

Failure of Radial (Tainter) Gates Under Normal Operational Conditions

Best Practices in Dam and Levee Safety Risk Analysis

Part G

Chapter G-1

Last modified June 2017, presented July 2019



US Army Corps
of Engineers®



Failure of Radial (Tainter) Gates Under Normal Operational Conditions

OUTLINE:

- Descriptions of trunnion friction failure mode
- Risk factors for trunnion friction failure mode
- Actual Failures due to trunnion friction
- Case History Foster Dam (USACE-NWP) Inspection, Evaluation and Repairs
- Reclamation Trunnion Friction Response for Program
- Best Practices Trunnion Friction Summary
- Tainter Gate Trunnion Friction Analysis Module
- Example Trunnion Friction Event Tree
- Ongoing Trunnion Friction Research
- Other Potential Failure Modes for Radial Gates



Failure of Radial (Tainter) Gates Under Normal Operational Conditions

SUMMARY OF KEY TRUNNION FRICTION CONCEPTS:

- A failure mode that will occur only during gate operation
- Folsom Dam gate failure is the only recorded incident of this type in the U.S.
- Norwegian researchers report five such tainter gate failures have happened.
- Risk factors related to friction between the radial gate and the trunnion pin.
- Current practice is to perform field inspections focused on documenting condition of strut arms and bracing.
- Research is ongoing to develop better ways to diagnose likelihood of failure mode development.
- Discussion of phased approach commensurate with level of risk assessment.



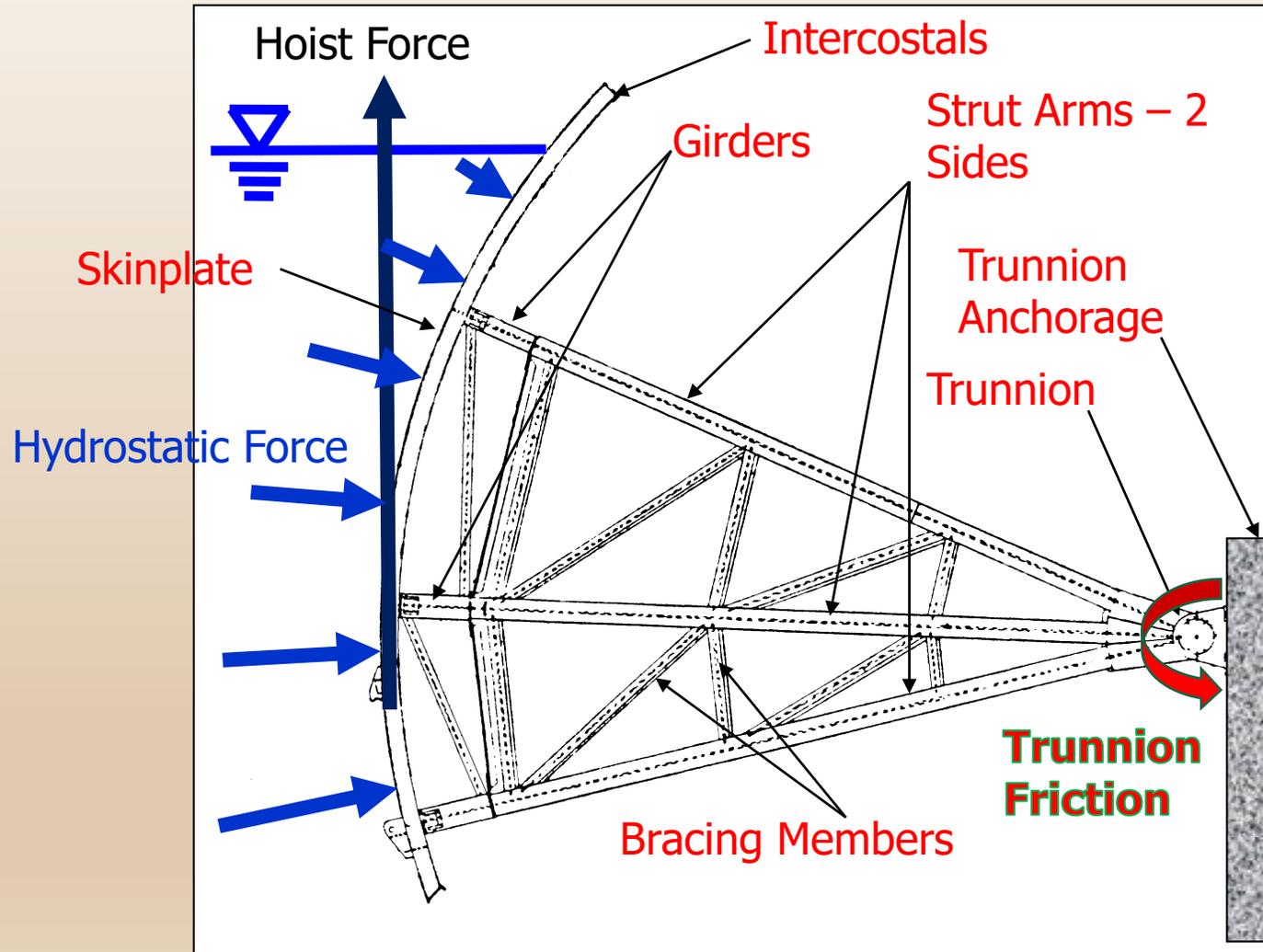
Failure of Radial (Tainter) Gates Under Normal Operational Conditions

SUMMARY OF KEY CONCEPTS for OTHER FAILURE MODES:

- Reduction in member cross section due to corrosion
- Examples of radial gates with heavy corrosion-induced section loss
- Deformations in gate arms or bracing members;
- Binding or racking of radial gate;
- Ice loading
- Examples of failures due to ice loading
- Failure of trunnion anchorage



Trunnion Friction: Tainter Gate Assembly and Load Path



Load Path

- Water Force
- Skin Plate
- Intercostals (transfer load from skin plate to horizontal girders)
- Girders
- Strut Arms
- Trunnion
- Trunnion Anchorage
- Concrete Pier

Strut arms are the critical feature for this failure mode

Failure of a strut arm may lead to gate collapse

Trunnion Friction Risk Factors

- Larger diameter trunnion pins have larger surface areas, and thus have higher potential for imposing greater trunnion friction forces vs. smaller pins. Can significantly increase bending moment.
- Hollow pins likely to have larger diameter.
- Lack of lubrication at trunnion connection
 - Greasing history (maintenance history)
 - Faulty grease lines
- Limited range of motion
- Infrequent gate operation, especially under hydraulic loading
- Graphite-insert bushings (popular in late 1940's-1950's)
- Carbon Steel trunnion pins
- Corrosion of the contact surfaces between the trunnion pin, bushing and trunnion hub is also critical.
- Older gates not designed or previously evaluated for trunnion friction.

Typical Pin Friction Values for Different Pin-Bushing Arrangements (As-Designed Conditions)	
Pin-Bushing Arrangement	Typical Friction Coefficients
Steel Pin on Steel Plate	0.4 - 0.8
Plain Bronze Bushings on Steel Pin	0.3
Externally Lubricated Bushings on steel pin	0.1 – 0.2
Self-Lubricating Bushings	as specified by the bushing manufacturer
Graphite Insert Self-Lubricated Bushings	0.1



Ulefoss Dam Gate No. 1 Failure (1984)



Photo supplied by H. Fosker

- Dam is located in Norway
- Failed during normal operation – cause attributed to trunnion friction
- Dam was constructed in 1961; Two radial gates
- 14.0 meters wide x 4.8 meters (46 x 16 ft); max. head 4.8 meters (16 ft)
- Trunnion pin dia. 300 mm/11.8 inches.
- Norconsult planned the repair works, including stop logs in running water, recovery of gate body, redesigning of bearings and gate arms.



Photo supplied by Symen Postema

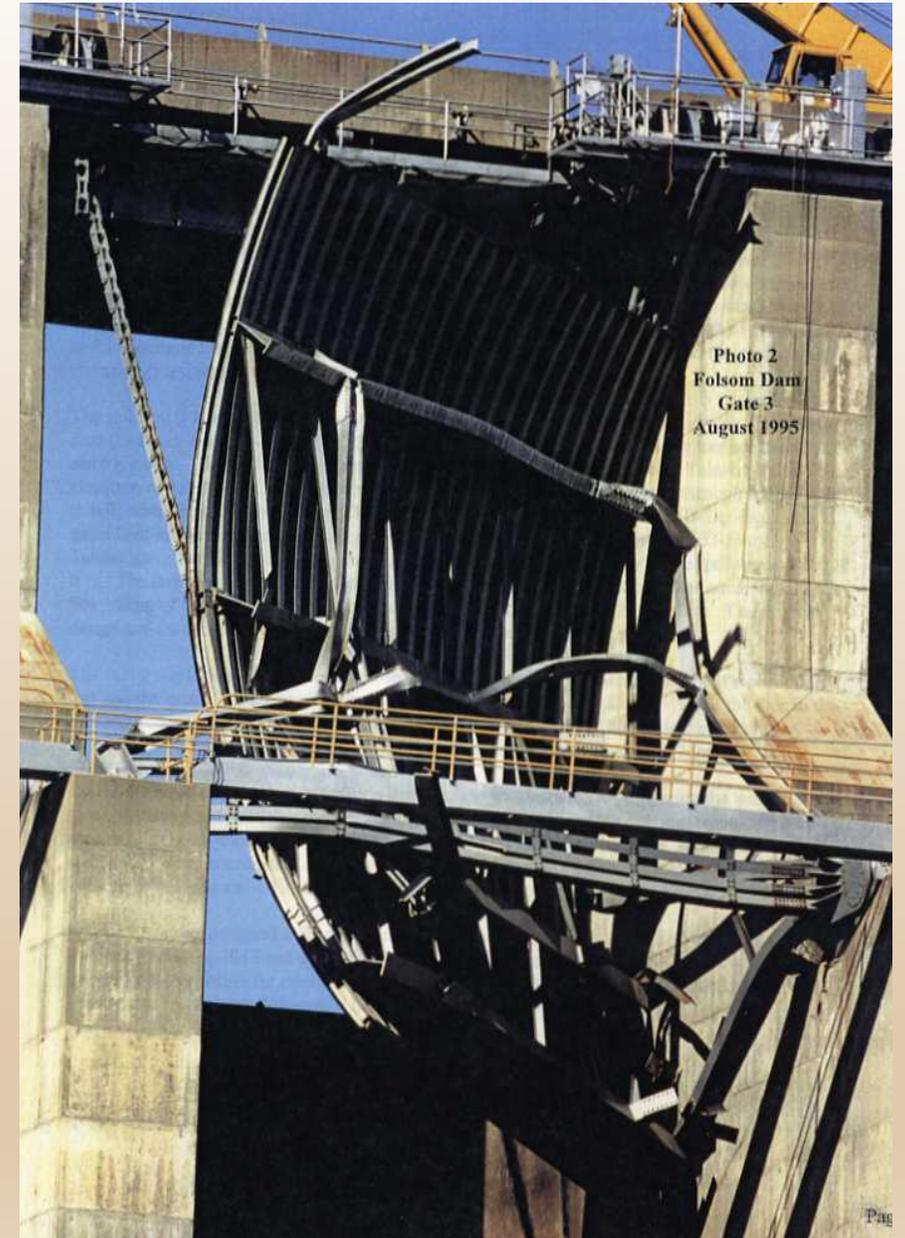
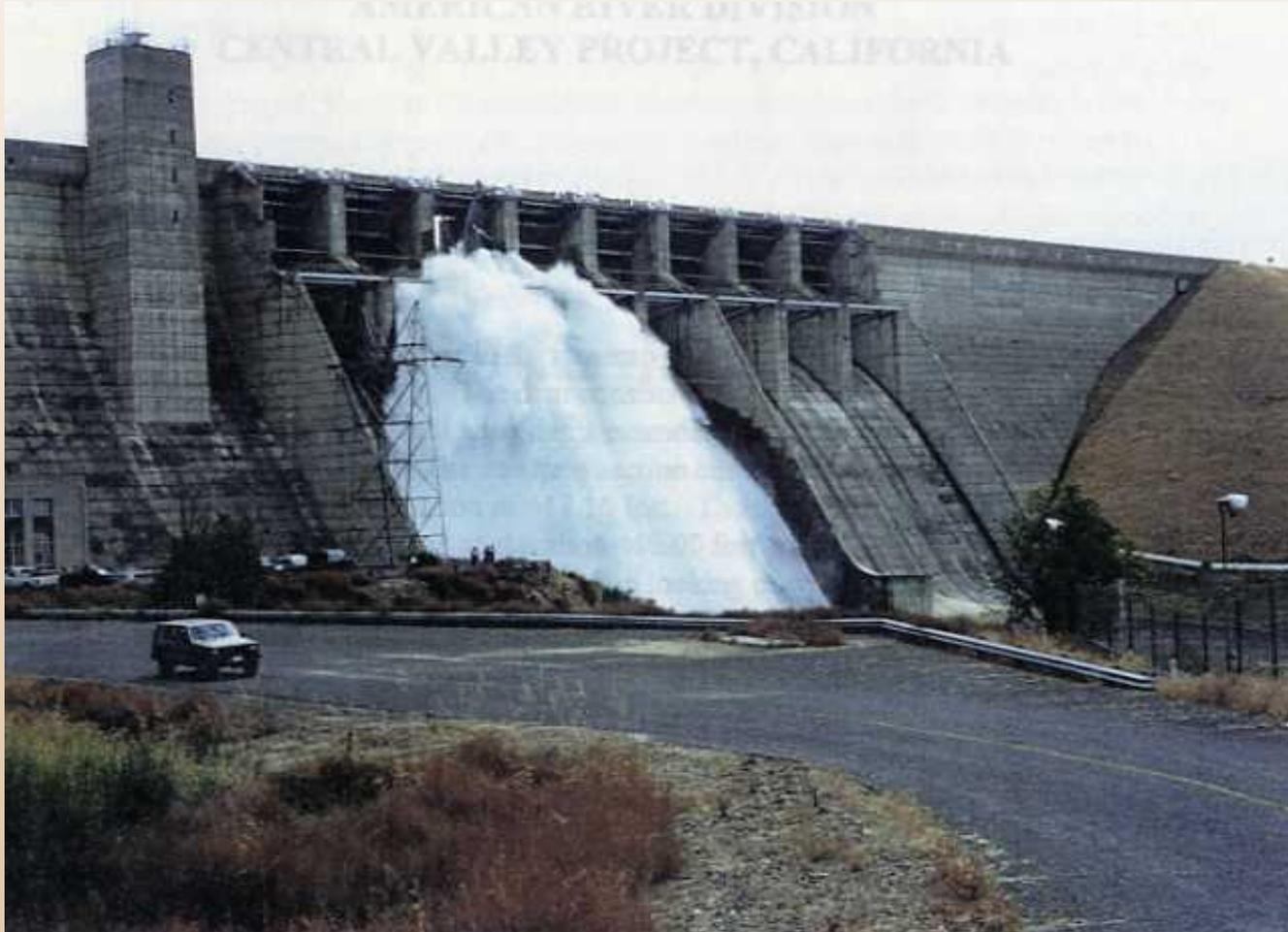
Liwonde Barrage Tainter Gate Failure: Malawi, Africa



- Dam was constructed in 1965
- Maximum differential head of only 4 meters (13 feet)
- Small diameter trunnion pins
- Poorly maintained
- Date unknown when trunnion bearing seized and arm was bent.
- *Gate continues to be operated in severely damaged condition today.*
- A new dam with new gates is currently being constructed.

Photo Supplied by H. Fosker of Norconsult, Norway

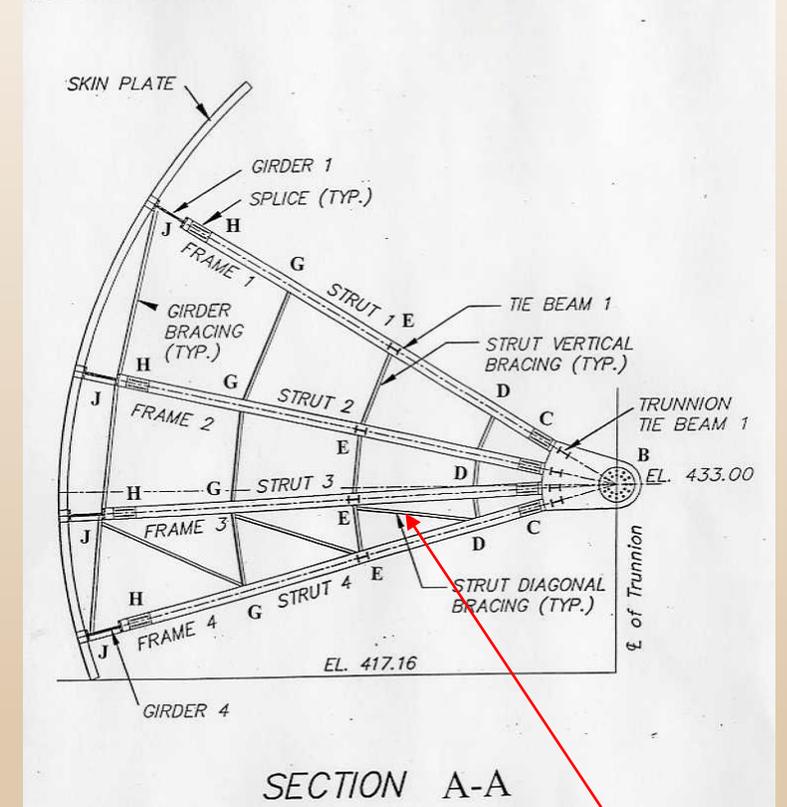
Folsom Gate No. 3 Failure



Folsom Dam Gate Failure

- Spillway has eight spillway Tainter gates (5 service, 3 emergency)
- Gate No. 3 failed suddenly on 7/17/95 with reservoir full
- Uncontrolled release peak – 40,000 ft³/s
- Failure started at lower strut brace, proceeded to adjacent braces and then arms buckled (determined to be trunnion pin friction)
- Contributing factors
 - Spillway gates weren't designed for trunnion friction loads
 - Large, hollow pin (32" diameter)
 - Reduced frequency of lubrication and lack of weather protection at ends of pin resulted in corrosion and increased friction over time
 - Struts 3 & 4 post failure evaluation led to conclusion about failure sequence

FORENSIC INVESTIGATION: IDENTIFICATION CODE FOR GATE CONNECTIONS



Initial Failure

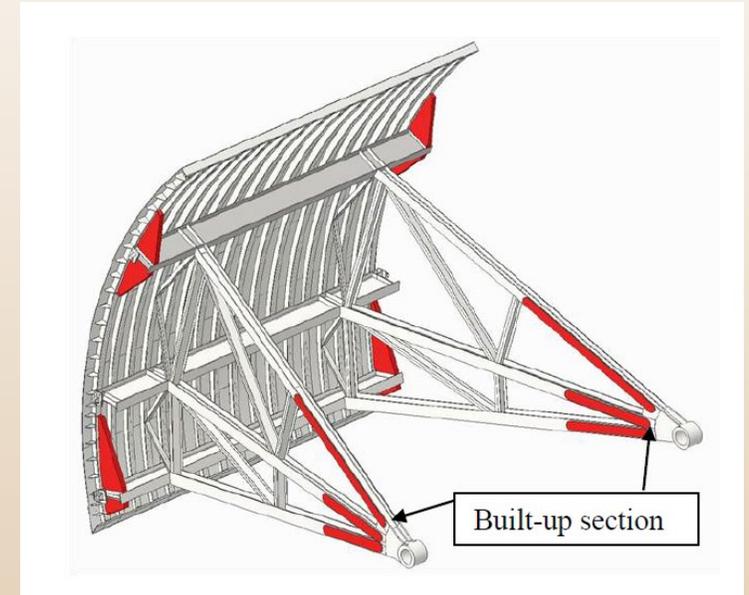
Reclamation Post-Failure Radial Gate Evaluation Procedure:

- Screening studies initiated after Folsom gate failure
- Analyses and evaluations triggered by either Comprehensive Reviews or Gate Inspections
- Screening studies are underway to evaluate radial gates for ice loading



Portland District (NWP) Tainter Gate Spillway Gate Evaluation and Repair Program

Project	Total Number of Gates	Placed In Service	Status
Willamette Valley Basin Projects			
<i>North Santiam Subbasin</i>			
Detroit	6	1950	In Design
Big Cliff	3	1951	Repairs Complete
<i>South Santiam Subbasin</i>			
Green Peter	2	1962	Repairs Complete
Foster	4	1964	Repairs Complete
<i>McKenzie River Subbasin</i>			
Cougar	2	1959	Construction to start in 2016
Blue River	2	1965	In Design
<i>Middle Fork Willamette Subbasin</i>			
Hills Creek	3	1957	In Construction
Lookout Point	5	1951	In Construction
Dexter	7	1953	Repairs Complete
Fall Creek	2	1963	Repairs Complete
<i>Coast Fork Willamette and Long Tom Subbasins</i>			
Fern Ridge	6	1940	Structural Repairs not Required Mechanical and Electrical Repairs are Planned
Rogue Valley Projects			
Applegate	2	1988	Repairs not Required
Lost Creek	3	1976	Structural Repairs not Required Mechanical and Electrical Repairs are Planned
Columbia River Projects			
The Dalles	23	1952	Future Work
John Day	20	1966	Future Work



Strengthening (Red Highlights) of Fall Creek Dam Spillway Gates

Source: Ebner, L., Fortuny, W., Hamernik, D., Hess, M., Sawka, M. (2016). USACE Portland District Spillway Gate Rehabilitation Program. In B. Crookston & B. Tullis (Eds.), Hydraulic Structures and Water System Management. 6th IAHR International Symposium on Hydraulic Structures, Portland, OR, 27-30 June. (ISBN 978-1-884575-75-4).

Case Study: Foster Dam Gate Evaluations

(Courtesy of Travis Adams, NWP)

Inspection and Evaluation - Chronology of Events

Tainter gates are inspected two at a time on a 5 yr. cycle.

June 2002 - Climbing inspection of gates 3 & 4.

- No signs of distress found.

June 2008 - Climbing inspection of gates 1 & 2.

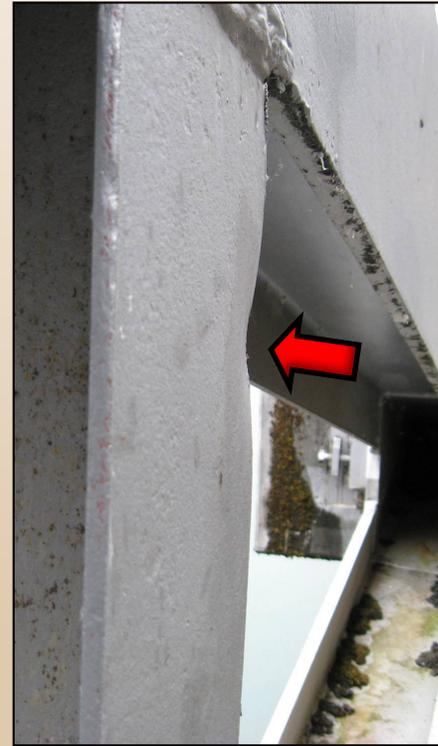
- Top strut arms and diagonals showed signs of distress.

July 2008 – Climbing inspection of gates 3 & 4

- Top strut arms and diagonals showed signs of distress.

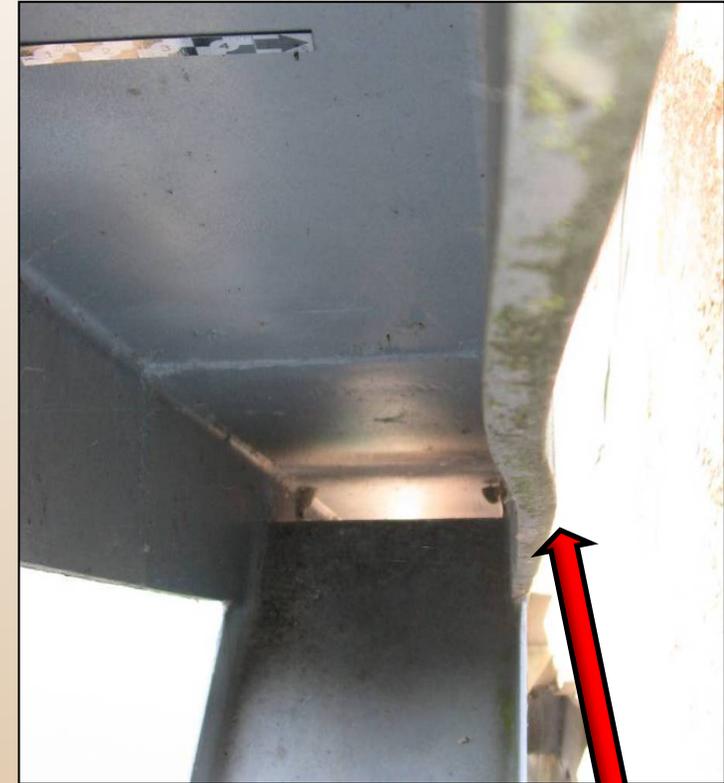


Evidence of Buckling of Strut Arms at Foster Dam



Foster Dam Gates 1, 2 and 3

Gates 1 & 2 in 2008: Deformation in North Top Strut; Twist, Bending, Buckling



**Gate 3 in 2008:
Deformation occurred
after 2002 inspections**

Foster Dam Inspection and Evaluation – Evaluation

Maintenance - Greasing to reduce trunnion friction

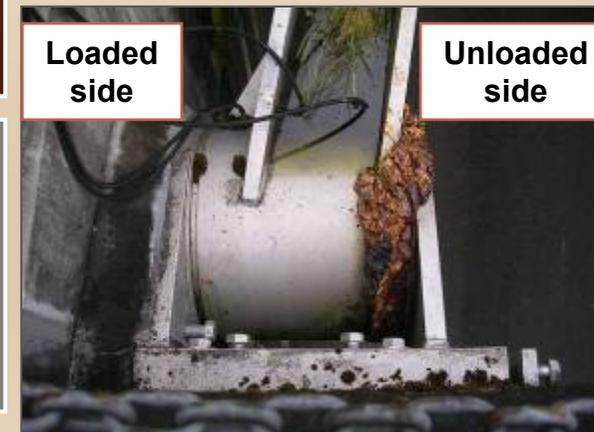
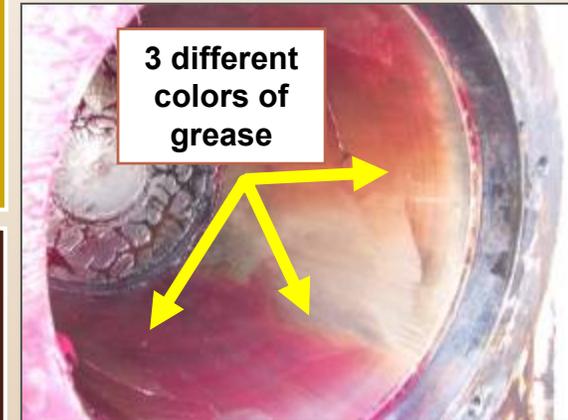
- Grease follows the path of least resistance.
- Gates should be operated through full range of motion annually.
- Different colors of grease show inadequate greasing (Pink = new; Tan = old)
- Inadequate greasing = excessive trunnion friction = additional moment forces.

Design

- Original calculations ignore single-sided hoisting, skew, debris load, wave load.
- Original design used 0.2 as the coefficient of friction. New design criteria recommends 0.3.
- Thrust washer friction – does not receive grease

Operation

- Debris damage
- Gates have been operated at full pool for the last two years (powerhouse downtime prompted spill from Tainter gates).
- Deformations were load-induced



Foster Dam: Emergency – Change in Operation

Lower Pool to 622' (limit load on top strut)

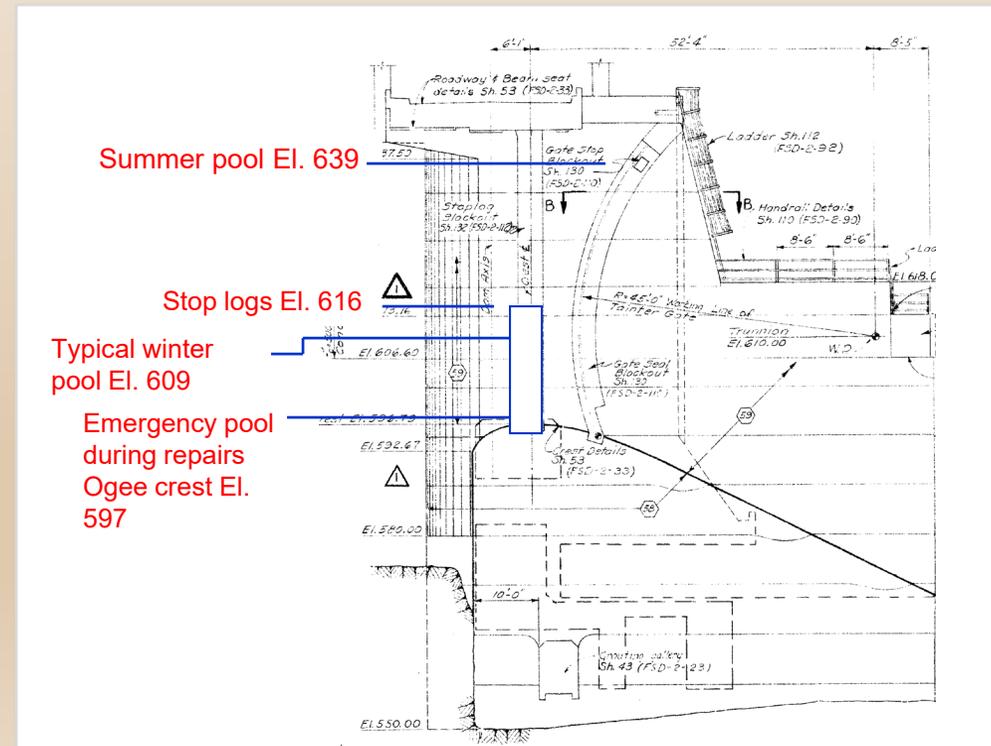
Ranked gates according to condition for priority of use until repairs could be implemented

- Gate 3 – worst damage to struts – do not use
- Gate 1 – damage to struts – do not use
- Gate 2 – some damage to struts - restricted
- Gate 4 – some damage, restricted

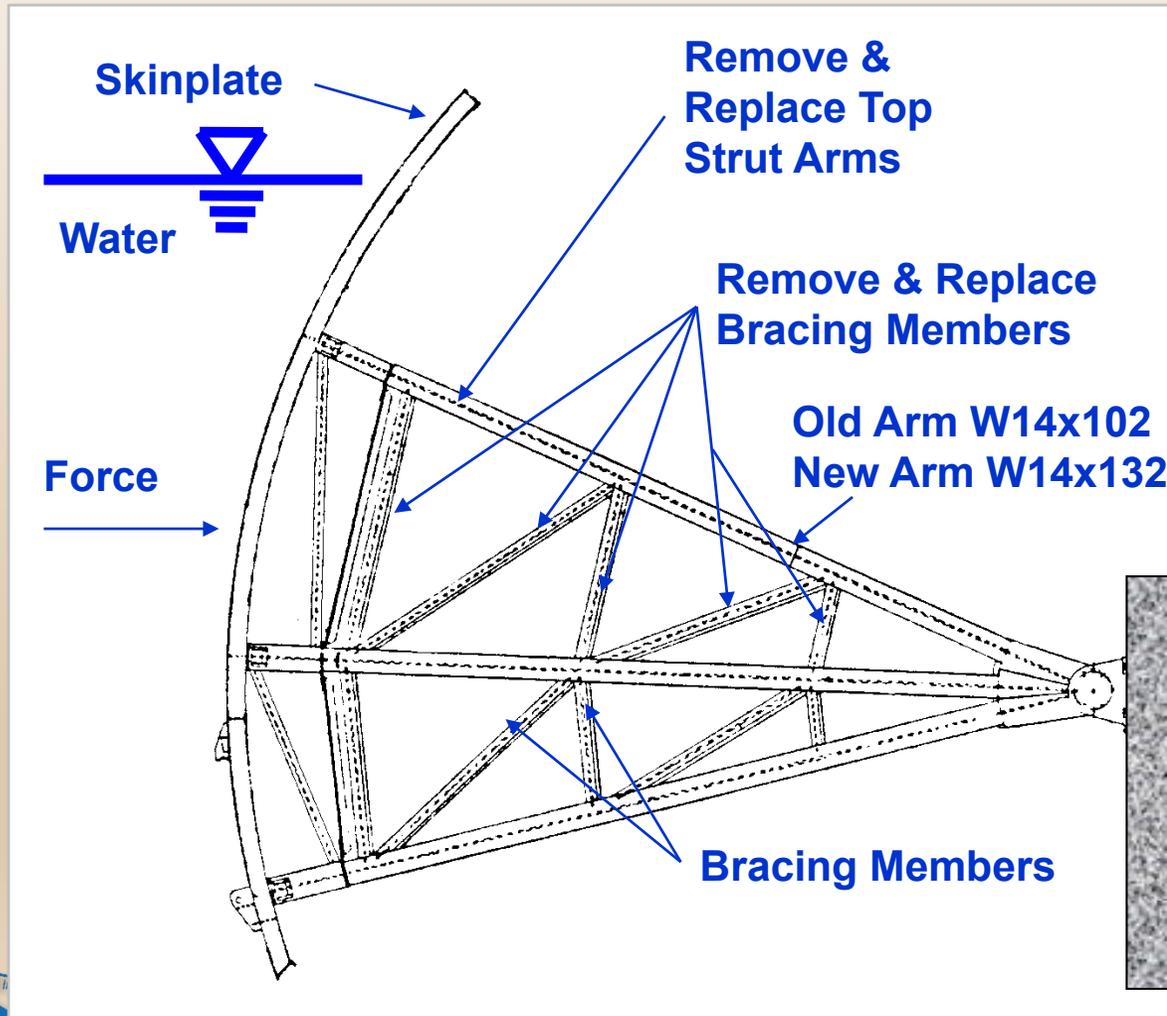
Project went to ogee crest operation during repair (run of the river)

Ogee crest required to facilitate repair

- Accepted some flood risk



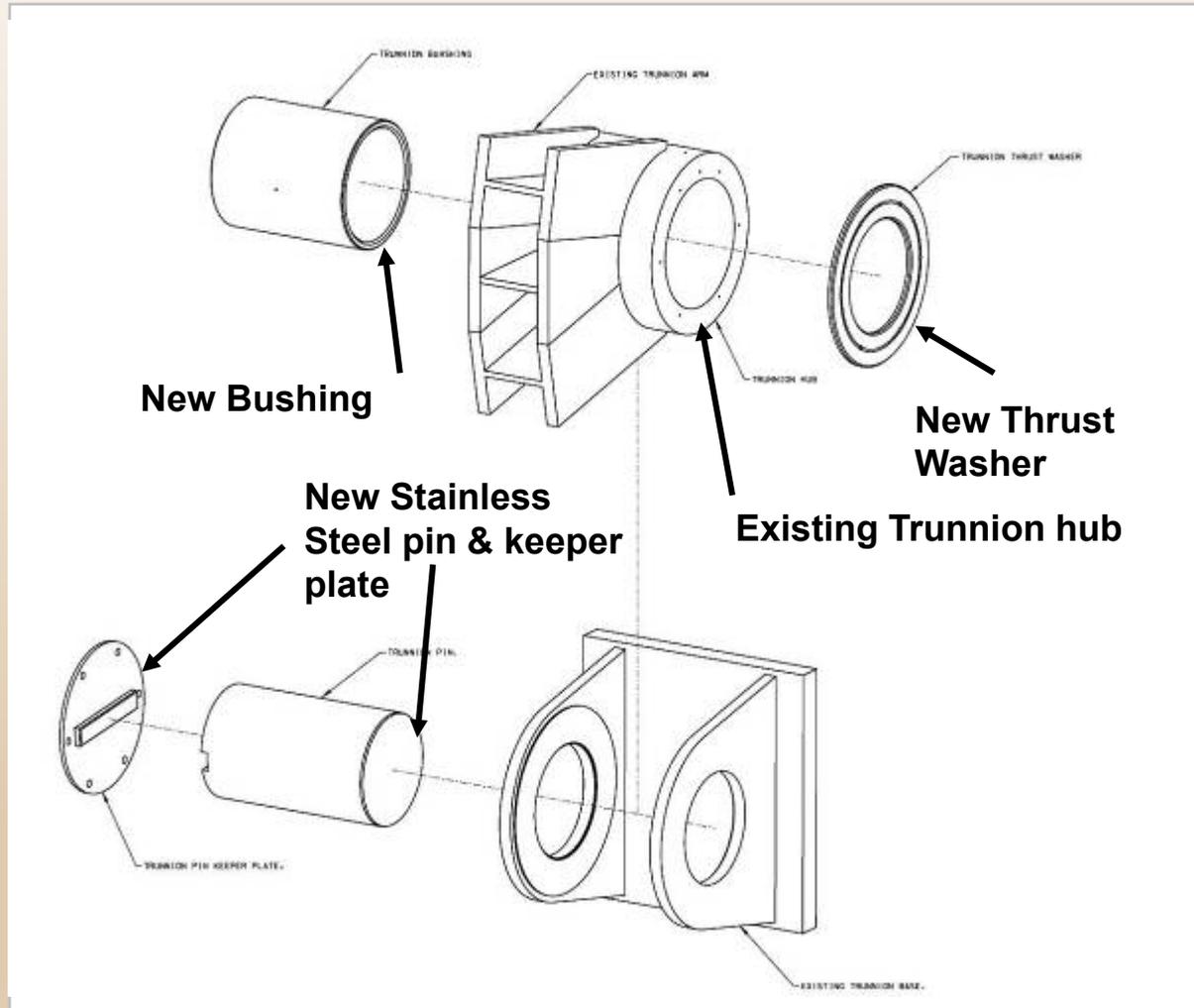
Foster Dam: Emergency Repairs - Construction



Strut Arm / Bracing Repairs

- Remove top strut arms
- Remove bracing members that attach between the top and middle arms
- Replace top arm with a bigger member size and 50 KSI steel.
- Replace braces with same member size using 50 KSI steel.

Foster Dam: Emergency Repairs - Construction



Trunnion Repairs

- Remove existing keeper plates, pins, thrust washers, and bushings.
- Replace bushings and thrust washers with composite specified materials.
- Use of correctly specified composite materials allow the system to be greaseless.
- Replace old pins, keeper plates, and fasteners with new stainless steel material.

Trunnion Friction Induced Failure of Radial (Tainter) Gates

RECLAMATION APPROACH FOR TRUNNION FRICTION EVALUATION

- Screening Level Analysis – hand calculations along with an approximate second-order approach can be used to evaluate gate arms for a simple arm frame arrangement
- Refined Analysis – Finite element model of the entire gate (including skin plate, skin plate ribs, girders, arm frames and trunnions) is typically developed
- Stability analysis of gates needs to consider all load combinations together with the initial imperfections of the gate geometry



Trunnion Friction Induced Failure of Radial (Tainter) Gates

BEST PRACTICE RISK EVALUATION BASED APPROACH:

LEVEL 1: Consider the risk factors previously noted incl. gate operating history, design, maintenance and consequences to determine if likely to be a risk-driving PFM (Typical of evaluation used for PA or possibly SQRA). Ideally a detailed inspection report would be available to inform the input.

LEVEL 2: Complete a basic structural analysis by estimating the interaction ratio for the gates. The Tainter Gate Module could also be used for this level of evaluation. Generally part of an IES or similar.

LEVEL 3: If trunnion friction is still considered a risk driver, a more detailed structural analysis (finite element) may be warranted to get a better handle on loading and performance. If possible the model should be scaled to results from strain gauges installed on at least one arm in a gate, to determine a typical value of trunnion friction. Ideally the gate should be subjected to hydrostatic head and operated under flow. However operation under dry conditions should provide an indication of trunnion friction. Typically done as part of a Phase II IES.



Tainter Gate Trunnion Friction Module

- Analysis Module Version 2.0
- Purpose was to develop a relatively easy means to assess buckling of radial gate arm w/o finite element analysis
- Includes condition assessment inputs and detailed structural members input.
- Provides relatively simplistic analysis to determine if trunnion friction loading is a concern.
- Doesn't include second order effects in the analysis
- Used only for screening purposes to determine if buckling of arms is potentially a problem
- If the combination of failure likelihood and consequences are sufficient enough to approach or exceed TRG, then more detailed FEM analysis is undertaken to better estimate performance

TWO GIRDER TAINTER GATE TRUNNION FRICTION EVALUATION

Row	Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K	Column L	Column M
1	TWO GIRDER TAINTER GATE TRUNNION FRICTION EVALUATION												
4	PROJECT NAME	0											
6	FIELDS IDENTIFIED WITH A YELLOW BACKGROUND REQUIRE USER INPUT												
8	GATE GEOMETRY												
10	El Top of Gate in Closed Position	Ele _{TOG}	0.00	ft									
11	El Trunnion	Ele _{trun}		ft									
12	El Gate Sill	Ele _{sill}	0.00	ft									
13	Gate Radius from centerline of Pin to Skin Plate	r		ft									
14	Approximate Weight of Gate	F _{gw}		kips									
15	Width of Gate	w _g		ft									
16	angle - sill to bottom strut	α ₁		deg									
17	angle - bottom to top strut	α ₂		deg									
18	angle - top strut to top of gate	α ₃		deg									
19	strut arm inclination	α ₄		deg									
21	HEADWATER ELEVATION												
22	Load Case 1	Ele _{hw-LC1}											
23	Load Case 2	Ele _{hw-LC2}											
24	Load Case 3	Ele _{hw-LC3}											
26	STRUT ARM & GIRDER PROPERTIES						SIDE SEAL						
28		Top Strut			Bottom Strut								
29	Type of shape									Width of J seal exposed	d		in
30	Name of shape									Force due to preset deflection	S		kips
31	Area	A		in ²	A		in ²			Coefficient of friction	μ _s		
										El Tailwater (Load Case 1)	Ele _{hw-LC1}		ft

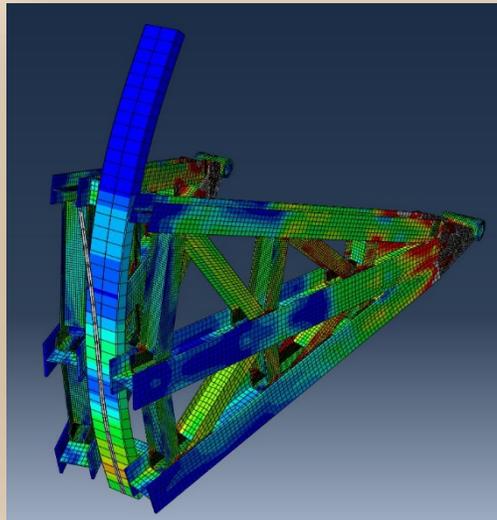
Module Overview for Use in Risk Assessment

- Can be used for tainter gates with 2, 3 or 4 girders
- Spreadsheet based
- Probabilistic analysis (@Risk)
- Allows user to select headwater elevations to be analyzed
- Not suited for seismic evaluation
- Doesn't include second order moment effects
- Used as a screening tool and when evaluation is coupled with potential consequences, helps give a sense if PFM approaches USACE tolerable risk guidelines



Detecting Trunnion Friction w/Minimum Instrumentation

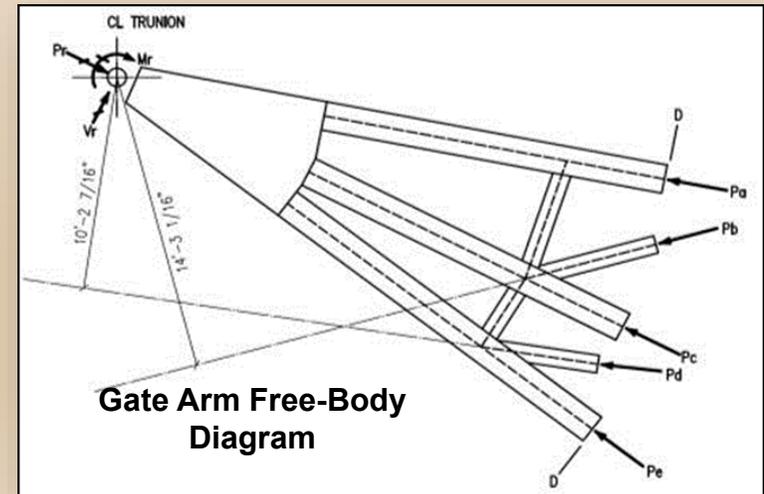
- ERDC researching low cost method to detect and accurately quantify trunnion friction forces using as few as two strain sensors per gate.
- ERDC proposes the use of low-cost monitoring system consisting of only minimal instrumentation. This effort consists of four elements:
 - Develop a numerical model for a typical Tainter gate.
 - Design and fabricate a physical model of this gate.
 - Conduct laboratory experiments to validate the field method.
 - Deploy the prototype Trunnion Friction Monitoring System at a USACE project.
- Dr. Matthew Smith (CHL) is the Research Structural engineer who developed the approach,
- Bruce Barker is the working the instrumentation side of the problem.
- Results look very promising from a modeling standpoint but ERDC is just starting the field testing phase in summer 2016.



Numerical Model



Structural Model



Gate Arm Free-Body Diagram

Spillway Gate Member Failure Mechanisms

- Yielding (Inelastic Buckling)
- Buckling
- Fatigue



Gate Failure Fragility Curve

Interaction Ratio	Probability of Failure (1 gate)
< 0.5	0.0001
0.5 to 0.6	0.0001 to 0.001
0.6 to 0.7	0.001 to 0.01
0.7 to 0.8	0.01 to 0.1
0.8 to 0.9	0.1 to 0.9
0.9 to 1.0	0.9 to 0.99
> 1.0	0.9 to 0.999



Failure of Radial (Tainter) Gates Under Normal Operational Conditions

OTHER FAILURE MODES:

- Reduction in member cross section due to corrosion
- Examples of radial gates with heavy corrosion-induced section loss
- Deformations in gate arms or bracing members;
- Binding or racking of radial gate;
- Ice loading
- Examples of failures due to ice loading
- Failure of trunnion anchorage



Reduction in Member Cross Section Due to Corrosion

Chittenden Locks Tainter Gates

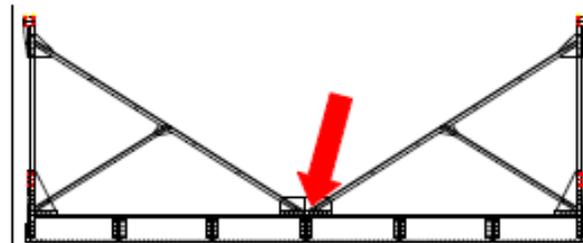


- Dam was completed in 1916
- Gates are 32 feet wide and 8.5 feet wide; max. differential head -13 feet
- There are no emergency bulkhead slots and no emergency bulkheads.
- Gates underwent rehabilitation in 1944, 1953, 1977 and 1987
- Paint loss and extensive pitting of girders and channels.
- Rivet heads noted to have between 20-100% section loss.
- Gates at end of useful life in regard to safe/reliable operation

- The gates did not meet current criteria with regard to single sided hoisting operations, stall torque, trunnion friction, and/or impact.
- All gates replaced in 2014



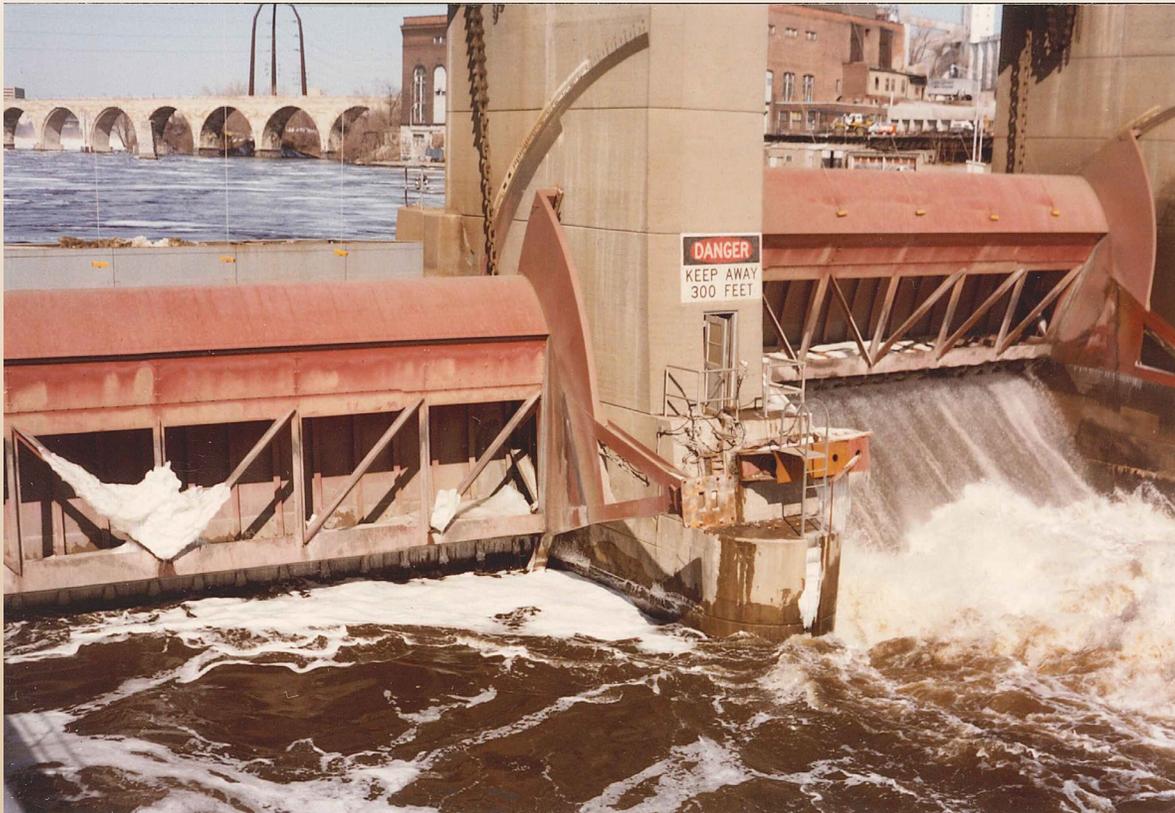
Photo 90: Gate 4 – Heavy corrosion of top horizontal center gusset plate. Up to 100% section loss on downstream edge of plate. Up to 100% section loss of rivets. Welded diagonal strut connections heavily corroded.



Information for this slide supplied by Seattle District from 2010 Chittenden Lock Radial Gate Inspection Report, from HDR, Inc.

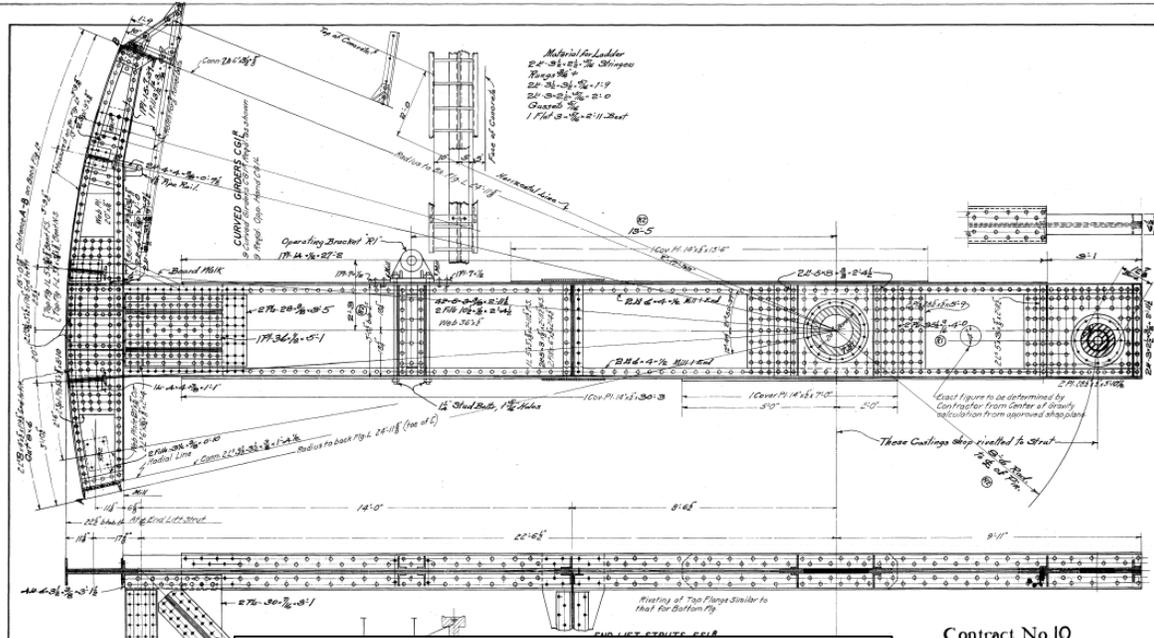


Failure of Lower St. Anthony Falls Trunnion Girder Due to Ice Loading (1982)



- Dam was completed in 1956
- Gates are 56 feet wide and 15.2 feet wide
- Maximum differential head of 25 feet
- Well maintained
- Designed to pass ice/debris over gate crest
- ***Failed on 17 January 1982, at 1500. Temperature was +8°F; the previous night, temp was -20°F.***
- Considered a brittle failure; cracked welds and cracks in base metal subsequently discovered
- Original design did not allow for lateral ice load as now required by EM 1110-2-2702.
- 5,000 lb/ft. ice load would significantly overstress the trunnion girders
- Significant ice loads (>5' thick) have occurred

Failure of Dresden Island Tainter Gates Due to Ice Loading (1982)



Contract No.10
STATE OF ILLINOIS
DEPARTMENT OF PURCHASES AND CONSTRUCTION
DIVISION OF WATERWAYS
THE ILLINOIS WATERWAY
DRESDEN ISLAND LOCK & DAM
GATES-CURVED GIRDS
AND END LIFT STRUTS

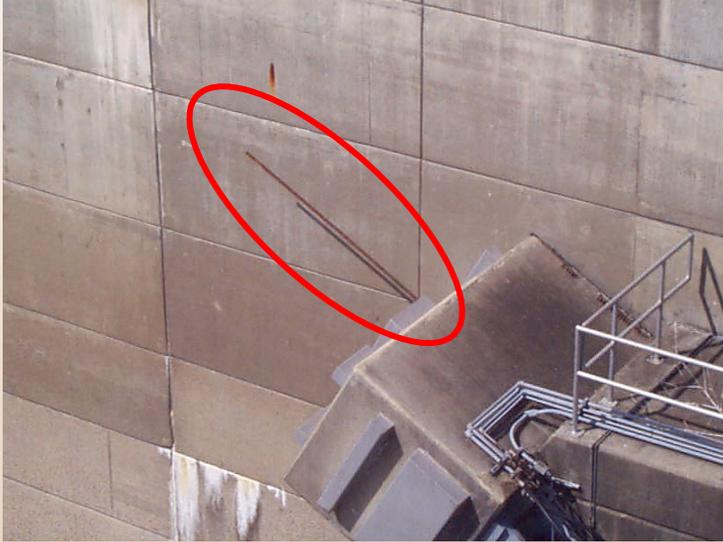
Submitted April 27, 1928, recommended May 1, 1928
Approved May 2, 1928, authorized May 16, 1928
Contracted 2-6-28 Rec. No. 1541 V. 1

- Ice problems more numerous and severe in recent years as water quality has improved.
- Ice discharges from the Kankakee River, especially when ice jams break loose upstream, create difficulties in maintaining pool level as well as causing problems with ice at the tainter gates.
- Tainter gate electric motors do not have sufficient power to lift the gates when a mass of ice has accumulated on them.
- The gates are then operated manually using hand cranks or a heavy-duty electric drill.
- Hand chipping and steam are used to free ice from the gates.
- In March, 1982, Tainter gates No. 4 and 9 partially failed as a result of a buildup of floating ice and required replacement.
- Top cantilevered portions of these gates suffered ductile failure due to overload.



Failure of Trunnion Anchorage Due to Corrosion

- R. F. Henry Dam (Mobile District) – construction completed in 1969
- 12 spillway piers containing 464 main trunnion girder anchor rods, each 1¼-inch diameter
- Radial gates are 50-ft wide by 31 ft tall
- As of November 2007, six anchors failed; one each in piers 1 (in 2006) and 3 (in 1969) and two each in piers 2 (in 1972) and 9 (in 2006).
- Specified rods were brittle. Also 100% loss of grease had occurred.
- Factor of Safety of 1.0 with loss of four rods per pier
- If there is loss of 3 rods, gate will be closed, stoplogs placed



Takeaway Points

- There are several potential failure mechanisms for radial (tainter) gates under normal operating conditions, but there are only limited case histories.
- Many failures have been well documented for radial (tainter) gates on navigation structures, mostly resulting from barge impact.
- Very few failures of radial (tainter) gates have been documented that were the result of structural failures under expected design static loads.
- Structural steel material properties are generally well understood.
- Few radial (tainter) gates have been instrumented in order to assess actual trunnion friction.
- There are no recorded case histories of a radial (tainter) gate failing due to corrosion-induced section loss. So far, replacement of gates has intervened before a catastrophic failure.
- Ice loading can lead to both Ductile and Brittle Failure mechanisms.
- No failure of a radial (tainter) gate due to a trunnion anchorage failure has been recorded, but as embedded anchorages age, corrosion will progress, undoubtedly resulting in more failures of individual bars.

