Operational Failure Modes
Key Concepts

- Operational failures can include:
  - Debris plugs spillway (perhaps with log boom failure), dam overtops
  - Gates fail to open (hoists, chains, binding, electrical, remote communications), dam overtops
  - Gates open inadvertently – life-threatening flows
  - Communication breakdown – no warning d/s
  - Loss of access to operate gates, dam overtops
  - Loss of release capacity (e.g. turbine), dam overtops
  - Overfilling off-stream reservoir, dam overtops
  - Reluctance to open gates and flood people out
  - Other external events
To answer the question as to whether 50 years of successful operation means we don’t need to worry about a dam any more, the data suggests that >50% of incidents of dams that survived their first 5 years occur after the dam is 50 years old.
How are Incidents for Different Types of Dams Distributed?

% of Incidents That Occur At An Age Greater Than
By Type of Dam

- Earthfill
- Rockfill
- Gravity
- Arch
- All

Age
% of Incidents that Occur at an Age Greater Than  
by Failure Mode  
After 1st 5 Years of Operation
# of Incidents by Type of Dam vs. Decade Built
Dams that Survived 1st 5 Years of Operation

Time Period

- <1850
- 1850-1899
- 1900-1909
- 1910-1919
- 1920-1929
- 1930-1939
- 1940-1949
- 1950-1959
- 1960-1969
- 1970-1979
- 1980-1989

- Buttress
- Crib
- Rockfill
- Multiple Arch
- Gravity Concrete
- Gravity Masonry
- Earthfill
- Arch
- Other
Earth Dam Seepage Incidents % of Incidents Beyond a Given Year by Era of Construction (Data Beyond 45 Years of Age Removed)
Failure to Operate on Demand

Lake Delhi, Iowa 2010
Overtopping of Palagnedra arch dam during 1976 flood in Switzerland (Courtesy T. Martinoli)
Background Information

- Spillway has two bays
- Each bay is closed by a set of four steel stoplogs
- The stoplogs are raised by a hoist mounted on a trolley. One hoist services both bays.
- Dam is operated from a central control room located 50 km from the site.
- The dam is visited a few times a week.
- Radio and telephone service is available at the site.
Antecedent Conditions

- In central Sweden the summer of 1985 was exceedingly wet. July saw 175% of average precipitation, August 137%, and September 244%, most of which fell in the beginning of the month.
- Rainfall was estimated to be a 1:2000+ event.
- As the rainfall was diminishing on September 5, 1985, the stoplogs, which had been removed earlier, were replaced in the left spillway bay and a single log was placed in the right bay. This stoplog was hooked to the hoist.
Failure Mode

- Rainfall is increasing in intensity
- An operator is dispatched to the site from the central station
- The main access road is blocked by flooding. The secondary route to the dam is 90 km (rather than 50 km) on secondary roads.
- The operator attempts to remove the stoplog
- The stoplog gets stuck in the spillway bay
Failure Mode

- The design of the hoist system precludes unhooking the stuck stop log from the hoist thereby preventing removal of left bay stoplogs.
- A crane is requested to assist in removing the left bay stoplogs.
- It’s late Friday night and the crane company has trouble locating an operator.
- A larger upstream dam is in danger of overtopping and releases from that dam are increased.
Failure Mode

- Operation of the powerhouse at Noppikoski is curtailed to minimize damage from the rising tailwater.
- The crane gets within a few hundred meters of Noppikoski Dam, and is halted by flooding across the road.
- The dam overtops
- The overtopping downcuts through the dam to bedrock.
After the failure the operator presented a paper describing the factors that contributed to the failure. In conclusion he stated:

“In my opinion, the important question of how to adapt the plants – with the exception of augmented discharge functions – to practical operation, in view of the complications of the kind previously listed, has not been considered or documented to the same extent.”
Sayano-Shushenskaya
Can a Problem in a PH Cause a Dam Failure?
Sayano-Shushenskaya

- Dam Type: Gravity Arch
- Dam Height: 242 meters / 794 ft
- Reservoir Capacity: 31.3 km³ / 25.4M ac-ft
- Spillway Capacity: 12,800 m³/s / 455K cfs
- Powerhouse Capacity: 3,500 m³/s / 124K cfs
- Flood of Record: 24,300 m³/s
Sayano-Shushenskaya

- No low-level outlet – maximum draft 45 m
- Est. storage volume in top 45 m – 18.1 cu km
- No TSV on the penstocks
- Reservoir filled as dam was raised
- Upstream monoliths raised first
Certification for Operation in 2000 noted need for additional spillway capacity

Construction of additional spillway capacity delayed due to lack of funding

Spillway currently being constructed on expedited schedule. 2,000 m³/s of additional capacity will be available in June 2010
Sayano-Shushenskaya

- Turbine has large area of rough operation
  - Need for new design recognized in 2000
  - Plant control system does not take into account area of rough operation
- Operates in Unified Electric System – Siberia
- Constructed under Russian state ownership
- Privatized in 1993
A Little Background

- During construction the spillway was used to pass water.
- During construction a flood resulted in 4500 m³/s being discharged through the spillway.
- The spillway stilling basin was severely damaged while passing 4500 m³/s - 7m of the foundation was eroded.
- The flood also overtopped the partially constructed dam cracking the dam-foundation interface and some concrete monoliths.
- The damage to the spillway was repaired.
A Little Background

- The foundation and monoliths were grouted (under 200 meters of head)
- In 1988 a flood of 4400 m³/s damaged the stilling basin again
- Again, the stilling basin was repaired
- A new tunnel spillway is being constructed
Potential Failure Mode

1) Under Normal Operation
2) A fire at a remote power plant causes the system dispatcher to transfer load-following responsibility to SSH hydro plant
3) SSH staff start Unit 2 and place in load following mode
4) Operation of Unit 2 over the course of 30 years caused partial to complete fatigue failure of the bolts holding down the turbine head cover
Potential Failure Mode

5) In load following mode Unit 2 transitions through the rough operating region on several occasions

6) The fatigue failure of the head cover bolts reaches a critical state

7) The turbine head cover tears loose ejecting the turbine through the generator
Potential Failure Mode

8) The open head cover allows water to flood into the powerhouse

9) The flooding water knocks out station power cutting power to the penstock intake gates

10) Water flows for half an hour until the gates can be closed using manual operators

11) The flooding damages the powerhouse to the extent that all 10 units are forced off line and only two units will be available to help pass flow in the coming runoff season
Potential Failure Mode

12. Damage to the powerhouse results in the majority of inflow passing through the spillway for an extended period.

13. Operation through the winter results in icing over the spillway and collapse of a crane used to access the stilling basing for repair.

14. Higher than normal snowfall in the watershed leads to large runoff (near the flood of record).
Potential Failure Mode Continued

15) The high runoff requires the spillway to run full
16) The excess inflow rapidly fills the reservoir
   - 17 days if one tunnel spillway is operable
   - 15 days if the tunnel spillway is unavailable
   - 8 days if the service spillway becomes inoperable
17) The excess inflow overtops the dam reinitiating the crack at the dam foundation interface
18) High spillway flows destroys the stilling basin bottom and begins to undercut the dam toe
19) Undercutting continues as the spillway passes flow.
Potential Failure Mode Continued

20) Cracking of the dam-foundation interface leads to increased uplift under the dam

21) The combination of continued toe undercutting and increasing uplift under the dam leads to a sliding failure of the dam
How Big a Problem is This?

- Everything except the last 2 slides was a reality
- Over one million people live downstream of the dam
- There is an embankment dam 12 miles downstream that would fail if overtopped
Hoover Dam

Height – 726.4’

Crest Length – 1244’

Res. – 28.5M ac – ft
Sayano-Shushenskaya

Height – 794’
Crest Length – 3524’
Res. – 25.4M ac – 830’ ft
Tirlyan Dam

- 10 m high
- 7,000 ac-ft

Tirlyan Dam Failure.wmv