Risk Assessments for Gates Other Than Radial Gates

Best Practices in Dam and Levee Safety Risk Analyses

Chapter G-2

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US Army Corps of Engineers

U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION

DEPARTMENT OF ENERGY FEDERAL ENERGY REGULATORY COMMISSION

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Risk Assessments for Gates Other Than Radial Gates

OUTLINE:

- Drum Gates
  - Description of potential failure modes
  - USACE and USBR Inventory
  - Incidents and Brief Case History
- Roller Gates
  - Description of potential failure modes
  - USACE and USBR Inventory
- Vertical Lift Gates
  - Description of potential failure modes
  - USACE and USBR Inventory
- Caterpillar Gates
  - Description of potential failure modes
  - USACE and USBR Inventory
- Sluice Gates
  - Description of potential failure modes
- Miter Gates
  - Description of potential failure modes
  - USACE Inventory
  - Incidents and Brief Case History

Risk Assessments for Gates Other Than Radial Gates

OBJECTIVES:

- Understand the mechanisms that affect gate failures
- Understand how to construct an event tree to represent gate failures
- Understand how to estimate event probabilities and probability of breach

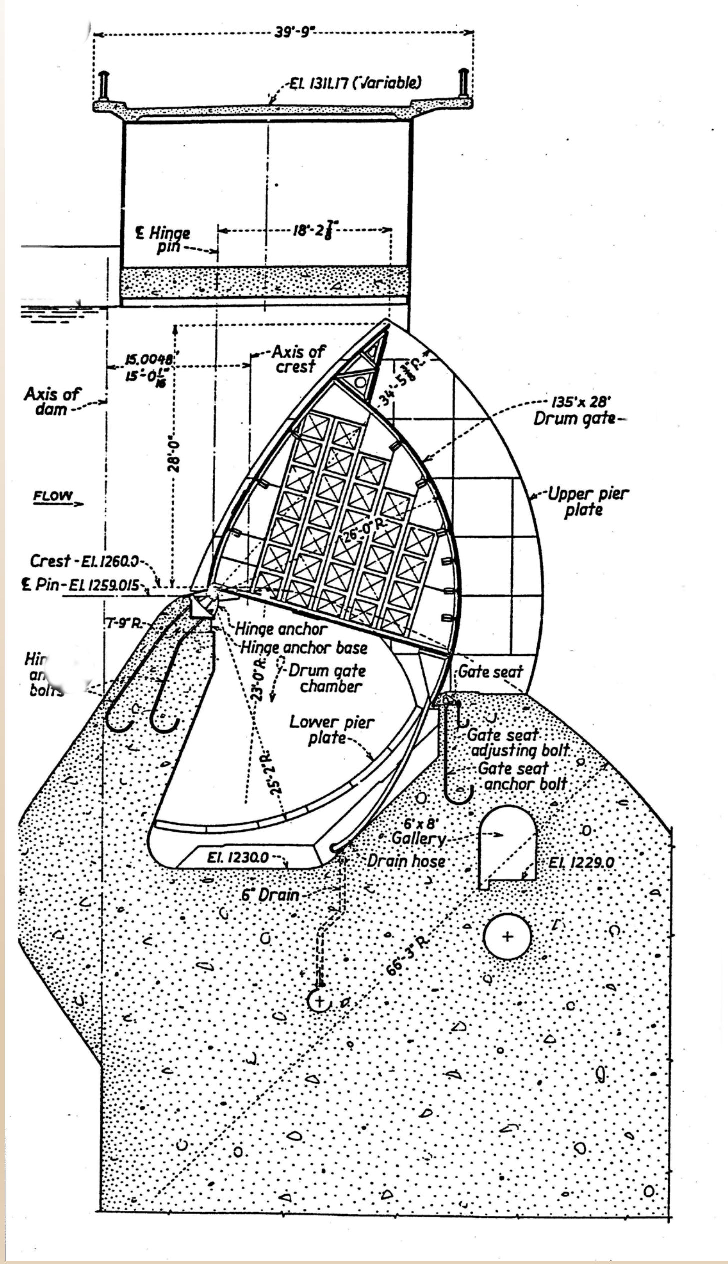
Risk Assessments for Gates Other Than Radial Gates

SUMMARY OF KEY CONCEPTS:

- Drum, Roller, Vertical Lift and Miter Gates are the most common non-radial gates in the USACE and USBR dam and/or navigation lock inventories
- Each gate type has particular vulnerabilities that should be considered when performing a risk assessment
- Base failure rates for some of these gate types

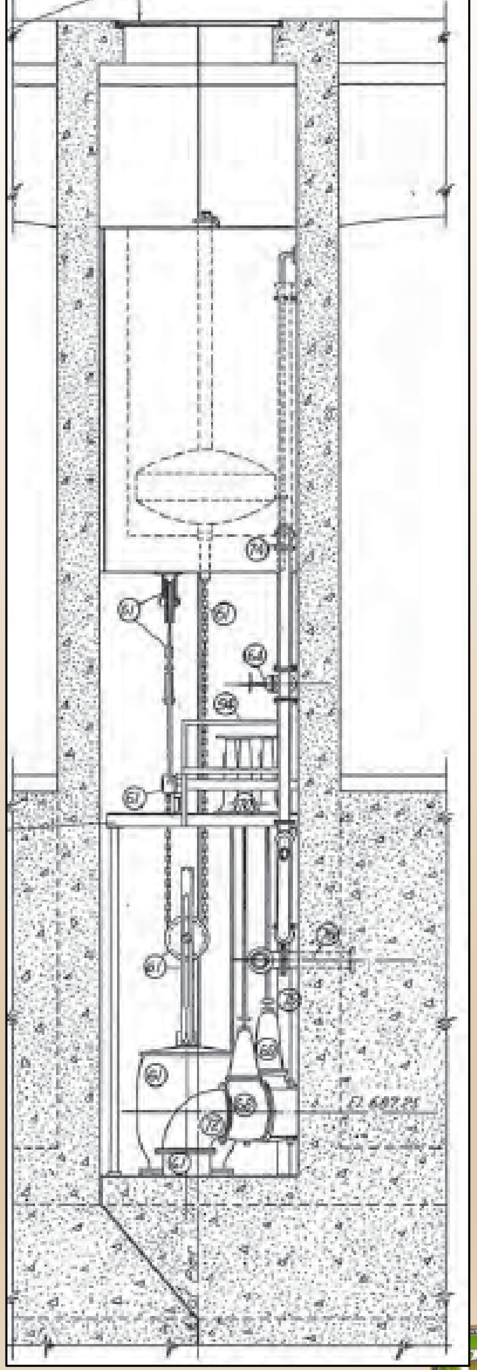
Drum Gates

- Gates raise by floating in chamber – lowered to release water
- Drain line through chamber to outlet
- Valves/piping let water into and out of chamber to control gate operations



Drum Gate Vulnerabilities

- Complicated “plumbing” with multiple potential failure points.
- The floatwell inlet pipe can develop leaks. The condition of this pipe needs to be assessed since a major leak or break in this line during the reservoir filling can result in spillway gate inoperability.
- Inadvertent gate lowering
  - Outlet valve fails in open position
  - Inlet valve doesn’t supply water fast enough
  - Drain line severed or plugged
- Puncturing (e.g. rockfall)
- Seismic Loading
  - Hinge pins and hinge pin anchorage
  - Float chamber walls (reinforced concrete failure mechanisms)
- Drum gates have been filled with Styrofoam to prevent inadvertent lowering, but this limits the ability to inspect and maintain



Drum Gates: USACE and USBR Inventory

Dam	Completion Year	Years of Service**	No. of Gates	Gate-Years of Operation
Arrowrock	1915	101	6	606
Black Canyon	1924	92	3	276
Tieton	1925	91	6	546
Guernsey	1927	89	2	178
Easton	1929	87	1	87
Hoover	1936	80	8	640
Grand Coulee	1942	74	11	814
Friant[1]	1944	72	3	216
Shasta	1945	71	3	213
Sepulveda[2]	1941	75	7	525
Pit River No. 4[3]	1927	89	2	178
Cresta[3]	1949	67	2	134
Rock Creek[3]	1950	66	2	132
Total			56	4545

NOTES:

All are USBR projects unless noted otherwise.

1. Two drum gates replaced
2. Only type of spillway gate at Sepulveda is drum gate
3. PG&E has drum gates at three projects

** Data as of 2016

Two Reclamation Incidents

- Guernsey Dam (Wyoming)
  - 1986
  - Lowering of drum gate on South spillway
  - d/s flows within safe channel capacity
  - No reported injuries
  - Trash within gate plugged drain line

- Hoover Dam
  - 1941
  - Unexplained lowering of drum gate on Arizona side
  - 38,000 cfs release
  - No reported injuries

Cresta Dam (PG&E) Drum Gate Incident

Description of Project/Incident:

- Dam is in Feather River Canyon, CA.
- Owned/operated by PG&E for generation of electric power.
- Two 28-ft diameter by 124-ft long drum gates.
- Summer mid-afternoon in 1997.
- Left side drum gate dropped uncontrollably
- EAP initiated due to dropping reservoir/rising tailwater alarm
- 20-30 minutes to drop completely
- D/S water level rose from 1.6’ to 15’ in 40 min.
- Maximum downstream discharge ~ 15,100 cfs
- No fatalities

Root Cause:

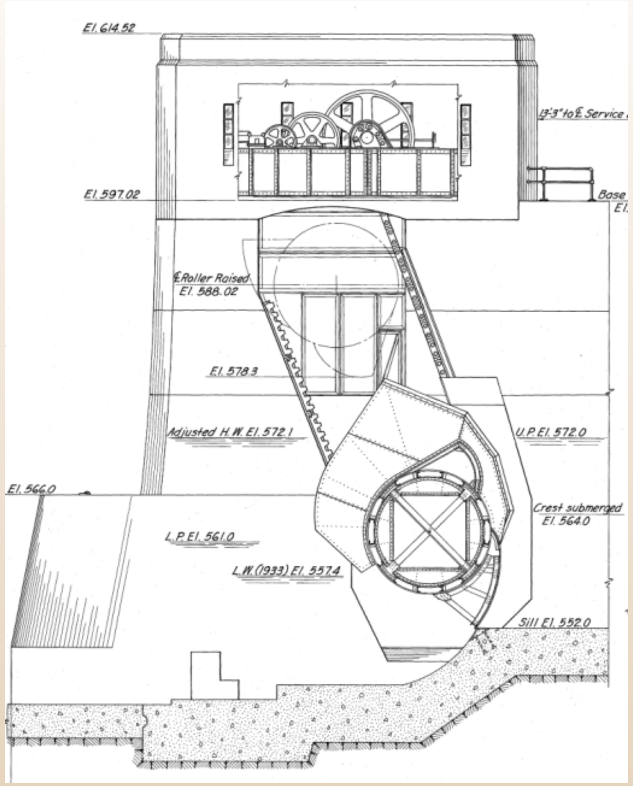
- Failure of drum gate drain line prevented removal of water from inside of gate
- Allowed water into gate through faulty check valve ultimately resulting in the forces acting to lower the gate overcoming the forces acting to raise the gate
- Exacerbating Conditions:
  - Excessive seal leakage
  - Impaired inlet capacity

Base Frequency for Drum Gate Incidences

- 3 known incidents in 4545 gate years of operation
- Annual Probability of Failure of 6.6 x 10^{-4}
- Adjust up or down based on site specific adverse and favorable factors
  - General condition of gate (maintenance, operational history)
  - Area of known rock falls adjacent to drum gates
  - Piping details and condition

ROLLER GATES

- Simply supported, but internally redundant structures
- Used in older, lower head navigation locks with wide pier to pier distance.
- Steel cylinder, usually riveted.
- Despite no ice loading or seismic considerations in design, these gates have a long history of robust performance on the Mississippi River for low head structures
- Hoisted by chains from one end only – simplifying O&M
- Used to pass ice over the top.
- Significant vibration during lowering of gate has changed operation of dam at certain locations.
- Fatigue cracking has been seen at end frames and at welded details used for repairs or strengthening.



Roller Gates
Potential Distress or Failure Modes:

1. **Noise, Jump & Vibration** (NJV) Possible causes for NJV are debris caught in the rack/rim, damaged gate, damaged seals or end shields or damaged rim or rack teeth.

2. **Vibration with Flow** (FV) is the vibration of the gate caused by water flowing over or under the gate. Possible causes for FV are loose connections, damaged bottom seal or damaged aprons.

3. **Torsional Misalignment** (TM) is excessive twist in the roller gate due to torsional forces acting on it. Possible causes for TM are corrosion of skin plate, corrosion of internal trusses & longitudinal purlins, or corrosion & loosening of connections.

4. **Rack Deterioration** (RKD) is the damage of rack teeth and rack anchorage. Possible reasons for RKD are debris, damage during construction, corrosion of rack teeth/anchorage, misalignment, previous chain failure, gate vibration etc.

5. **Rim Deterioration** (RMD) is the damage of rim teeth and rim anchorage. Possible reasons for RMD are debris, damage during construction, corrosion of rack teeth/anchorage, misalignment, previous chain failure, gate vibration etc.

6. **Seals/End Shield Damage** (SESD) is any damage to the timber or rubber seals or the steel end shield. Possible causes are debris, ice, aging of timber or rubber seals, improper fastening, corrosion etc.

7. **Cracks** are narrow openings, breaks or discontinuities in steel caused by fatigue, brittle fracture or overstressing of components.

8. **Dents** are disfigurations or point deformations of skin plate caused by vessel or barge impact, debris impact or ice build up between gate and pier.

9. **Corrosion/Erosion** is a uniform loss of section thickness due to chemical reaction with the environment and Erosion is a loss of section thickness due to a mechanical type of interaction with the environment.

10. **Downstream Deflection** (DD) is an excessive bending of the gate in the downstream direction due to overload or corrosion of skin plate, internal trusses, purlins etc.

Roller Gate Other Potential Failure Modes

- L&D 25 on the Mississippi River
- April 2010
- Failure of a limit switch that resulted in a roller gate over traveling and coming off the rack.
- The hoist chain failed, the gate fell and became racked.
- The operator, after starting gate movement, walked away and went to operate another gate.
- If the operator had not walked away they would have been able to notice that the gate had over traveled before it came off the rack
- USACE Operations removed the damaged gate and completed repairs.

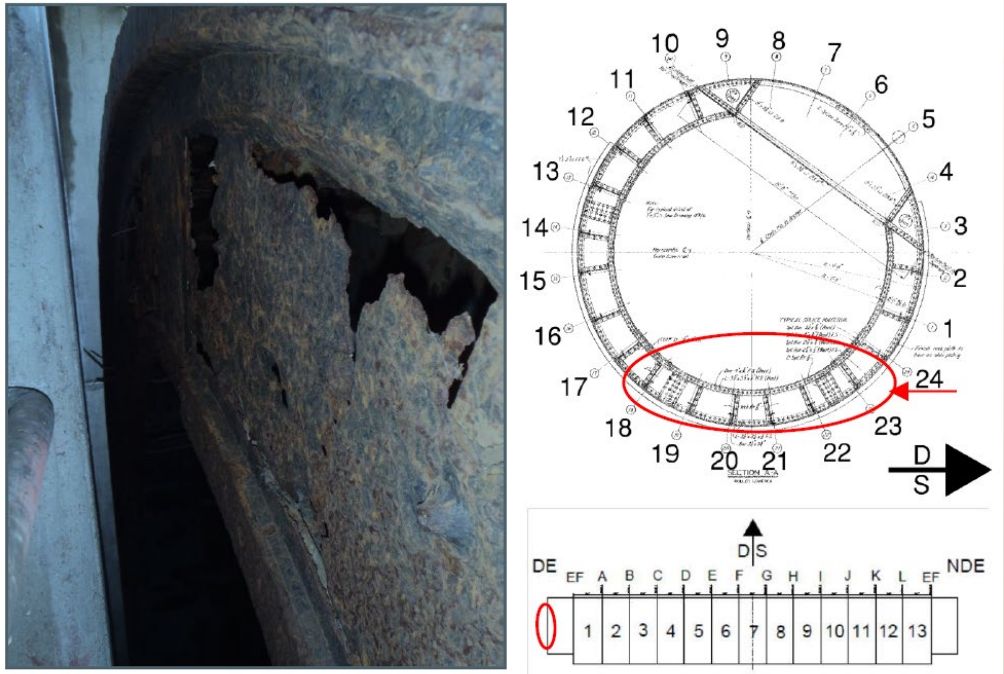
Roller Gate
Other Potential Failure Modes

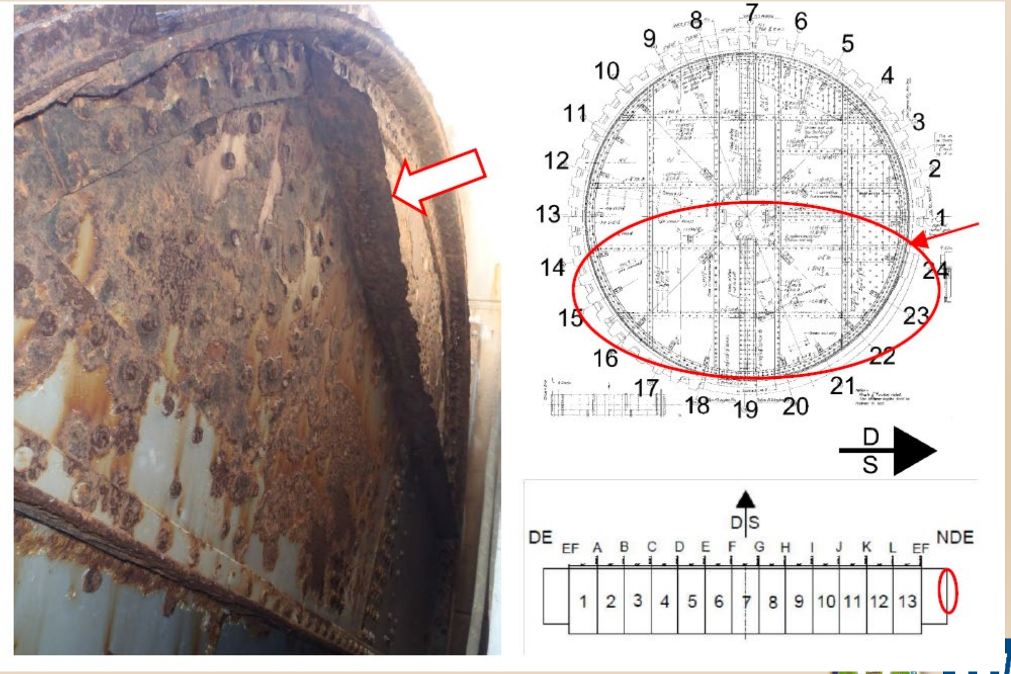
- There have been numerous barge collisions with the roller gates on L&D #3 on Mississippi River
- None have resulted in a loss of pool.
- Concrete-filled barge that impacted Gate 5 on L&D #14 on Mississippi River, July 2014
- Pool was not lost, and gate alignment was not compromised.
- Repairs completed by USACE Operations personnel

Roller Gate
Other Potential Failure Modes

- Corrosion leading to advanced section loss to main load carrying members plus total loss of many rivet heads could lead to sudden catastrophic failure of gate

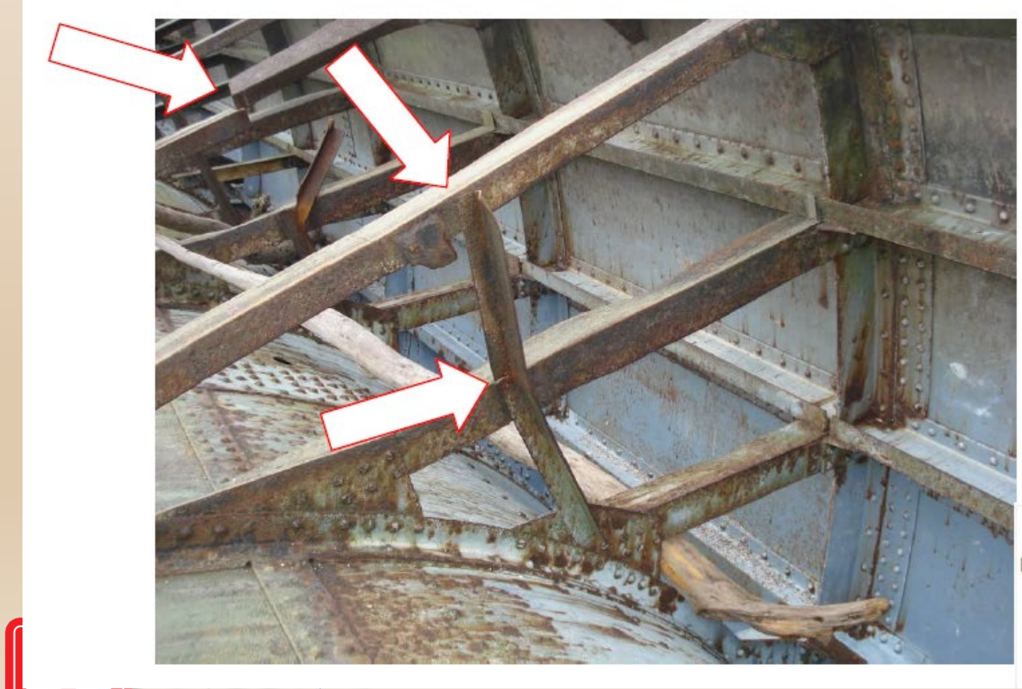
- Photos from Winfield L&D

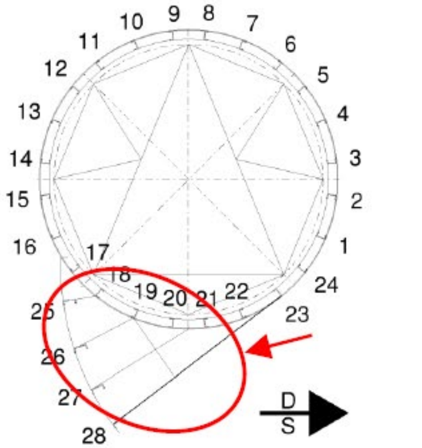


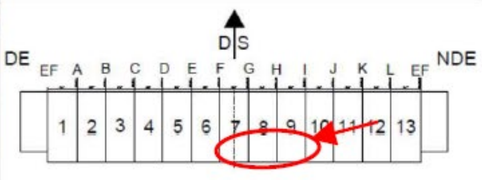


Roller Gate
Other Potential Failure Modes

- Damage from debris to apron bracing could lead to collapse of apron and loss of pool – note missing bracing
- Damage to end shields allows debris to foul hoist; gate jams
- Photos from Winfield L&D







Roller Gates: Current USACE Inventory

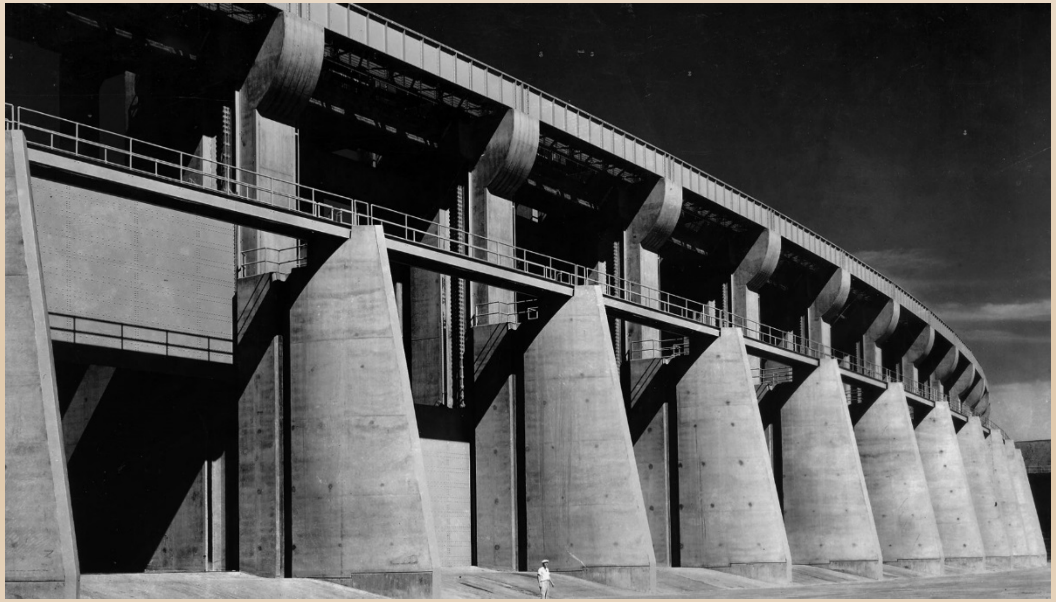
Waterway/River	Corps District	Dam Name	Year Constructed	# Roller Gates	Years of Service	Gate Years
Kanawha River	Huntington Dist.	Winfield Dam	1937	6	79	474
	Huntington Dist.	Marmet Dam	1934	5	82	410
	Huntington Dist.	London Dam	1934	5	82	410
Mississippi River	St. Louis Dist.	Lock 25 Dam	1939	3	77	231
	Rock Island Dist	Lock 22 Dam	1939	3	77	231
	Rock Island Dist	Lock 21 Dam	1935	3	81	243
	Rock Island Dist	Lock 20 Dam	1935	3	81	243
	Rock Island Dist	Lock 18 Dam	1937	3	79	237
	Rock Island Dist	Lock 17 Dam	1939	3	77	231
	Rock Island Dist	Lock 16 Dam	1937	4	79	316
	Rock Island Dist	Lock 15 Dam	1934	11	82	902
	Rock Island Dist	Lock 14 Dam	1935	4	81	324
	Rock Island Dist	Lock 13 Dam	1939	3	77	231
	Rock Island Dist	Lock 12 Dam	1938	3	78	234
	Rock Island Dist	Lock 11 Dam	1937	3	79	237
	St. Paul Dist	Lock 10 Dam	1937	4	79	316
	St. Paul Dist	Lock 9 Dam	1937	5	79	395
	St. Paul Dist	Lock 8 Dam	1937	5	79	395
	St. Paul Dist	Lock 7 Dam	1937	5	79	395
	St. Paul Dist	Lock 6 Dam	1936	5	80	400
	St. Paul Dist	Lock 5a Dam	1936	5	80	400
	St. Paul Dist	Lock 5 Dam	1935	6	81	486
	St. Paul Dist	Lock 4 Dam	1935	6	81	486
	St. Paul Dist	Lock 3 Dam	1938	4	78	312
Ohio River	Huntington Dist.	R.C. Byrd Dam	1937	8	79	632
				115		9171

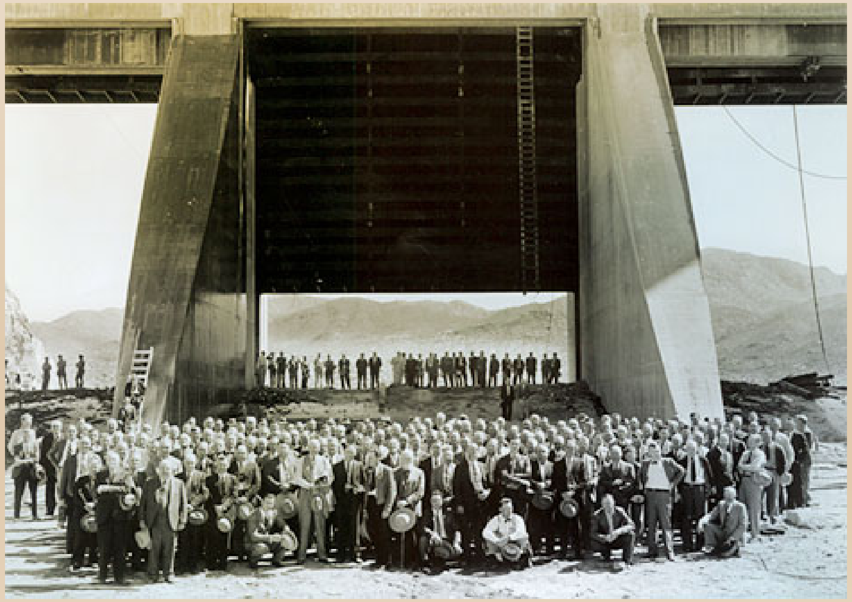
Base Frequency for Roller Gate Incidences

- There are only two *known* incidents in 9171 gate years of operation. This yields an annual probability of failure of 2.2×10^{-4}
- It is further noted that both incidents occurred in the last ten years.
- However the average age of the roller gates in the USACE inventory implies there is a moderate to high likelihood that numerous earlier incidences occurred that have not been recorded.
- An estimated annual probability of failure of 1.0×10^{-3} may be reasonable based upon the fact that multiple other incidents have likely occurred, but simply aren't available in documentation form.
- Adjust up or down based on site specific adverse and favorable factors

Vertical Lift Gates

- Used both in Navigation and FRM dams.
- For Navigation dams, used in lock chamber and as part of the moveable dam.
- Slide gates or fixed-wheel gates not as susceptible to failure – more robust and loaded in bending (ductile behavior)
- But may have massive hoist house and counter weights that should be evaluated under seismic loading





Vertical Lift "Tractor" or "Caterpillar" Gates

- Tractor/Caterpillar Gates are roller-mounted vertical lift gates supported along either side by a continuous series of stainless or carbon steel rollers.
- Otherwise, their construction and function is very similar to that of Wheeled Vertical Lift Gates.
- Serve functionally as service gates, spillway gates, emergency gates and powerhouse closure gates
- Caterpillar Gates are sometimes called Coaster or Tractor gates.
- There are historical problems with the design, leading to decreased reliability.
    - 1. Roller pins or links break, causing chain to separate.
    - 2. Rollers or links corrode and chain does not
    - 3. No way to grease of lubricate chain roller pi
- Found in FRM dams.
- Approximately 288 in USACE inventory

Tractor/Caterpillar Gates: Current USACE Inventory

Flood Control Dams with Caterpillar Gates

			Flood Control Dams							Powerhouse Unit		
Total Caterpillar Gates	**288**		Service Gates		Spillway Gates		Emergency Gates			Closer Gates		
			Total Gates	114	Total Gates	21	Total Gates		30	Total Gates		123
		Total	2	112	0	21	1	3	26	19	21	83
Dam Name	**District**	Year Constructed	Hydraulic	Wire Rope	Chain	Wire Rope	Chain	Hydraulic	Wire Rope	Chain	Hydraulic	Wire Rope
WHITNEY POINT DAM	Baltimore	1942	0	3	0	0	0	0	1	0	0	0
6 Ft. Worth projects	Fort Worth		0	10	0	0	0	0	3	2	0	0
9 Huntington projects	Huntington		2	27	0	21	0	0	5	0	0	0
2 Kansas City projects	Kansas City		0	0	0	0	0	0	0	0	12	3
4 Little Rock projects	Little Rock		0	2	0	0	0	0	0	10	0	4
BREA DAM	Los Angeles	1942	0	2	0	0	0	0	0	0	0	0
3 Mobile projects	Mobile		0	2	0	0	0	0	0	0	0	10
5 Nashville projects	Nashville		0	0	0	0	0	0	0	0	0	19
3 New England projects	New England		0	13	0	0	0	0	0	0	0	0
5 Omaha District projects	Omaha		0	16	0	0	0	0	4	0	9	26
BLUE MARSH DAM	Philadelphia	1977	0	0	0	0	0	0	1	0	0	0
WOODCOCK CREEK DAM	Pittsburgh	1974	0	0	0	0	1	0	0	0	0	0
2 Portland District projects	Portland		0	0	0	0	0	0	1	0	0	3
SAYLORVILLE DAM (Bladder Dam)	Rock Island	1975	0	3	0	0	0	0	0	0	0	0
2 Savannah District projects	Savannah		0	0	0	0	0	0	0	7	0	8
2 Seattle District projects	Seattle		0	0	0	0	0	3	2	0	0	0
8 Tulsa District projects	Tulsa		0	23	0	0	0	0	4	0	0	10
4 Vicksburg District projects	Vicksburg		0	11	0	0	0	0	3	0	0	0
LUCKY PEAK	Walla Walla	1955	0	0	0	0	0	0	2	0	0	0

Possible Event Tree for Hoist Houses Seismic Loading

Hoist houses are typically massive structures carrying suspended massive gates - seismic loading is most obvious PFM.

- Reservoir is at high elevation and vertical lift gate is in fully lowered position, not suspended from hoist house
- Strong earthquake occurs in weak axis direction
- Hoist House piers begin cracking as weight of hoist house oscillates
- Piers fail in moment/shear
- Hoist houses and piers collapse onto vertical lift gate
- Vertical lift gate is heavily damaged
- Rainfall event raises reservoir, gate cannot be operated
- With spillway unusable, the reservoir rises and overtops dam
- Dam breaches

A similar event tree can be developed for the case where the vertical lift gate(s) is(are) suspended.

Dams with Multiple Vertical Lift Gates

- Similar to Tainter gates on dams, the likelihood of losing pool as the result of the loss of one gate is lower if the dam has multiple gates. The more gates are on the spillway, the lower the likelihood.
- The likelihood of overtopping as the result of the loss of one gate is lower if the dam has multiple gates. The more gates are on the spillway, the lower the likelihood.
- Pascal's Triangle can be employed to estimate likelihood of multiple gate failures

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Fatigue Cracking of Vertical Lift Gates

- Fatigue cracking found in vertical lift gates at John Day and Ice Harbor Locks and Dam
- Both had similar design and age.
- Cracking first found at Ice Harbor in 1980 and John Day in 1982.
- Cracking in tension tie at welded connections.
- FEM showed cracking due to exceeded fatigue limit due to cyclic loading.
- Ice Harbor gates replaced in 1996 due to excessive cracking and maintenance. 2 month shut down and cost of $6.5M.
- John Day gates replaced in 2011 for $12M.

Hoist-Induced Failure of Vertical Lift Gate

- For Bluestone Dam, analysis was performed of hoisting loads on the Hoist Assembly Pin Plate Connection
- Each crest gate weighs 113,000 pounds
- Uninhibited rolling resistance associated with the roller chain assemblies of approx. 2.5% of maximum water load (26,000 lbs.)
- Side seal friction of 175 lb/ft (11,000 lbs.)
- The above assumptions equate to a total normal running load of 150,000 lbs, for which the gate was designed.

Load Condition	Force (lbs)	Pin Plate Factor of Safety [1]	Hoist Rope Factor of Safety [2]
Normal Running Load	150,000	2.6	6.05
Hoist Design Load	195,000	2.0	4.66
Hoist Stall Load	487,500	0.8	1.86
Overstress Load	387,800	1.0	2.34
Hoist Rope Failure	487,500 (on one connection)	0.4 [3]	0.93 [3]

1: Lug Factor of Safety is calculated for yield state and includes AISC allowable stress factors
2: Hoist Rope Factor of Safety is based on the minimum breaking strength of the wire hoist rope per original design
3: Factors of Safety should serve as reference values only, as this load condition is initiated by failure of a wire rope, and is covered in the risk assessment as a mechanical failure mode

Based on the above factors of safety, the potential exists for the hoist assembly pin plate connection to fail at loads greater than the overstress load of 387,000 lbs.

Sluice Gates

- Used both in Levees and FRM dams.
- For levees, used in gatewells to prevent backflow during floods.
- Generally cast steel (ductile) or cast iron (non-ductile behavior)
- Generally operated with steel stems but also may be hoisted with wire ropes

Sluice Gates

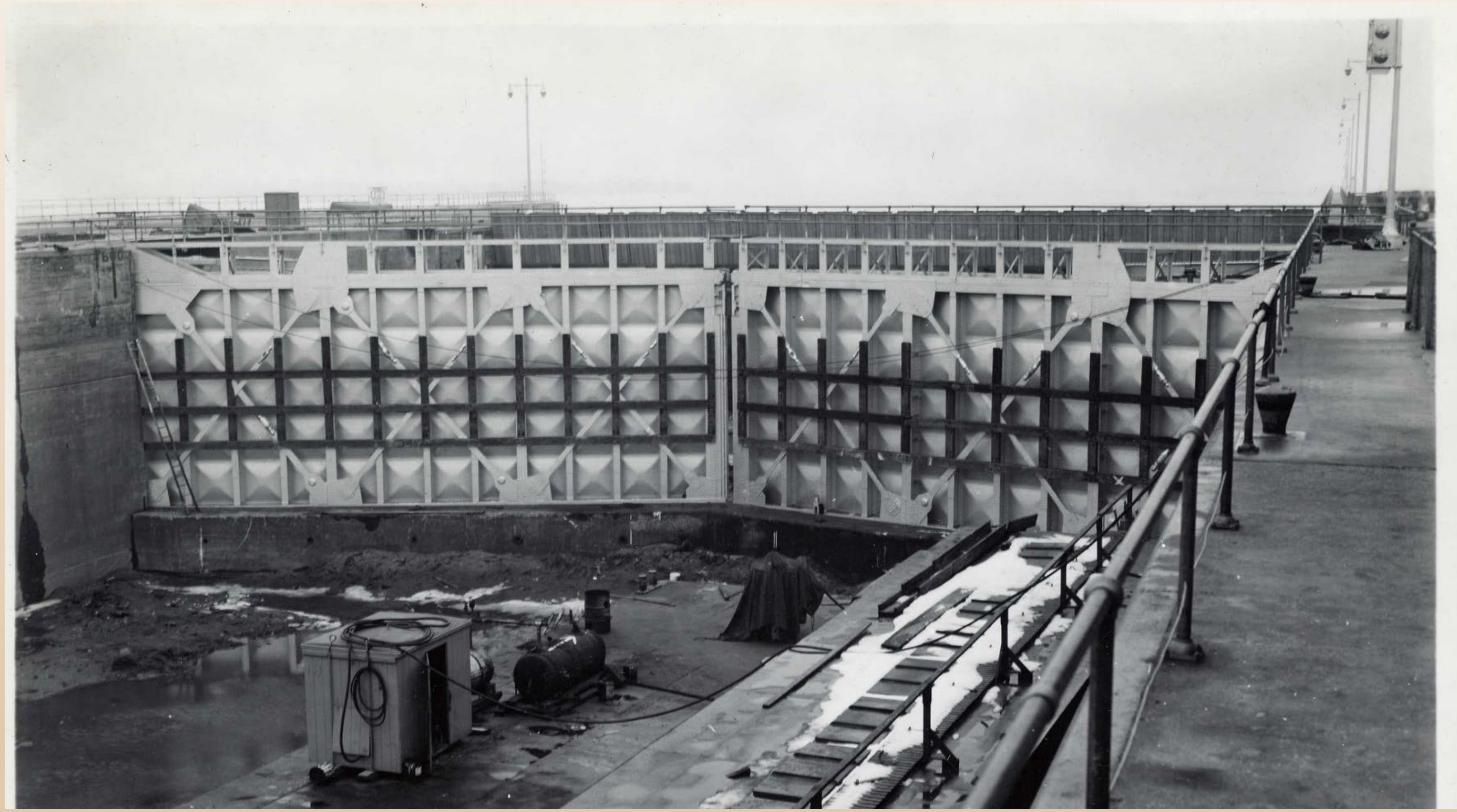
- Typically sluice gates refer to smaller vertical slide gates used for day-to-day reservoir control and minimal releases. Spillway gates are typically used for flood releases. There are thousands of these in USACE/USBR inventory.
- The consequences of a sluice gate failure would be mostly economic in nature for flood control dams as discharges would most likely be limited resulting in non-life threatening flows through the failed gate.
- Sluice gates are generally highly reliable. Failure has never resulted in a loss of pool and/or potentially life-threatening flows primarily due to their reliable operation and limited discharge capability.
- Sluice gates are generally horizontally framed with narrow spans.
- Fatigue cracking has been observed in some sluice gates in USACE dams (Belton Dam) and in some levee gatewells (Cannelton LFPP).
- Operating gates under low openings (1/10-2/10) often leads to vibrations. Extended operations at this rage can result in fatigue cracking, which could lead to a catastrophic failure of a gate.
- Incorrect operation of the stem could lead to buckling of stem, resulting in inoperability, or cracking and breakage of the cast steel/iron gate body. It is also possible they can be ‘stuck’ in the partially open position due to debris blockage or mechanical/electrical issues.
- Damage from cavitation and erosion from sediment-laden flows can also result in premature wear of a sluice gate, but there are no documented gate failures resulting from this scenario. Cavitation damage usually occurs downstream of the gate itself.

Miter Gates

- Most common gate in USACE navigation locks.
- There are 408 miter gates – 816 individual miter gate leaves. Failure of a miter gate will generally result in loss of navigation until repairs are completed, or unless the project has more than one lock chamber.
- The consequences of a miter gate failure are mainly economic.
- A miter gate failure has never resulted in a loss of pool and/or potentially life-threatening flows
- Gates are vertically or horizontally framed. Load path is very different for these two different types of gates.
- History of fatigue cracking at USACE lock chambers.
- Fatigue cracking can lead to excessive movement or sagging leading to loss of miter, or buckling of the member.
- Other gate components subjects to cyclic loading and fatigue cracking: Gudgeon anchor arms and pintle casting.
- Damage from barge impact can also result in gate failure, and loss of navigation.

Vertically Framed Miter Gates

- Loads are transferred from skin plate to vertical girders.
- Load is distributed equally between the top horizontal girder and at each vertical girder's contact point with the concrete gate sill. Horizontal loads do not collect at the pintle.
- Photo from Mississippi River L&D 16 (1951)



Horizontally Framed Miter Gates

- Hydrostatic loads are transferred from skin plate to vertical intercostals and from there to horizontal girders.
- The load from the horizontal girders is distributed to the quoin and miter posts.
- Horizontal loads collect at the quoin and miter contact blocks.
- Quoin block transfers horizontal loads to the lock walls from top to bottom.
- Miter blocks transfer horizontal loads to the other gate leaf's miter block.
- Horizontal loads should not be collected by the pintle (bottom) or the gudgeon pin (top).
- Photo from Cannelton L&D (Ohio River), 1980's

Fatigue Cracking of Miter Gates Markland Lock and Dam

- Severe cracking found at welded connections of horizontal girders in 1994.
- Gates considered to be in critical conditions and immediate repairs were done.
- Dewatering
- Gate was replaced in 2011 with a cost of $12M.
- Ice Harbor had a similar design. Gates were replaced in 1996 with a two month outage and $6.5M cost.

Failure of Miter Gate Anchor Arm Greenup Lock and Dam

- Sudden failure of anchor arm of main chamber miter gate caused a 26 day emergency closure.
- The failure initiated at the root of a fillet weld connecting the miter anchor arm to the top connecting link and propagated through the entire cross section of the miter anchor arm.
- The crack was not visible during prior inspections due to limited accessibility, paint and over spill of lubricating grease for the gudgeon pin.
- Gate fell on the sill in a vertical position.

- Anchor wedge assemblies, anchor arms, connector plates, gudgeon and link pins were replaced and the gate was reinstalled on February 21, 2010. February 22, 2010 the main lock chamber was reopened for traffic

Barge Impact Damage to Miter Gate Leaf Mississippi River L&D 5A

- Tow Impacts Upstream Landwall Gate while it was in the recessed position on 16 May 2013 at noon; Flows were High (Outdraft); there was < half a foot difference between upper and lower pool
- Initial Lock Closure/Inspection was conducted within 2 hours
- Initial Above the Waterline Inspection Complete by 1800 hours 16 May 2013
- Operations locks through remaining tows
- MVR's *Quad Cities* (crane barge) arrives and swaps out damaged gate with temporary replacement gate 23 May 2013
- Gate Swap is accomplished during a 24 hour lock closure

Typical Event Tree for Miter Gate Failure

- River is at normal low water condition (max differential)
  - Tow enters chamber heading downbound
    - Upper gate leaves are activated from recess toward miter position, to close behind the tow
      - Existing crack in the gate leaf's upper anchor arm that has formed as a result of fatigue (200,000+ cycles) widens; top of gate rotates toward chamber floor
        - Operator does not notice gate is tilted from normal position and continues to operate gate
          - Upper anchor arm catastrophically fails
            - Gate falls into lock chamber floor
              - Navigation traffic is halted

Takeaway Points

- Drum Gates are generally reliable but a number of incidents have occurred which have resulted in uncontrolled outflow from a dam.
- Roller Gates are robust and highly reliable and failures have occurred rarely; no known failure has ever resulted in loss of pool; however the USACE inventory is uniform in age (77-82 years); corrosion-induced deterioration to a portion of the inventory makes them vulnerable.
- Miter Gates are vulnerable to barge impact and fatigue cracking but pool has never been lost as the result of any historic accident.
- Vertical Lift Gates are reliable but some designs may be prone to fatigue cracking.
- Tractor/Caterpillar gates often have mechanical problems with the links/rollers.