DAM AND RESERVOIR FAILURES (19)

I Main Topics

A Overview

B Teton Dam

II Overview

A Wikipedia lists 85 failures of dams/reservoirs since 1800; 31 since 2000

B Dams with severe damage

1 Fontenelle Dam, WY, 1965, 1980

2 Glen Canyon Dam, US, 1983; 2nd largest reservoir in U.S.

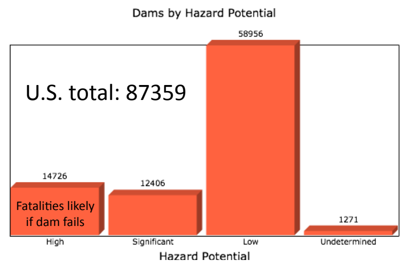
3 Sayano–Shushenskaya Dam, Russia, 2009; largest powerplant in Russia

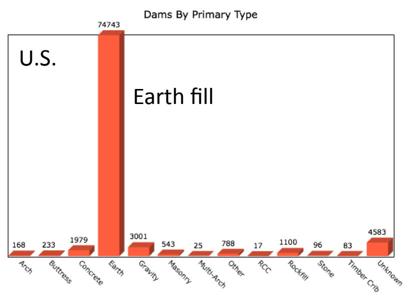
Year	Site	Fatalities
1889	South Fork Dam, PA	2,209
1928	St. Francis Dam, CA	600
1959	Malpasset Dam, France	423
1963	Baldwin Hills, Ca	5
1963	Vaiont, Italy	2,000
1975	Teton Dam, Idaho	1 $1-2B damage
1975	Banqiao and Shimantan Dams, China	171,000

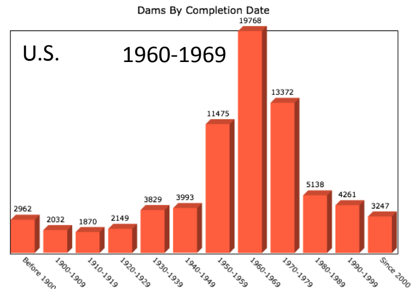
II Overview

C World inventory (1997)*
1 ~800,000 dams
2 ~40,000 dams > 15m tall

D U.S. inventory (2013)†
1 87,359 dams
2 6433 dams > 15m tall

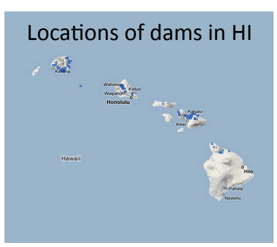


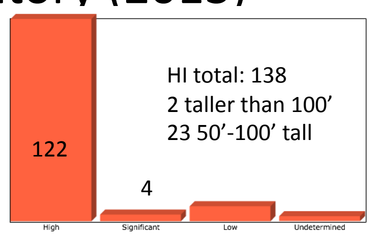


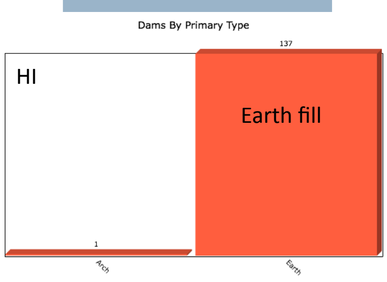


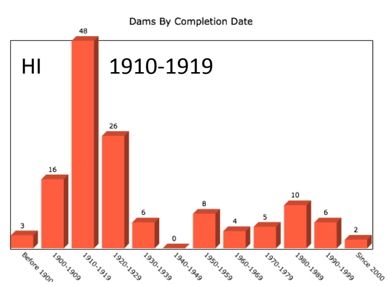
* http://en.wikipedia.org/wiki/Dam † http://geo.usace.army.mil/pgis/f?p=397:5:0::NO

II Overview
E Hawaii inventory (2013)







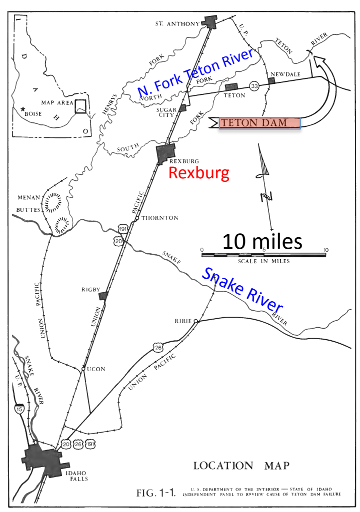


http://geo.usace.army.mil/pgis/f?p=397:5:0::NO

III Teton Dam

A Introduction

1 Dam failed June 5, 1976
  a Dam on Teton River, Idaho
  b First time full
  c 11 fatalities
  d $1-2 billion damage



https://archive.org/details/reporttousdepart00inde

B Key Milestones

1 1904: Initial reconnaissance
2 1946: Preliminary site selection
3 1956-1962: Site studies
(potential for seepage at site identified)
4 1962: Site recommendation
5 1963: U.S. Bureau of Reclamation proposes dam
6 1964: Construction bill approved
7 1971: Environmental Impact Statement issued
8 1972: Construction begins

Sources: Failure of Teton Dam by Independent Panel, 1976; http://en.wikipedia.org/wiki/Teton_Dam

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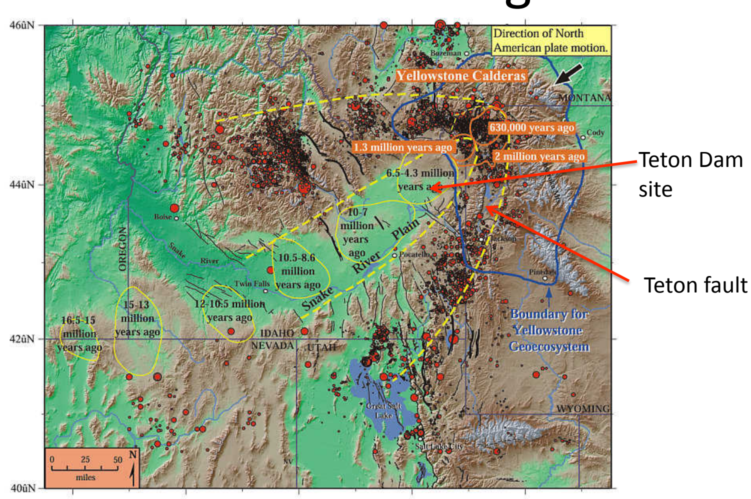
C Tectonic setting



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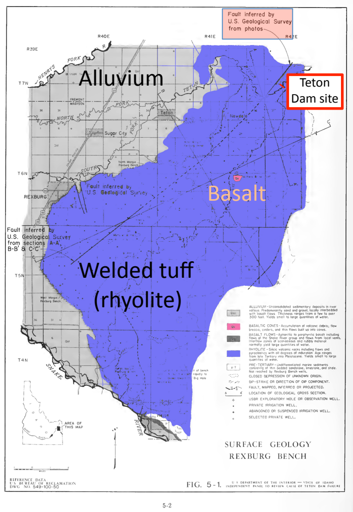
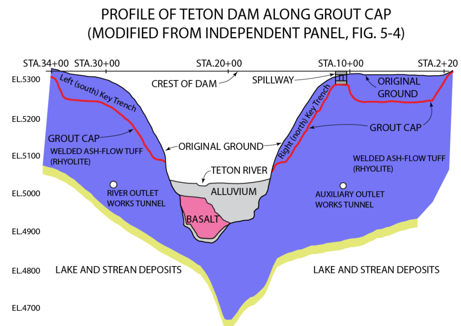
D Geology

Geologic Map of Area Around Teton Dam





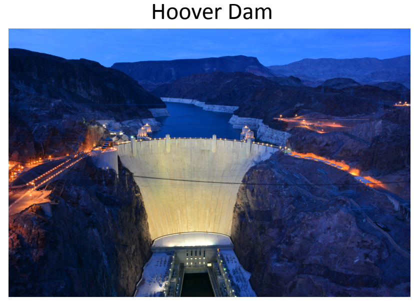
View downstream

From Independent Panel, 1976

E Design

1 Designed by U.S. Bureau of Reclamation
   - a Founded in 1902
   - b To provide water for the western states
   - c Maintains 476 dams
     - i Hoover Dam
     - ii Grand Coulee Dam
     - iii Shasta Dam
   - d Teton Dam design not reviewed externally

Hoover Dam



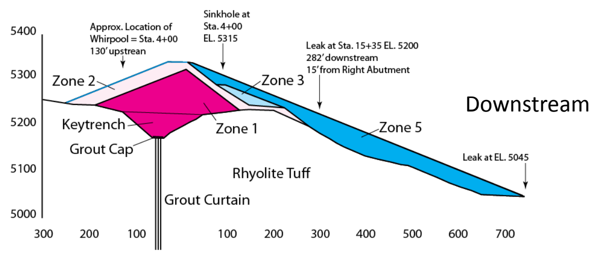
http://commons.wikimedia.org/wiki/File:Hoover_Dam_at_Night.JPG

http://www.nps.gov/nr/travel/ReclamationDamsIrrigationProjectsAndPowerplants/Mission_of_the_Bureau_of_Reclamation.html

E Design

2 Dimensions: Maximum height: 101 m (305'); Crest length: 945 m (3100')
3 Zoned earth fill dam
  a Zone 1: Silt for dam core. With some caliche.
  b Zone 2: Mix of fines, sand, and gravel for drainage. To control seepage through foundation.
  c Zone 3: Mix of clay, silt, sand, and rock for downstream shell (structural stability)
  d Zone 4: River sands and gravel. For upstream toe and cofferdam (not shown in diagram)
  e Zone 5: Cobbles and boulders, and rock fragments. For outer shell (armor).
4 Keytrench. Excavated to remove highly fractured rock near ground surface.
5 Grout curtain. Injections along vertical holes with 3m (10') spacing. Intended to seal joints.
6 Grout cap. Intended to seal base of keytrench.

Section Along Approximate Path of Failure



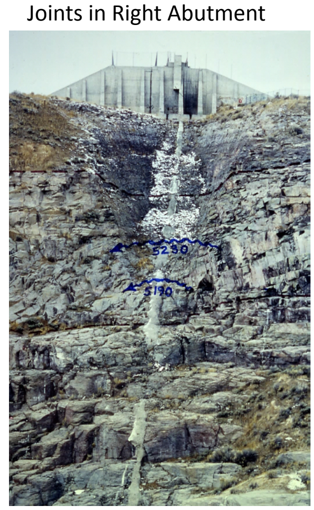
Modified from Fig. 2-2 of Independent Panel

F Recognition in Design and Construction Stages

1 Seismic hazards
2 Joints in rhyolite
  a Steep
  b Subhorizontal
  c Apertures of 1 cm to 2+m
3 Piping hazard recognized: silt (loess) fill in Zone 1 was highly erodible

http://en.wikipedia.org/wiki/Teton_Dam

Joints in Right Abutment



http://web.mst.edu/~rogersda/hs&college_years/
Right%20abutment%20of%20Teton%20Dam.jpg

G Characterization in Design and Construction Stages

1 ~ 100 holes drilled (1961-1970), most on south (left) canyon wall

2 Pilot grouting program conducted in 1969 on south (left) abutment
   a Twice the allotted grout for whole pilot program taken by a few fractures
   b Grout flowed 90m downstream in some fractures

3 Water injection in 1970 tests on north (right) abutment at rates of as much as 440 gallons/minute (before 1971 EIS)

4 In 1974, cavities found in north (right) key trench as wide as 3.4m (11')

5 Grout curtain took ~ 600,000 ft3, more than double expected amount

Sources: Independent Panel, 1976; Reisner, 1987

H Decisions in Construction Stage

1 No grouting of bottom of key trenches above EL. 5025

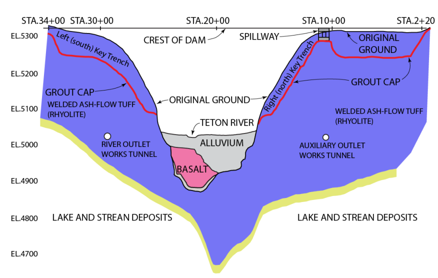
2 Grouting of bottom and walls of cuttoff and key trenches left to discretion of contractor

3 From EL. 5075 to 5205 joints wider than ~1 cm grouted individually

4 Hundreds of joints less than 1 cm wide grouted; some joints 15 cm wide left open

5 Sides of key trenches generally not grouted

PROFILE OF TETON DAM ALONG GROUT CAP
(MODIFIED FROM INDEPENDENT PANEL, FIG. 5-4)

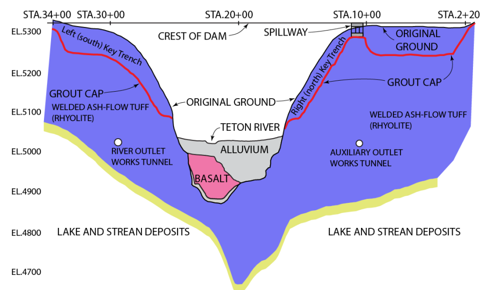


View downstream

I Assessment in Design and Construction Stages

4 Assessment
- a Level of risk acceptable
- b No mention of geologic or other safety problems in final EIS of 1971 (no need)
- c Earth fill dam appropriate
- d Permeable sediments to be excavated in cutoff trench
- f Key trench ~20m deep needed to retard flow in uppermost ~20m of rock
- g Trench floors to be grouted
- h Grout "curtain" to be formed from injections from vertical boreholes 60'-310' deep beneath trenches
- i Grouting successful (Aberle, 1976)

PROFILE OF TETON DAM ALONG GROUT CAP
(MODIFIED FROM INDEPENDENT PANEL, FIG. 5-4)



View downstream

J Construction

Date	Activity
02/22/72	First construction equipment arrives
03/17/72	Excavation of left key trench starts
04/17/72	Excavation of left key trench starts
04/25/72	Fill placement below cutoff trench starts
07/11/72	Excavation of right key trench starts
07/17/72	Stripping at spillway starts
10/20/72	Drilling & grouting in left key trench starts
12/01/72	Fill operations suspended
12/13/73	First steel liner set in river outlet works
04/10/73	Fill operations resume
06/05/73	River outlet works tunnel grouting done
06/08/73	River diverted through outlet works
06/25/73	Excavation of auxiliary outlet works and upstream coffer dam at El.5130

Date	
09/17/73	Grouting in cutoff starts
10/18/73	First Zone 1 fill in cutoff
11/07/73	All fill operations halted
12/12/73	Left abutment grouting completed
04/04/74	Fill placement resumed
11/27/74	Fill operations halted (mostly at El.5130)
04/29/75	Fill placement resumed
05/09/75	Concreting of auxiliary outlet works tunnel completed
10/03/75	River outlet works closed; river diverted to auxiliary outlet
10/21/75	Completed Zone 1 placement
11/26/75	Dam essentially complete; 200' of fill emplaced in 6.7 months
10/75 – 06/76	Modifications to outlet works. Repainting incomplete as of 06/05/76

K Instrumentation

1 Two strong-motion accelerometers installed by USGS
2 38 deformation measurement stations intended; 9 installed
3 No instruments installed to measure seepage flow
4 No piezometers installed to measure changes in local water table

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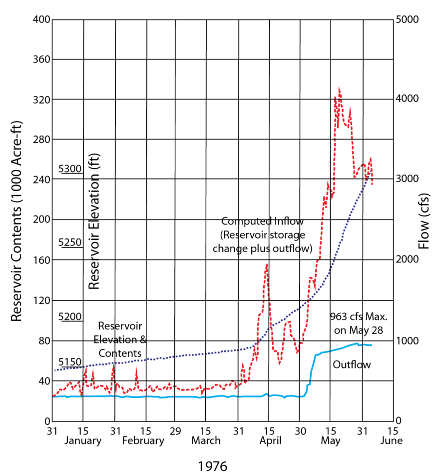
L Filling of reservoir

1 Filling begun before outlet works operable
2 Specified fill rate: 1'/day
3 Very heavy snow pack and runoff in 1976
4 3/3/76: Fill rate of 2'/day requested
5 3/23/76: Fill rate of 2'/day approved
6 Mid-May: Fill rate approaches 4'/day



Sources: Independent Panel , 1976; Reisner, 1986

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M Failure Sequence

- Color photographs taken by Mrs. Eunice Olson on June 5, 1976
- Digital copies of photographs courtesy of Dr. Art Sylvester http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/Teton%20Dam.html
- First signs of seepage noted at ~ 7:00 AM

~10:30 AM

Note D-9 bulldozer heading down to upper leak. Another leak at toe.

~11:20 AM

~11:30

Outlet works being flooded

11:30 AM+

http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/Teton%20Dam.html

~11:50

http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/Teton%20Dam.html

11:55-

http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/Teton%20Dam.html

11:55

http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/Teton%20Dam.html

11:57

Dam is breached

http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/Teton%20Dam.html

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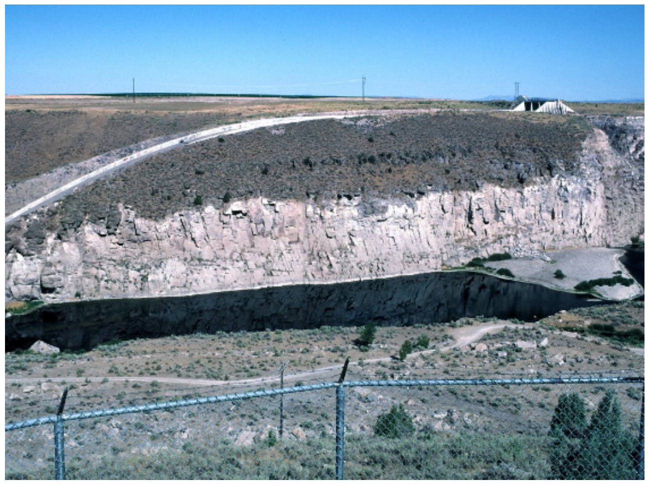


http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/Teton%20Dam.html

N Recognition (after failure)

1 Recognition
- a Seismic activity did not cause failure
- b Many joints in key trenches were open
- c Grouting did not seal all fractures
- d Flowing water could come into contact with silt core

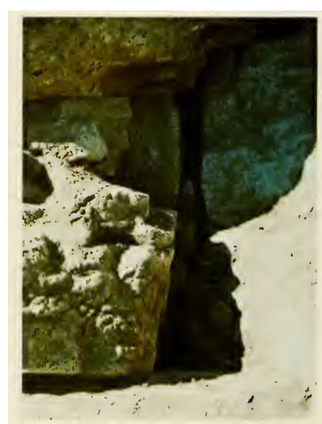


Fig. 3-12 2 in. open fracture crossing grout cap alignment near Sta. 13+90 (see Fig. 3-10 for location)

From Independent Panel, 1976

M Characterization (after failure)

2 Characterization
- a Remnant Zone 1 fill uniform and well compacted
- b Tests showed water could flow through grout cap and grout curtain
- c Excavations showed some open joints passed through grout curtain

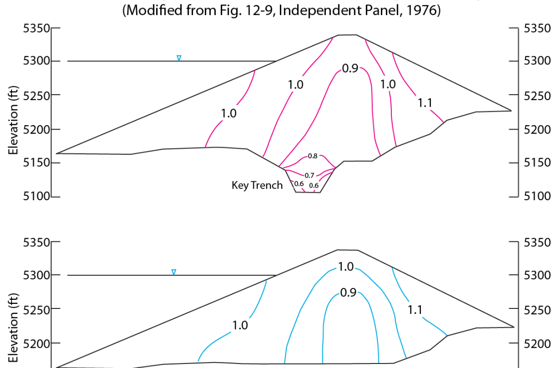
Fig. 3-12 2 in. open fracture crossing grout cap alignment near Sta. 13+90 (see Fig. 3-10 for location)

From Independent Panel, 1976

O Evaluation (after failure)

1 Poorly compacted fill found in key trench; stress analyses predict low compressive stresses in key trench

Ratio of Vertical Normal Stress in Embankment to Overburden Pressure
With and Without Key Trench at STA. 12+00 Before Wetting of Soil in Key Trench
(Modified from Fig. 12-9, Independent Panel, 1976)

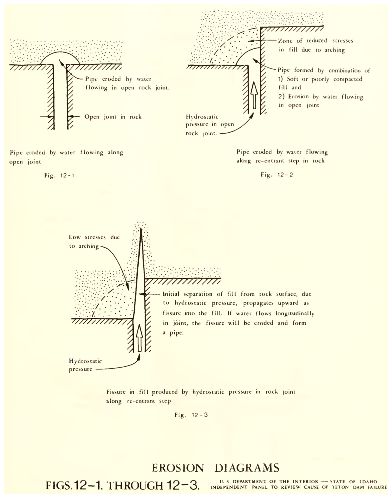


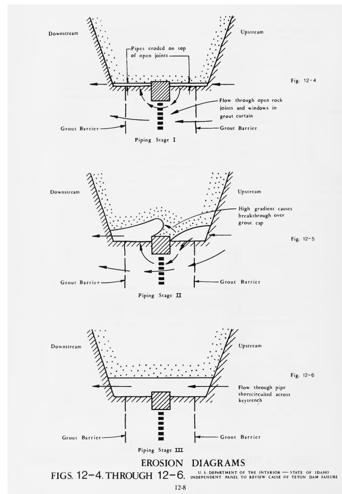
Soil Properties

γ (kcf)	ϕ	$\Delta\phi$	C (tsf)	K	K_{ur}	n	R_f	G	F	D	σ_{3T}	β
0/117	31°	0	1.65	470	750	0.12	0.79	0.35	0.10	4.0	0.0	0.003

O Evaluation (after failure)

2 Water flowing in open joints eroded and fractured the silt fill, probably aided by hydraulic fracturing



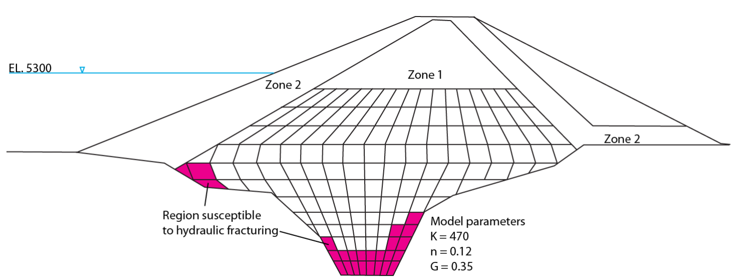


From Independent Panel, 1976

O Evaluation (after failure)

3 Stress analysis revealed parts of Teton Dam were susceptible to hydraulic fracturing

Model results showing portions of Teton Dam susceptible to hydraulic fracturing based on least compressive stress in plane of cross section
Modified from Independent Panel (1976), Fig. 12-11.



P Assessment (after failure)

1 The precise combination of geologic details, geometry of key trench, variation in compaction, or stress conditions in fill and porewater that caused the first breach of the key-trench fill is of course unknown and, moreover, is not relevant.

From Independent Panel, 1976

P Assessment (after failure)

2 The failure was caused not because some unforeseeable fatal combination existed, but because (1) the many combinations of unfavorable circumstances inherent in the situation were not visualized, and because (2) adequate defenses against these circumstances were not included in the design.

From Independent Panel, 1976

Q Assessment (after failure) From Independent Panel (1976)

1 Pilot grouting should have served as warning
2 Design did not account for geology adequately
3 Open joints provided routes for water to core
4 Silt core highly erodible
5 Construction competently executed
6 High filling may have hastened failure
7 Grouting inadequate
8 Steep-sided key trench favored opening of joints
9 Dam instrumentation inadequate
10 Hydraulic fracturing may have contributed to failure
11 Piping and erosion caused failure of Teton Dam
12 Failure not due to settling
13 Failure not due to seismicity