30. Trunnion Friction Radial Gate Failure

Key Concepts and Factors Affecting Risk

Load Carrying Mechanism

Spillway radial gates (sometimes called tainter gates) transfer the reservoir load to the trunnion pin through compression of the relatively slender gate arms (see Figure 30-1). Pin friction represents a special loading case for a radial gate under hydrostatic loading. A separate chapter is also provided on Seismic Failure of Spillway Radial Gates. An increase in pin frictional moment will increase the combined arm stresses, which can lead to a greater probability of arm buckling failure. This potential failure mode will only apply when the spillway gates are operated and frictional resistance is developed between the trunnion pin and trunnion bearings. Gate operation would typically occur during a flood but could occur when the gates are being routinely exercised. For this reason, flood load probabilities are typically not considered in estimating the risks. This is not a ductile failure (it involves buckling of the steel gate arm members) and can occur suddenly. Spillway radial gates are most vulnerable to this failure mode when they are initially opened, as the loading on the gate will be the highest at this time.

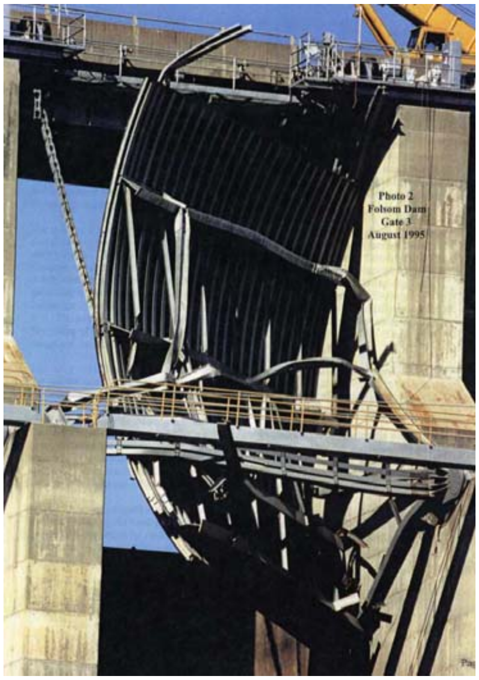

Figure 30-1 – Folsom Dam Radial Gate Failure

Fortunately, for most radial gates, trunnion pin friction has not been found to be a problem for arm overloading. Either the pin frictional moment has been accounted for in the gate design; or it represents a relatively small and manageable load that can be carried by the reserve buckling strength of individual arm members. When reviewing suspect radial gates which are capable of developing excessive pin friction, one should consider as candidates the larger, older-designed radial gate installations having obvious lubricant-deficient pin design, and a lack of hub stiffening and/or arm bracing.

Trunnion Pins and Bushings

When a spillway radial gates is operated, friction at the trunnion pin is transferred as an axial compressive force and bending into the gate arms. Lubrication at the trunnion pin is critical to ensure that the trunnion pin friction is minimized. If lubrication is not provided or if the trunnion has inadequate seals that allow moisture to access the trunnion pin, corrosion can occur which will increase the trunnion pin friction over time. Unless measured on a regular basis (for example using a laser pointer attached to the gate arm and measuring the bending of the arm during operation), trunnion pin friction should be assumed in the analysis of spillway gates. Based on studies at Folsom Dam, (Reclamation, 1996), the assumed trunnion pin friction coefficient should be at least 0.3. For large trunnion pins, this failure mode will be more critical because trunnion pin friction will result in more resistance to the gate being opened.

Size of Radial Gates

Spillway radial gates come in all sizes. Large radial gates, 50 feet or more on a side, are common. Larger gates are not necessarily more prone to failure but failure of a large gate will result in a large breach outflow and likely greater consequences than the failure of a smaller gate.

Mechanics of Pin Friction

All radial gate arm assemblies are subjected to a bending moment induced by pin frictional moment. Whenever radial gates (a.k.a. tainter gates) are operated, the pin friction develops at the interface of the surfaces of the fixed pin and the inside surface of the bushing.

Pin friction loading means the pin frictional moment which develops and acts in a direction opposing the motion of the gate. Pin frictional moment is generally at its peak when a gate is loaded under full reservoir head and is in its closed position. As the gate begins to rise and first begins to break free through its static coefficient of friction, the pin frictional moment develops and loads the hub end of the arm assembly.

The frictional moment, which lies in a vertical plane, is a function of the three parameters. The first is the hydrostatic load carried in axial compression through the arms to the hub, the second is the diameter of the pin acting as a lever arm to produce the friction, and lastly is the coefficient of static friction between the pin and the bushing.

Over the years, radial gates have utilized several types of pin bushing configurations. For old and small radial gates, the pin/bushing design may have been as simple as a small cantilevered steel pin passing through an oversized hole in a steel plate used as a and hub without any bushing. For large, new radial gates, the arrangement is more likely a self-lubricating bushing rotating around high strength, stainless steel pin. Beyond the simple arrangement without a bushing, there are four likely historical pin/bushing configurations.

Plain Bronze Bushing. - A simple bronze bushing and either a steel trunnion pin, SAE 1020 cold-finished steel trunnion pin, or a stainless steel trunnion pin.

Lubricated Bushing. – A bronze bushing with a means to inject lubricating grease to the pin/bushing interfaces. In some instances, the injection point provides an inadequate single point of lubrication. In major gate installations, the inner surface of the bronze bushing has been machined with grease grooves to allow a better and more even distribution of lubrication.

Graphite-Insert," Self-lubricating Bushings". – In the latter half of the 1940s, the bearing industry had developed so-called self-lubricating journal bearings. However, the lubricant used for the bushings was a graphite plug that was inserted into recesses on the inside of the bronze bushing. The graphite proved to be a bad choice for hydro applications because of the galvanic cell that it set-up with the steel pin that promoted corrosion, pitting, and increased coefficient of friction and greater pin frictional moment.

Self-Lubricating Bushings. – In the 1970s, self-lubricating bushings were often specified that utilized propriety lubricants formulated without the addition of graphite or molybdenum.

Reservoir Water Level

The reservoir water level on the gates is a key parameter since it affects the loading on the gates (stresses in gate members and normal force on trunnion pin which determines the frictional resistance) and also the consequences of gate failure (due to the effect on the breach outflow). It is most likely that the reservoir water surface elevation will be at the top of the gates when this potential failure mode is triggered, unless the gates are being operated as part of a routine exercise operation and the reservoir is down for some reason. This is because spillway radial gates are typically only operated under flood conditions and flood releases are typically not made until the reservoir exceeds the top of active conservation pool or the top of joint use pool, which is usually located near the top of the spillway radial gates when they are in the closed position.

Reservoir Operations

This potential failure mode requires operation of the radial gates to initiate the failure. If the gates remain in the closed position, trunnion pin friction will not be mobilized and the gate members will not be loaded by this mechanism. Reservoir operation levels will only be a factor if the spillway is operated at levels below the top of the gate elevation (or below a level within a foot or two of the top of the gates). If the reservoir level is typically at or near the top of the gates on an annual basis when the gates are likely to be operated or tested, this is a more hazardous situation than if the reservoir frequently does not reach the top of the gates on an annual basis, or the gates are typically tested when the reservoir is low. The likelihood of various reservoir levels at times when the gates will be operated can typically be estimated from the historic reservoir exceedance curves.

Combined Stress Ratio

The key parameter for evaluating this potential failure mode is the combined stress ratio which accounts for both axial and bending stresses, and can be used to estimate the likelihood of buckling in steel members. Combined stress ratios can be related to failure probabilities using a response curve. For radial gate arm buckling, the combined stresses are the axial compressive stresses and the vertical and horizontal bending stresses which act at the extreme fibers at the same cross section of the arms wide flange (or other) beam. The combined stresses were developed and presented by AISC (American Institute for Steel Construction; 1989) in equation H1-1 as shown below.

The equation is the sum of three ratios. The numerator of each ratio is the actual stress, and the denominator represents the allowable stress with its associated factor of safety. The first term is the axial compressive stress, the second term is the bending stress about the strong axis of the cross section, and the third term is the bending stress about the weak axis. For transition loadings, such as wind, seismic, or friction when operating a radial gate, the AISC code allows a one third increase in the stresses. That is, the allowable combined stresses (the sum of the three ratios) is less than or equal to 1.3. Evaluating the individual variables given in the combined stress equation is complicated, and requires background of other chapters with the AISC Specification for Structural Steel Buildings.

The simplest term and ratio to evaluate is first term – the axial compressive stress. A preliminary (simplified) arm buckling failure analysis would start with calculating the stress level for this axial stress term. It generally represents the largest contributor to the combined stress. If its value (ratio) is 0.8 or greater than a judgment whether a more refined (e.g. a 3D structural computer analysis) should be made. The pin frictional moment may be considered a transient moment acting on the arm sections in the vertical plane near the trunnion hub. Depending on the orientation of the arm's wide flange beam (or other), it would contribute to the bending stress of the second or third term).

$$\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{(1 - \frac{f_a}{F'_{ex}})F_{bx}} + \frac{C_{my} f_{by}}{(1 - \frac{f_a}{F'_{ey}})F_{by}} \leq 1.0$$

Combined Stress Ratios; AISC Eqn. H1-1 (1989)

Multiple Spillway Gates

For spillways with multiple radial gates, failure due to trunnion pin friction is most likely to result in only one gate failing, since the gates are typically operated one at a time, and failure of a gate would likely result in an evaluation, or at least extreme care in operating the other gates. However, there is more of a chance that one of the gates will suffer problems with trunnion friction if multiple gates are present, and failure of one large gate could exceed the safe channel capacity or surprise downstream recreationists with life-threatening flows.

Maintenance of Spillway Gates

Gates that are well maintained can usually be relied upon to have their original design capacity at the time they are operated. A key maintenance item for this failure mode is lubrication of the trunnion pin. If the pin is lubricated frequently, the pin friction will be reduced and the probability of this failure mode will also be reduced. Some trunnions have self-lubricating or graphite bearings. The condition of these should be evaluated and the trunnion friction measured periodically to ensure they continue to perform as intended. Also, if gates are not maintained and the gate members corrode, the original design capacity may be reduced. A recent examination is usually needed to determine the condition of the gates and trunnions. Finally, exercising of the gates at least annually helps to ensure that the trunnion pin lubrication is uniformly distributed around the trunnion pin and verifies that the gate is performing as expected. If any of these attributes are questionable, the potential for higher failure probabilities exists.

Hoist Ropes and Chains/Gate Binding

This section focuses on failure of spillway radial gates due to trunnion pin friction, but there are other mechanisms that could lead to inoperable spillway gates. These mechanisms include failure of wire hoist ropes or hoist chains and gate binding. While these mechanisms may not lead to gate failure and an uncontrolled release of the reservoir, they could result in inoperable gates during a large flood, which could initiate other failure modes, such as dam overtopping or internal erosion failure modes. If gates are well maintained and exercised, the chance of an inoperable spillway gate during a large flood will be significantly reduced. Inspections of the gates should focus on wear or corrosion of wire ropes and chains and connections of the ropes and chains to the gates and the hoists. Exercising of the gates will verify that the gate can travel freely within the gate bay, at least for smaller gate openings. The walls and piers in the area of the gate wall plates should also be inspected for plumbness, to identify if there are any potential problems with larger gate openings.

Event Tree

The example event tree shown in Figure 30-3 is relatively simple. The first node represents the reservoir load range and provides the load probability. The second node in the event tree is a reduction that accounts for regular lubrication of the trunnion pin. If this occurs, the failure probability estimate can be reduced. The third node allows for further reduction to the failure probability estimate, based on regular gate inspections and regular exercising of the gates. The fourth node is the conditional failure probability that is based on the calculated combined stress ratios in the arms, given the reservoir and trunnion friction loading. If the gates are loaded to the point of overstressing the radial gate arms, the gate arms can buckle and fail, leading to gate collapse and reservoir release without additional steps in the event sequence. The event tree for this failure mode was established by using the conditional failure probability generated from the response curve shown in Table 30-4 and then making adjustments that consider lubrication of the trunnion pin and inspections and exercising of the gates. The adjustments made were somewhat arbitrary but provide estimates that are consistent with the historic failure rate for spillway radial gates. Reclamation has 314 spillway radial gates in its inventory. There is a total of about 18,000 gate years of operation for these gates (as of 2009). The only failure due to trunnion pin friction (or any loading condition for that matter) was the Folsom Dam gate that failed in 1995. The base failure rate is 1/18,000 or 6 E-05. The results obtained by using the event tree proposed in this section seem consistent with this base failure rate. Annual failure probabilities greater than the historical rate can be achieved if the critical combined stress ratio is between 1.0 and 1.3 and the pin/bushing arrangement is less than ideal and/or inspections/exercising of the gates are infrequent. If the critical combined stress ratio is less than 1.0 the resulting annual failure probabilities will be negligible. Given the judgments that are needed to evaluate this potential failure mode, judgmental probabilities are typically used to assign likelihoods to each node as described in the section on Subjective Probability and Expert Elicitation. Refer also to the section on Event Trees for other event tree considerations.

Gate Analyses

Gate analyses are needed to evaluate the stresses in the gate members under combinations of reservoir and trunnion friction loadings. A finite element model of the spillway gate is typically created, in which all members are modeled and evaluated. The key parameter to evaluate in the gate arms is the combined stress ratio, which is a parameter that reflects the combined axial and bending stresses in steel members. If the combined stress ratio is high in a gate arm, there is the potential for buckling of that arm. If a gate analysis is being performed, the trunnion pin friction coefficient should be varied to evaluate the sensitivity of this parameter. Methods may be employed to estimate the current trunnion pin friction coefficient for spillway radial gates. One approach that has been used is to measure deflections of spillway radial gate arms as the gate is being opened. Given a known reservoir load, a finite element model of the gate can be used to back-calculate the trunnion pin friction needed to match the measured deflections. It should be noted that radial gates typically include bracing to reduce the unsupported length (and hence buckling potential) of the gate arms. The finite element analysis may indicate that a bracing member is the critically stressed component, and a judgment will be needed as to the likelihood that the bracing would fail, perhaps leading to a greater unsupported length and combined stress ratio for the gate arms.

Reservoir Load Ranges

Some thought needs to go into selecting reservoir ranges and the associated probabilities. One case would involve the threshold where the first gate operation would take place to release flood inflows, and the flood range probability would be associated with the flood frequency for this case up to the flood at which the next gate would be opened. A second gate discharge may be needed during a large flood, to prevent the reservoir water surface from rising and overtopping the dam. Then, similarly, as each additional gate is opened for flood operations, the flood range and associated probability associated with that level of flooding is included. Additional discussion of multiple gate failures during a flood is provided in the Consequences discussion that follows. If there is the possibility that testing of the gates could cause a gate failure, then the time of year the gates are typically tested is determined, and the likely reservoir ranges at the time of testing are used. If a spillway gate failed due to trunnion pin friction during testing, it is expected that additional gates would not be opened and that the failure would be limited to one gate. Historical reservoir elevation data can be used to generate the probability of the reservoir being within the chosen reservoir ranges, as described in the section on Reservoir Level Exceedance Curves.

Reduction Due to Regular Trunnion Pin Lubrication

A good trunnion pin/bushing design and regular lubrication of the trunnion pin will reduce trunnion pin friction. The reduction factors in Tables 30-1 and 30-2 relating to trunnion pin lubrication can be applied to the conditional failure probabilities of gate failure. It is recognized that a self-lubricating bushing is the most reliable design, followed by a plain bronze bushing and then a lubricated bushing. Graphite inserts have been found to be the least desirable design due to their vulnerability to corrosion. If there are other conditions which would compromise the effectiveness of lubrication (such as a lack of or ineffective seals for the pin/bushing), no reduction factor should be applied and a factor of 1.0 should be used.

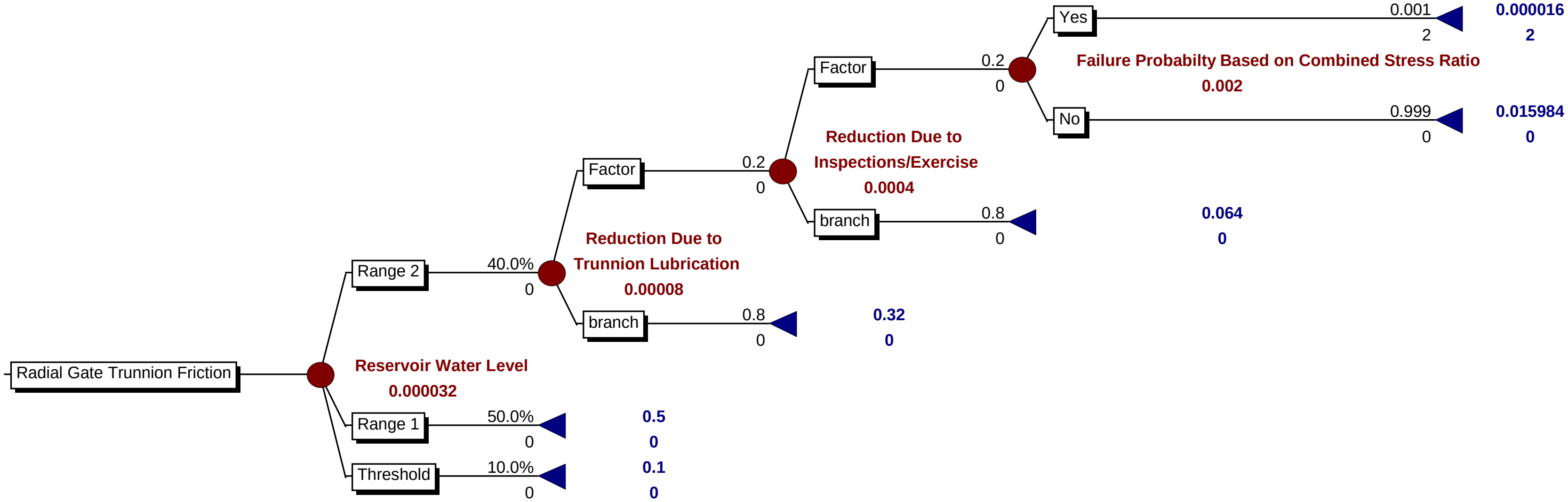

Figure 30-3 – Example Event Tree

Table 30-1 - Reduction Factors Due to Trunnion Lubrication w/o Detailed Analyses

Combined Stress Ratio	Pin/Bushing Arrangement								
	Pin Passing Through Steel Plate w/o Bushing		Plain Bronze Bushing		Lubricated Bushing[1]		Graphite Insert	Self-Lubricating Bushing	
	Pin dia. < 15 in	Pin dia. ≥ 15 in	Pin dia. < 15 in	Pin dia. ≥ 15 in	Pin dia. < 15 in	Pin dia. ≥ 15 in	All Pin Dia.	Pin dia. < 15 in	Pin dia. ≥ 15 in
<1.0	0	0	0	0	0	0	1.0	0	0
1.0	0.1	0.2	0.2	0.3	0.2	0.3	1.0	0.1	0.2
1.3	0.2	0.3	0.3	0.4	0.3	0.4	1.0	0.2	0.3
1.4	0.3	0.4	0.4	0.6	0.4	0.6	1.0	0.3	0.4
1.6	0.6	0.8	0.8	0.9	0.8	0.9	1.0	0.6	0.8
> 1.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

[1] If SOP done not require lubrication of when gates are exercised, the factor becomes 1.0 for all combined stress ratio values.

Table 30-2 - Reduction Factors Due to Trunnion Lubrication w Detailed Analyses[1]

Combined Stress Ratio	Pin/Bushing Arrangement				
	Pin Passing Through Steel Plate w/o Bushing	Plain Bronze Bushing	Lubricated Bushing[2]	Graphite Insert[3]	Self-Lubricating Bushing
<1.0	0	0	0	0	0
1.0	0.1	0.1	0.1	0.1	0.1
1.3	0.2	0.2	0.2	0.2	0.2
1.4	0.3	0.3	0.3	0.3	0.3
1.6	0.6	0.6	0.6	0.6	0.6
> 1.6	1.0	1.0	1.0	1.0	1.0

[1] Detailed analysis consists of finite element model of gate, incorporating all key gate members. Trunnion pin friction coefficient of 0.3 or coefficient determined from recent field testing should be used.

[2] A constant factor of 1.0 for all Combined Stress Ratios should be used if SOP does not require lubrication of trunnion pin when gates are exercised.

3 These values may be used if the combined stress ratio is based on an analysis with a trunnion pin friction coefficient of 0.5 or twice the coefficient determined from field testing. Otherwise a constant factor of 1.0 should be used.

Reduction Due to Regular Gate Inspection and Regular Gate Exercising

The reduction factors in Table 30-3 relating to gate inspections and gate exercising can be applied to the conditional failure probabilities of gate failure, provided that any items identified by the inspections and exercising are promptly corrected:

Table 30-3 – Reduction Factor Due to Inspections/Exercise

Combined Stress Ratio	Gates Exercised Annually and Inspected at Least Every 3 yrs	Gates Exercised and Inspected Every 3 yrs	Gates Not Exercised and Inspected at Least Every 3 yrs
< 1.0	0	0	0
1.0	0.1	0.2	1.0
1.3	0.2	0.3	1.0
1.4	0.3	0.5	1.0
1.6	0.6	0.9	1.0
> 1.6	1.0	1.0	1.0

Conditional Failure Probabilities

The results of a finite element gate analysis can be used to estimate failure probabilities under a given set of loading conditions. The response curve in Table 30-1 (taken from the section on Seismic Failure of Spillway Radial Gates) relates the combined stress ratio to the probability of a buckling failure, based largely on the judgments of those familiar with the AISC structural steel "code" and the safety factors implicit in that code. The safety factors have been accounted for in the response curve and should not be removed when calculating combined stress ratios. For seismic conditions (a transient load similar to trunnion friction), the AISC code allows a combined stress ratio of 1.3. Because this is a code design, which incorporates a number of safety factors, the probability of failure is estimated to be very low, or about 0.001 for this condition. When the combined stress ratio reaches about 1.8, the steel gate arms should be close to their ultimate buckling capacity. For this reason this combined stress level was assigned a failure probability of 0.9.

Table 30-4 - Gate Failure Response Curve

Combined Stress Ratio	Probability of Failure (1 gate)
< 1.0	0
1.0 to 1.3	0.0001 to 0.001
1.3 to 1.4	0.001 to 0.01
1.4 to 1.6	0.01 to 0.3
1.6 to 1.8	0.3 to 0.9
1.8 to 2.0	0.9 to 0.99
2.0 to 2.2	0.99 to 0.999
> 2.2	0.999

With the response curve as a guide, estimates can be made for the probability of a single gate failing under the conditions analyzed. These estimates are made based on the highest combined stress ratio for the gate arms from the structural analyses.

Consequences

Consequences are a function of the reservoir level at the time of failure (which determines the breach outflow). Loss of life can be estimated from these breach flows (typically resulting from the failure of one spillway gate) and the estimated population at risk that would be exposed to the breach outflows using the procedures outlined in the section on Consequences of Dam Failure.

When spillway gates are operated, they typically are opened slowly to ramp up the flows. Failure of a spillway gate due to trunnion friction would likely result in a sudden large increase in spillway flows. While the flows may be within the "safe channel capacity," they may be large enough to endanger recreationists, especially during sunny day testing of the gates.

If a spillway with multiple gates is being operated during flood conditions and the spillway capacity provided by more than one gate is needed to pass the flood, it may be possible that multiple gates would fail due to trunnion pin friction. The scenario would be that one spillway gate is initially opened to pass flood inflows and the gate fails suddenly due to trunnion pin friction. The increased discharge through the failed gate bay would likely be enough to match incoming flows for a while. At some point, the inflows would increase to the level that discharge from a second spillway gate would be needed to prevent the reservoir from rising to the level that dam overtopping would be possible. The decision would likely be made to open the second gate, recognizing that it too may fail due to trunnion pin friction. Mitigating this situation is the likelihood that the initial gate failure would evacuate the channel of the recreation populations and the fact that there would some delay in between the first gate failure and the time when a second gate would need to be opened. This would allow for downstream warning and evacuation. If conditions are such that incremental loss of life would occur with successive failure of spillway gates, and if the probability of a flood that would require more spillway capacity than that provided by a single gate is large enough, this scenario may need to be considered.

Accounting for Uncertainty

Typically, the reservoir elevation exceedance probabilities are taken directly from the historical reservoir operations data, directly, which do not account for uncertainty. Uncertainty in the failure probability and consequences are accounted for by entering the estimates as distributions (as describe above) rather than single point values. A "Monte-Carlo" simulation is then run to display the uncertainty in the estimates, as described in the section on Combining and Portraying Risks.

Relevant Case Histories

Folsom Dam is located on the Sacramento River, about 20 miles northeast of Sacramento, California and was completed in 1953. The dam consists of a concrete gravity section across the river channel with a structural height of 340 feet, flanked by long earthfill wing dams. The concrete dam has a gated overflow spillway section that is regulated by eight tainter (radial) gates: five service gates that are 42 feet wide and 50-feet high and three emergency gates that are 42 feet wide and 53-feet high. The trunnion anchorage for the spillway gates consists of three steel plates (2-inch by 29-inch plates, 60 feet long, which are welded together) covered in cork to prevent bonding to the concrete. The end anchorage for the steel plates consists of a bearing plate that is located in the mass concrete of the spillway crest concrete, below the bottom elevation of the piers.

Spillway gate No. 3 failed during a morning operation with a nearly full reservoir at about 8:00 am on July 17, 1995. Gate No. 3 was being opened to maintain flow in the river during a powerplant shutdown. As the gate was opened, it was allowed to stop at 6 inches automatically and again at 1 foot. The auto-stop function was overridden (normal procedure) with no stop being made at the 2-foot level. As the gate opening approached 2.4 feet, the gate operator felt an "unusual vibration" and he stopped the gate hoist motor. As the operator turned to check the gate, he saw the right side of the gate swing open slowly, like a door hinged on the left side and saw water pouring around both sides of the gate leaf. The time from the operator's initial awareness of the vibration to observing gate displacement and uncontrolled flow of water was estimated to be no more than 5 seconds. The failed gate released a peak flow of about 40,000 ft^3/s. The rated downstream safe channel capacity was 115,000 ft^3/s. No injuries or fatalities occurred as a result of the failure. Nimbus Dam, the afterbay dam for Folsom immediately downstream, did not overtop due to the prompt action of the dam operator at Folsom Dam. He immediately identified dispatch about the gate failure then drove 7 miles to Nimbus Dam and opened the gates there.

The gate failure started at the diagonal strut brace nearest the trunnion (see Figure 30-4) when the upper connection's four bolts sheared. The diagonal brace connected the bottom two struts and bracing was provided to reduce the effective column lengths and prevent column buckling of the struts. Once the original diagonal brace failed, load was transferred to the adjacent brace connections, which failed in turn. Immediately following the strut brace connection failures, the right side struts buckled downward.

More than 30 different types of tests, examinations and analyses were performed to assist a Forensic Team in determining the cause of gate failure. The cause of the failure was determined to be trunnion pin friction. The Folsom tainter gates were not designed for any trunnion friction, which was consistent with the engineering practice at the time. The gates had only a marginal factor of safety when they were installed. One unique feature of the trunnion pins at Folsom Dam was there large diameter (32-inch) which added significantly to the load imparted to the gate due to trunnion friction, since there was more area and a greater chance for higher friction coefficients. A reduced frequency of lubrication and lack of weather protection (at both ends of the trunnion pin, where gaps between the trunnion hub and the bearing housing allowed rainwater, spray and water vapor to enter) increased the rate of corrosion over the years.

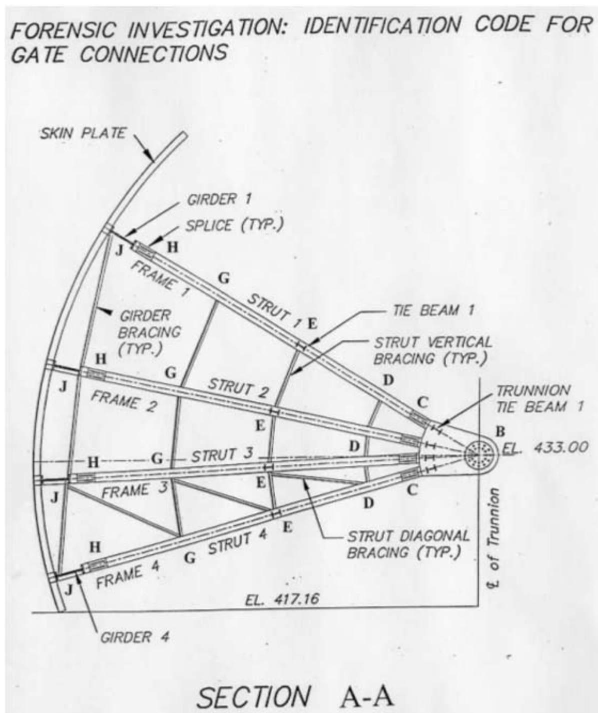

Figure 30-4 – Folsom Radial Gate Arms (Struts)

Exercise

Consider a spillway with two radial gates, each 34.5 feet high by 51 feet wide. Trunnion pins for the gates are 12-inches in diameter. The reservoir is at the top of the gates at least two months of every year. Finite element analyses of the gates have been performed with the reservoir at the top of the gates and assuming a trunnion friction coefficient of 0.3. The critical combined stress ratio for this condition is 1.3. The trunnion pins have a self-lubricating bushing and the gates are exercised annually and thoroughly inspected every three years. Estimate the expected value annual failure probability for gate failure due to trunnion pin friction, during the annual exercising of the gates.

References

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Bureau of Reclamation, "Forensic Report on Spillway Gate 3 Failure, Folsom Dam," Technical Service Center, Denver, Colorado, November 18, 1996.