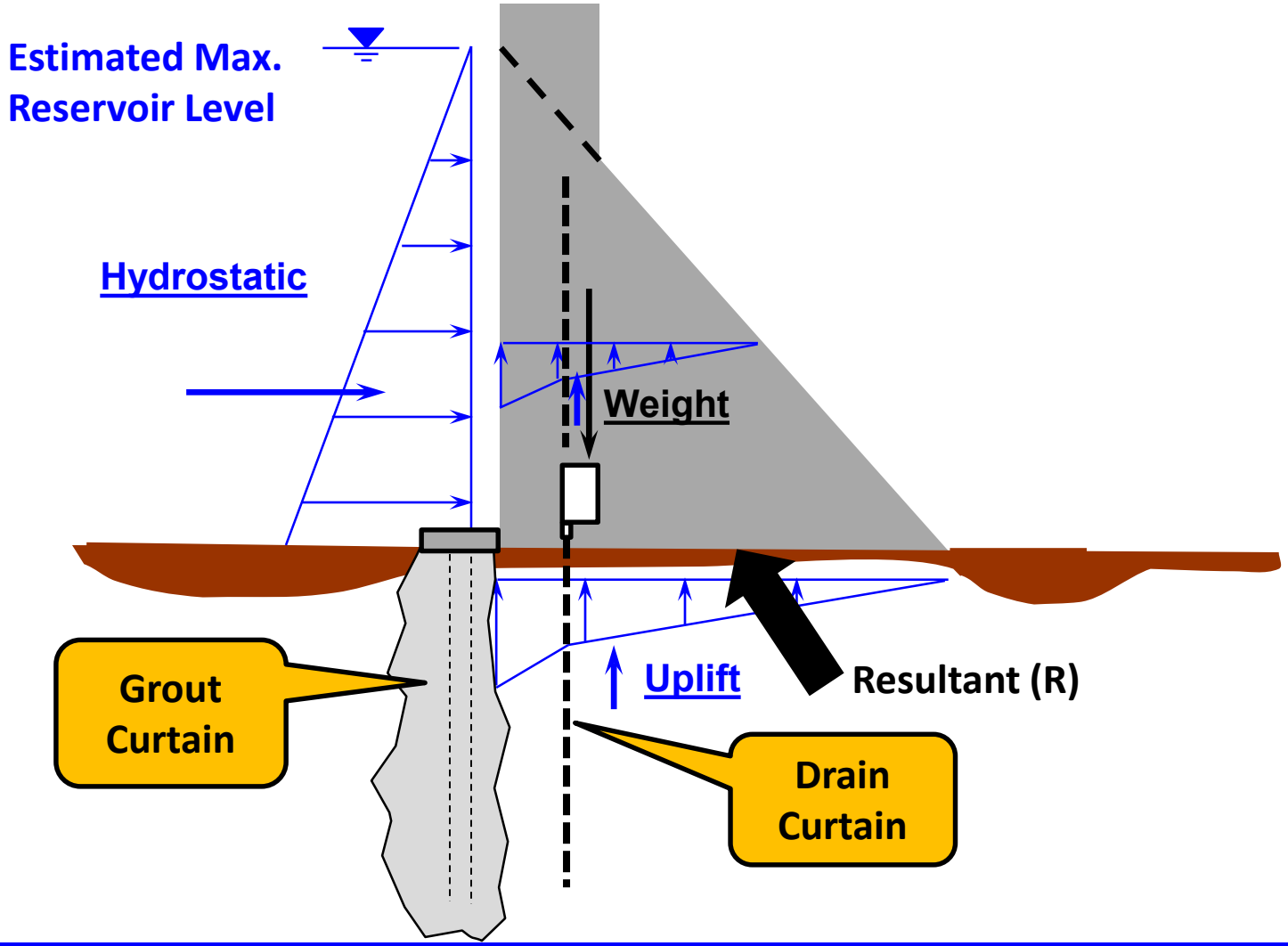

Height = 70 Feet
Length = 1,170 Feet
18 Tainter Gates
Shih Kang Dam, Taiwan, Sept. 21, 1999



- **No concrete dams are known to have failed due to earthquake loading**
- There have been some near misses *(Koyna Dam, India, M6.5; Pacoima Dam, CA, M6.8)*
- Landslides have been triggered by earthquakes
- It is not difficult to envision sliding failure modes triggered by an earthquake

Source: Gregg A. Scott,USBR PFMA Concrete Dam Failures

Foundation Improvement Options



Gallery and Drainage System

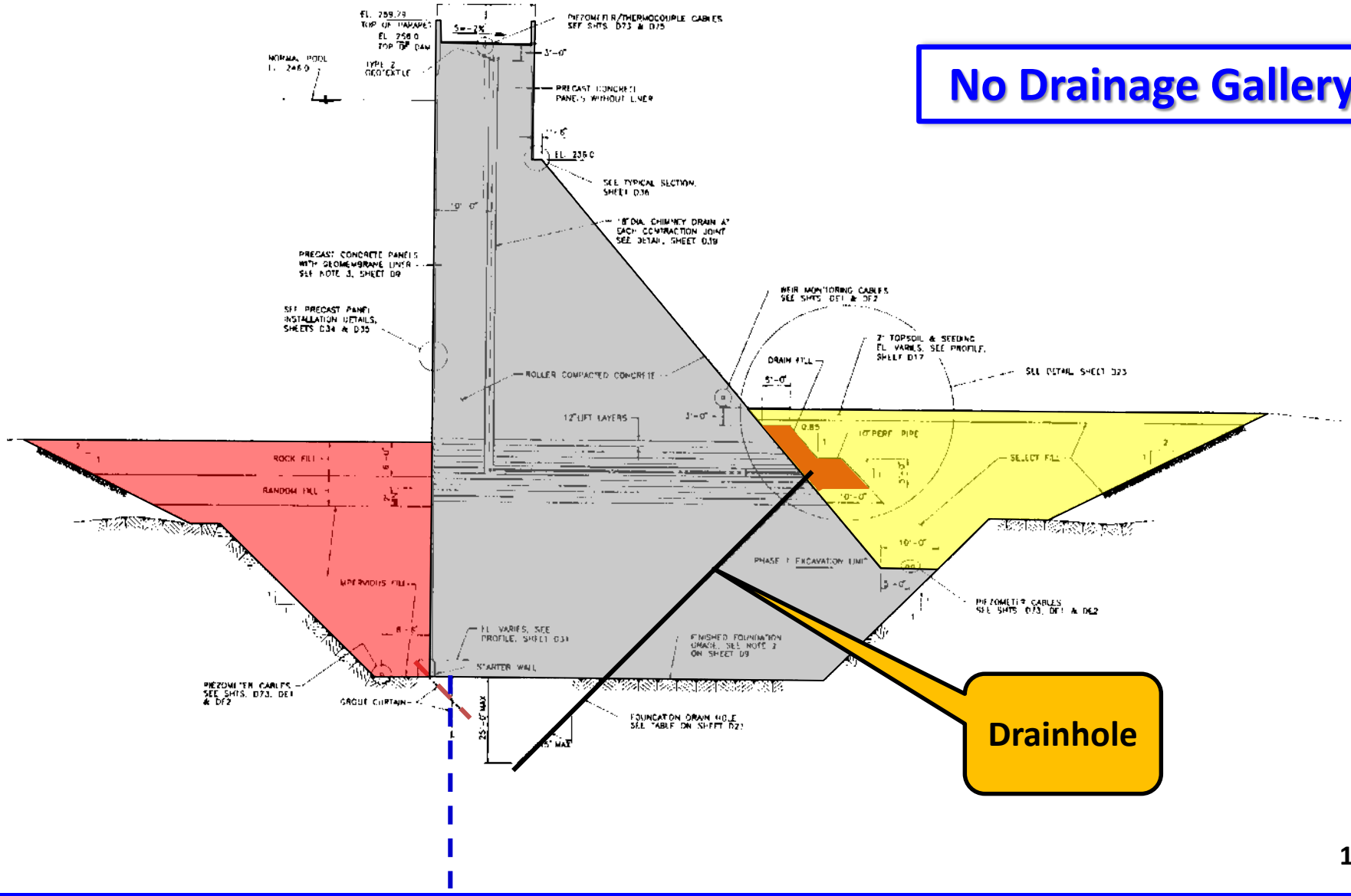
Drainhole Pressure Testing


Calcium Carbonate Deposits
Flushing Clogged Drainholes
08.20.2008

Re-Drilling Drainholes

Re-Drilling Drainholes

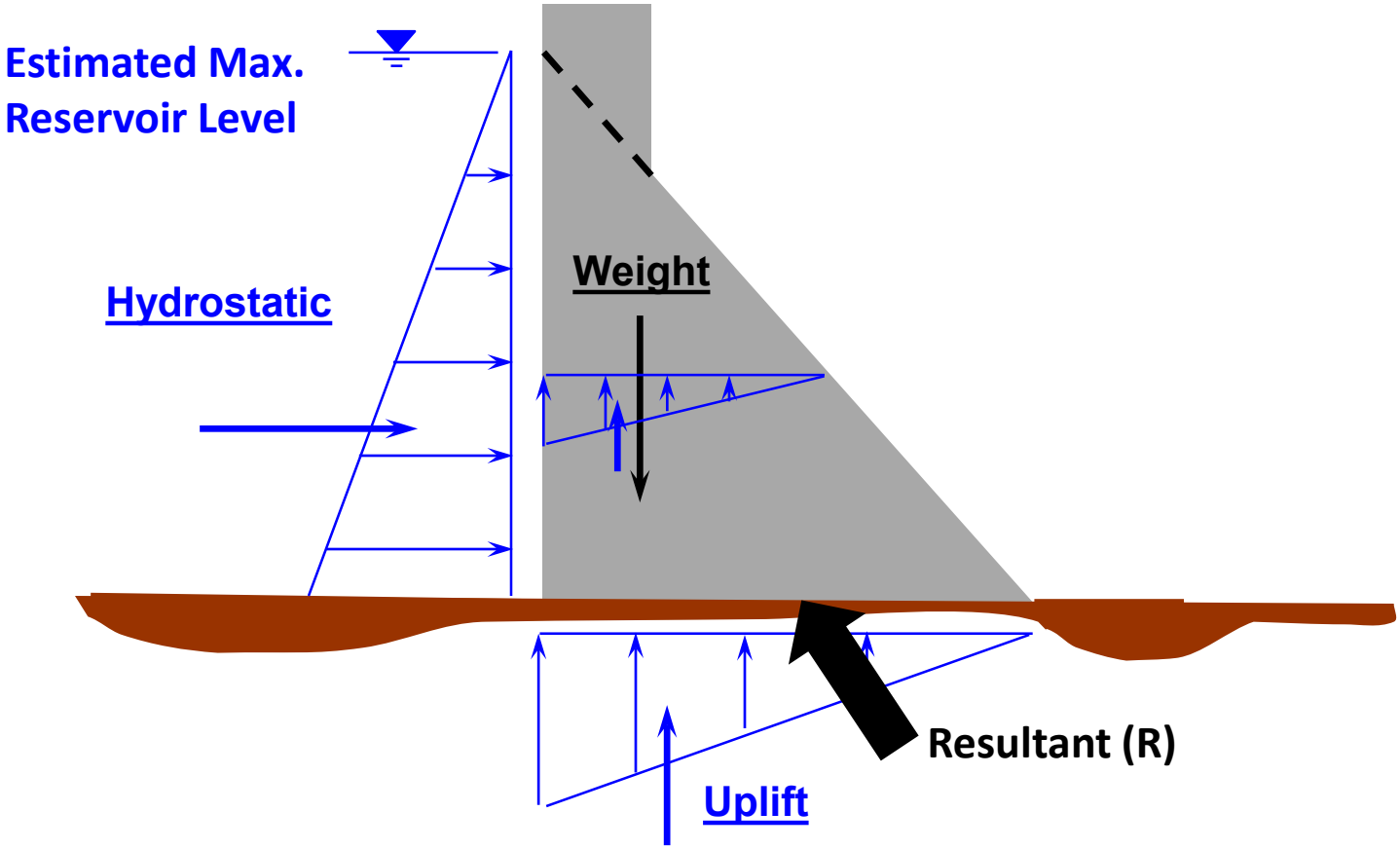
Drain Curtains



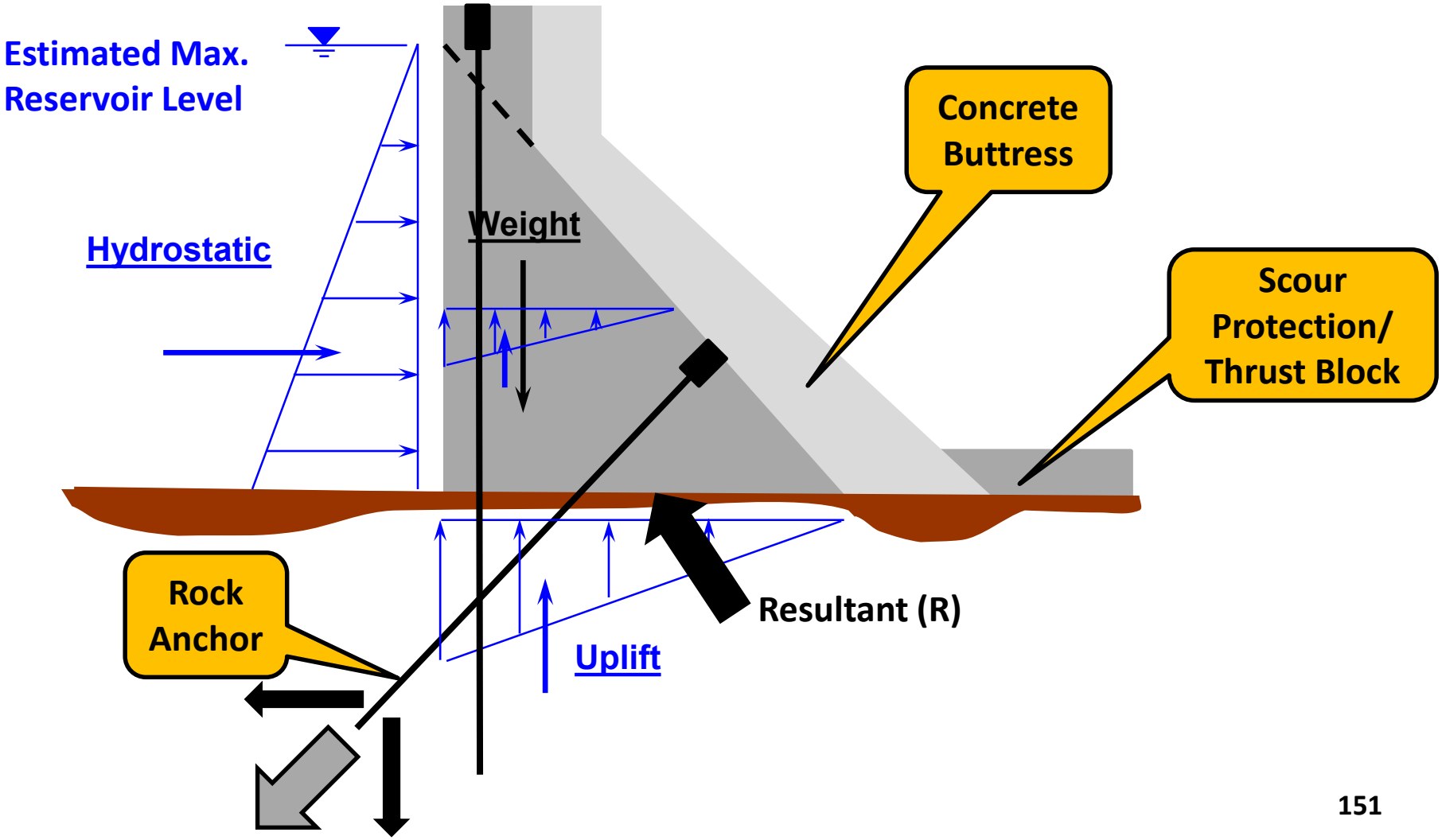
Structure Improvement Options

- Post-Tensioned Rock Anchors
- Concrete Buttresses
- Geomembrane Sealing Systems

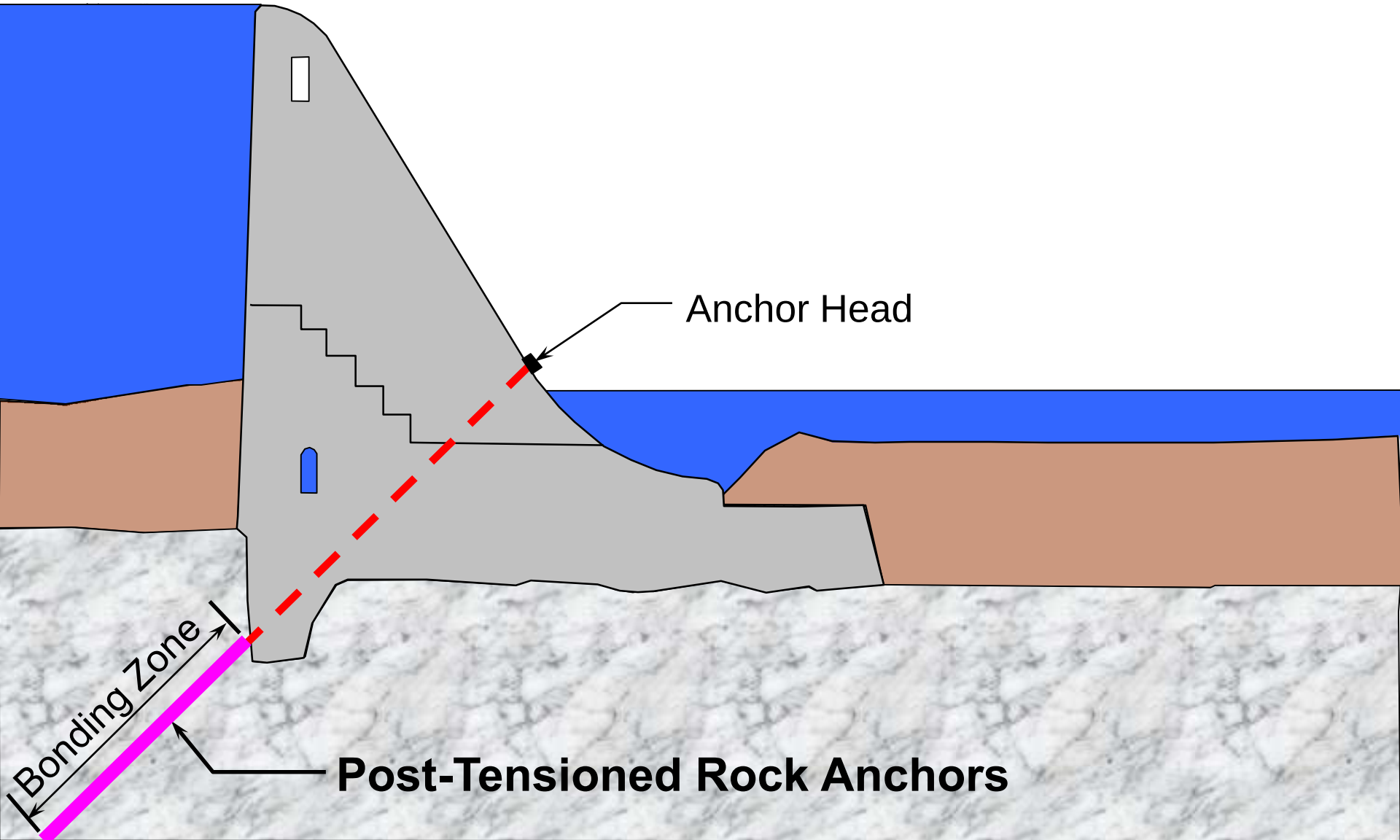
Structure Improvement Options



Structure Improvement Options

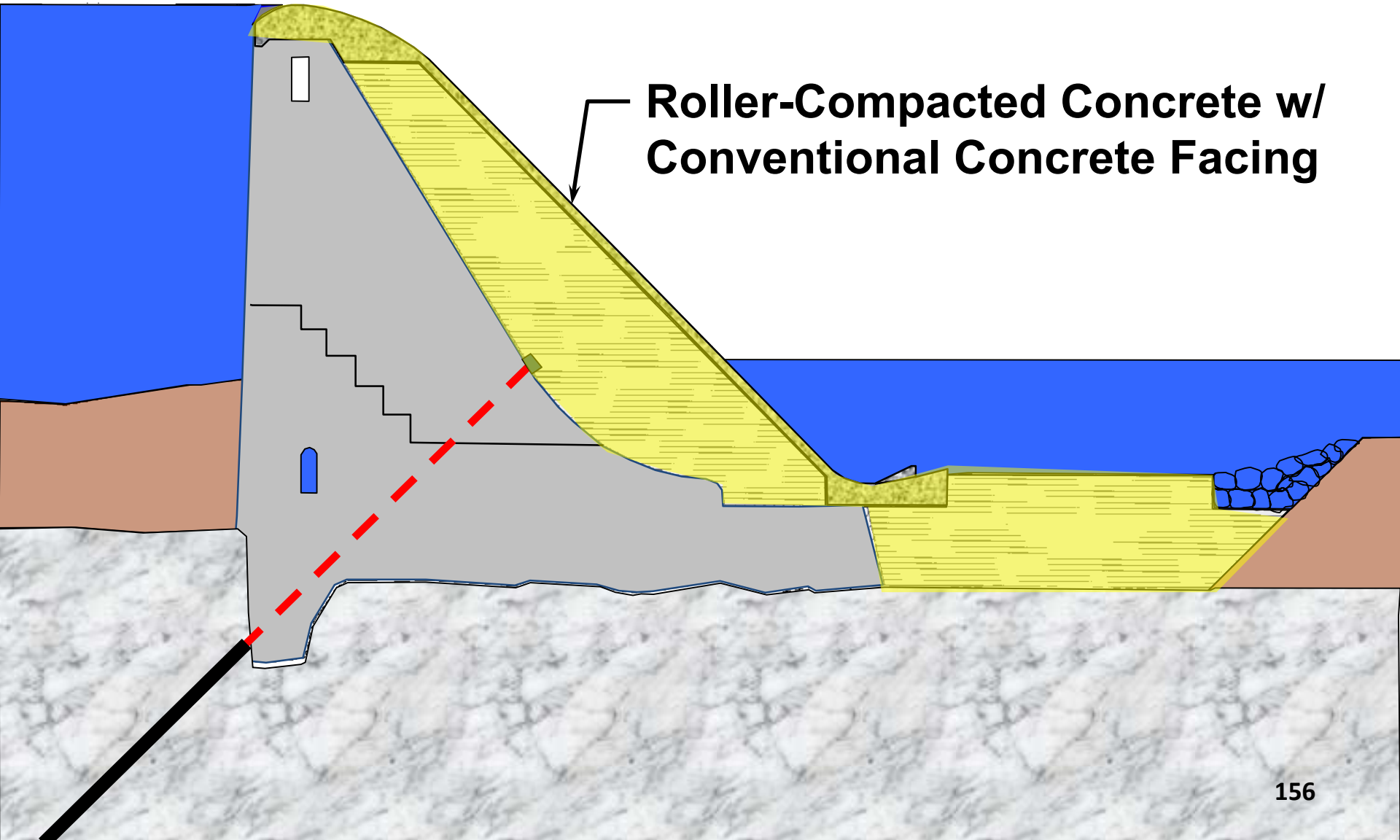


Loch Raven Dam, Baltimore, MD


Anchor Head
Bonding Zone
Post-Tensioned Rock Anchors


Rock Anchor Head
2003.01.30

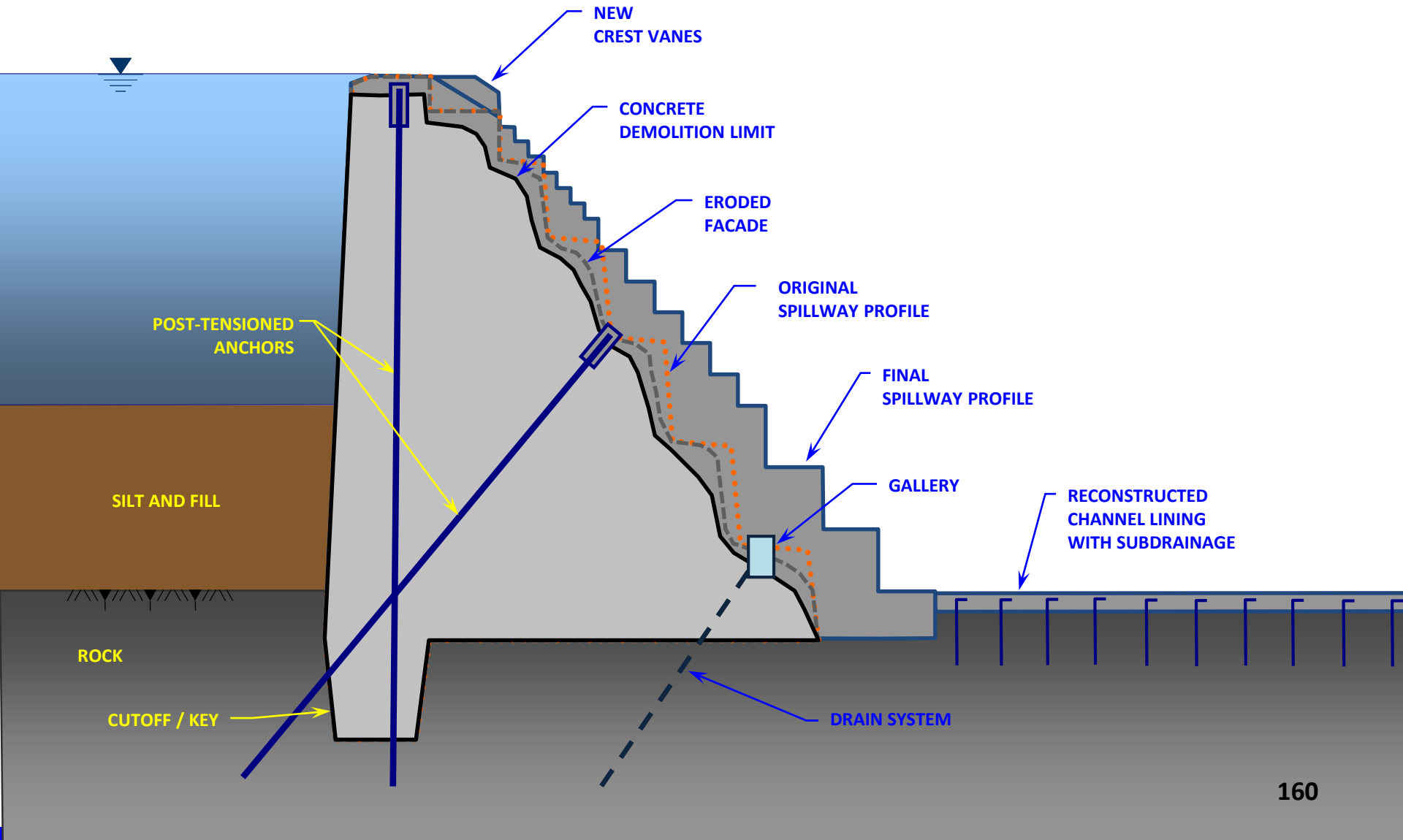

Rock Anchor
Tensioning


Roller-Compacted Concrete w/
Conventional Concrete Facing


RCC Buttress
2004.09.03
157


LOCH RAVEN DAM
1914
1922
2005

Gilboa Dam Spillway, NY


NEW
CREST VANES
CONCRETE
DEMOLITION LIMIT
ERODED
FACADE
ORIGINAL
SPILLWAY PROFILE
FINAL
SPILLWAY PROFILE
GALLERY
RECONSTRUCTED
CHANNEL LINING
WITH SUBDRAINAGE
POST-TENSIONED
ANCHORS
SILT AND FILL
ROCK
CUTOFF / KEY
DRAIN SYSTEM

Vertical Rock Anchors

Inclined Rock Anchors


Drainage
Gallery

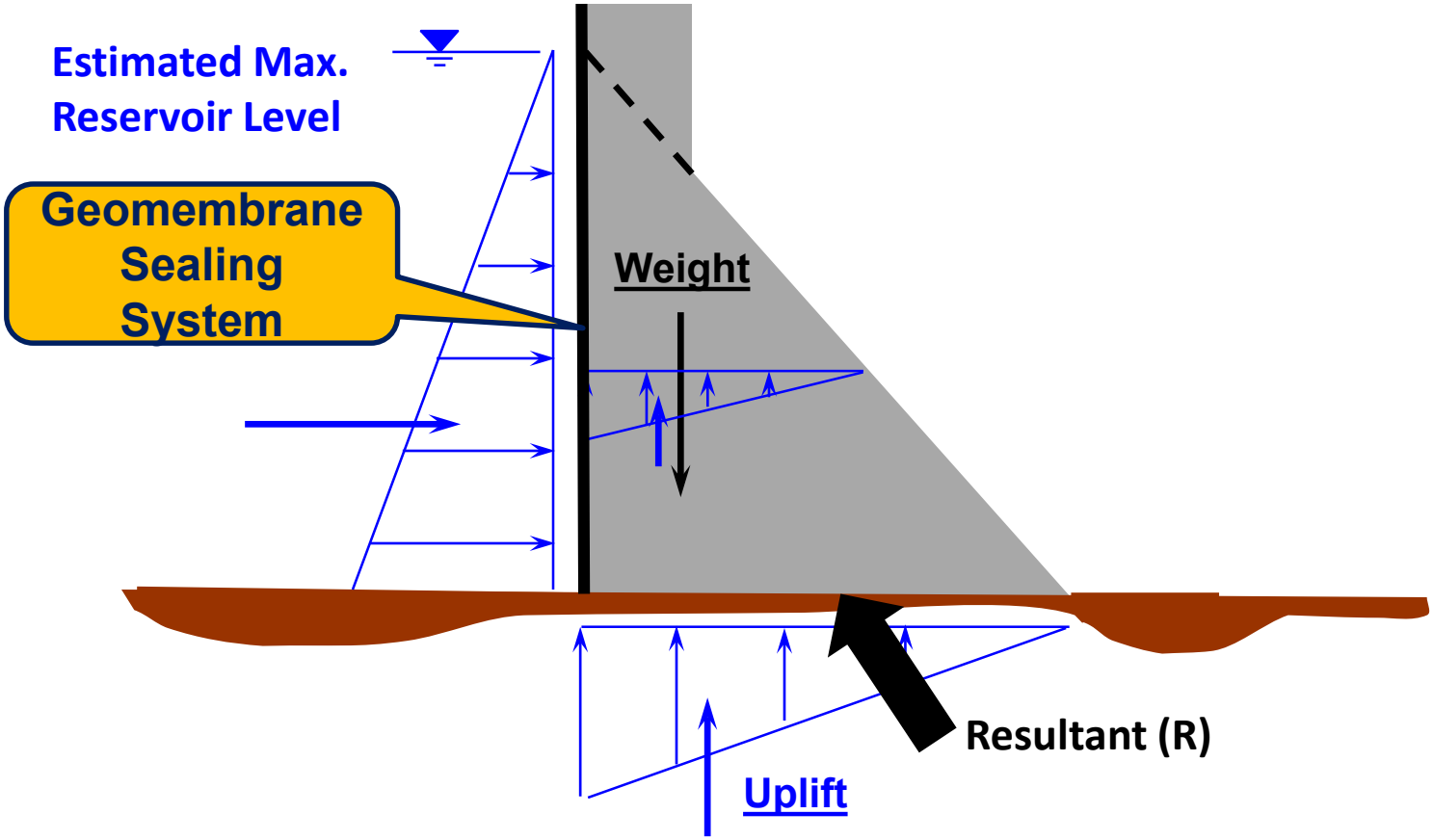
Erosion at toe of Gravity Spillway (2011)

09.19.2011


05.01.2013


05.29.2013

Structure Improvement Options




APR 24 2003


APR 30 2003

Lost Creek Dam, OR

Exposed Geomembrane with Fully Drained Interior Face


Drainage System
PROF
72
72
72
MAY 7 2003

Multiple-Arch Dam

Lost Creek Dam, OR

Animal Activity

QUESTIONS ?

Lessons Learned from Concrete Dam Failures

Gannett Fleming

Maryland Department of the Environment