# Best Practices in Dam and Levee Safety Risk Analysis

## VII-1, VII-2 and VII-3

## Spillway Gates

11 June 2015

U.S. DEPARTMENT OF THE INTERIOR
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# Spillway Gates

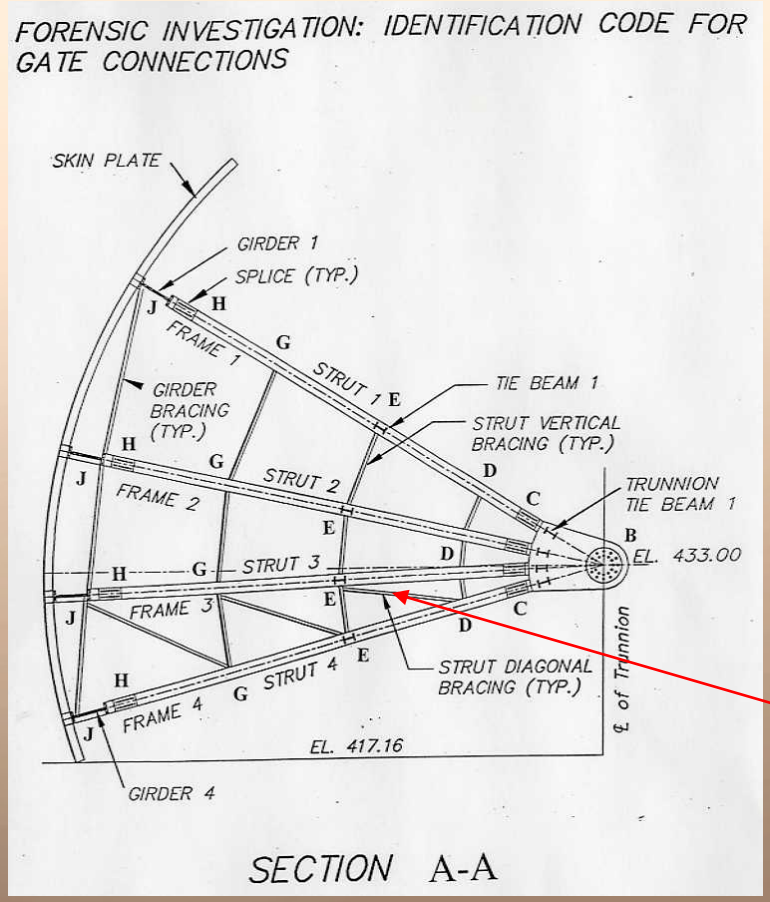
- There are several different types of spillway gates
- Radial/tainter gates are the most common and are vulnerable to trunnion pin friction causing gate overstresses and to seismic loading
- Drum gates are vulnerable to inadvertent lowering
- Slide or fixed wheel gates are generally not an issue but hoist house and counterweights could be an issue under seismic loading

# Folsom Gate

# Folsom Dam Gate Failure

- Spillway has eight tainter gates
  - Five service gates
  - Three emergency gates
- Gate No. 3 failed suddenly on 7/17/95 with reservoir full
- Uncontrolled release peak – 40,000 $ft^3/s$
- Failure started at lower strut brace, proceeded to adjacent braces and then arms buckled

# Folsom Dam Tainter Gate




Initial Failure

# Gate No. 3, Struts 3 and 4

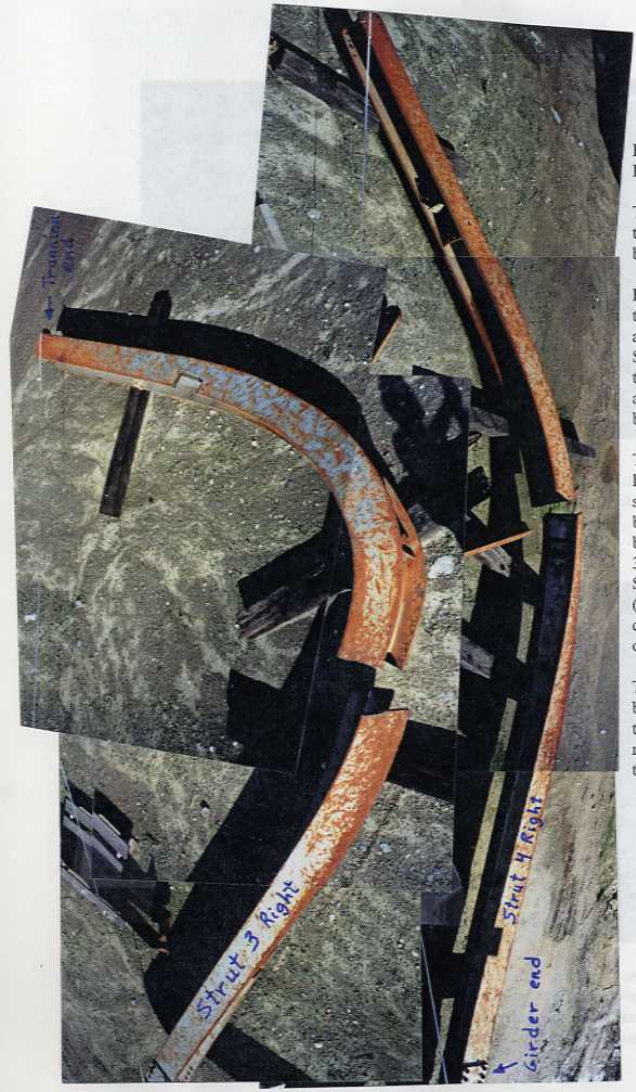





Photo 9. Struts 3 and 4 Right, Outside.

Trunnion end is at the top, girder end is at the bottom of the page.

Photo montage showing that Strut 3 was bent into a sharper radius than Strut 4. This indicates that Strut 4 broke loose at one end before Strut 3 broke loose at either end.

The total centerline length of each of the two struts is 35'-10 1/8". The bowstring length between the ends of Strut 3 is now 24'-8" and of Strut 4 is now 32'-10" (after subtracting the gap distances between halves of each strut as they lay).

The notches cut out of both struts were pieces taken after the failure for mechanical properties testing.

1/17/96

# Folsom Dam Gate Failure

- Cause of failure was determined to be trunnion pin friction
- Folsom tainter gates were not designed for any trunnion friction
- Large diameter pin – 32 inches
- Reduced frequency of lubrication and lack of weather protection at ends of trunnion pin resulted in corrosion and increased friction over time

# Failure of Radial/Tainter Spillway Gates Key Concepts and Factors

- Load Carrying Mechanism
- Trunnion Pins and Trunnion Anchors
- Size of Radial Gates
- Reservoir Water Level
- Hydrodynamic Loads
- Seismic Hazard
- Mechanics of Pin Friction
- Interaction Ratio
- Number of Gates
- Maintenance of Spillway Gates
- Hoist Ropes and Chains/Gate Binding

# Load Carrying Mechanism

- Spillway Radial Gates (Tainter Gates) transfer reservoir load to trunnion pin through compression of relatively slender gate arms
- Concern is buckling of gate arms during seismic loading
- Failure can be sudden

# Trunnion Pins and Trunnion Anchors – Structural Failure

- These features need to be evaluated, but are typically not the weak links
- Seismic failure typically assumed with gates in closed position (pin friction not an issue)
- Trunnion anchorage typically carries load in tension

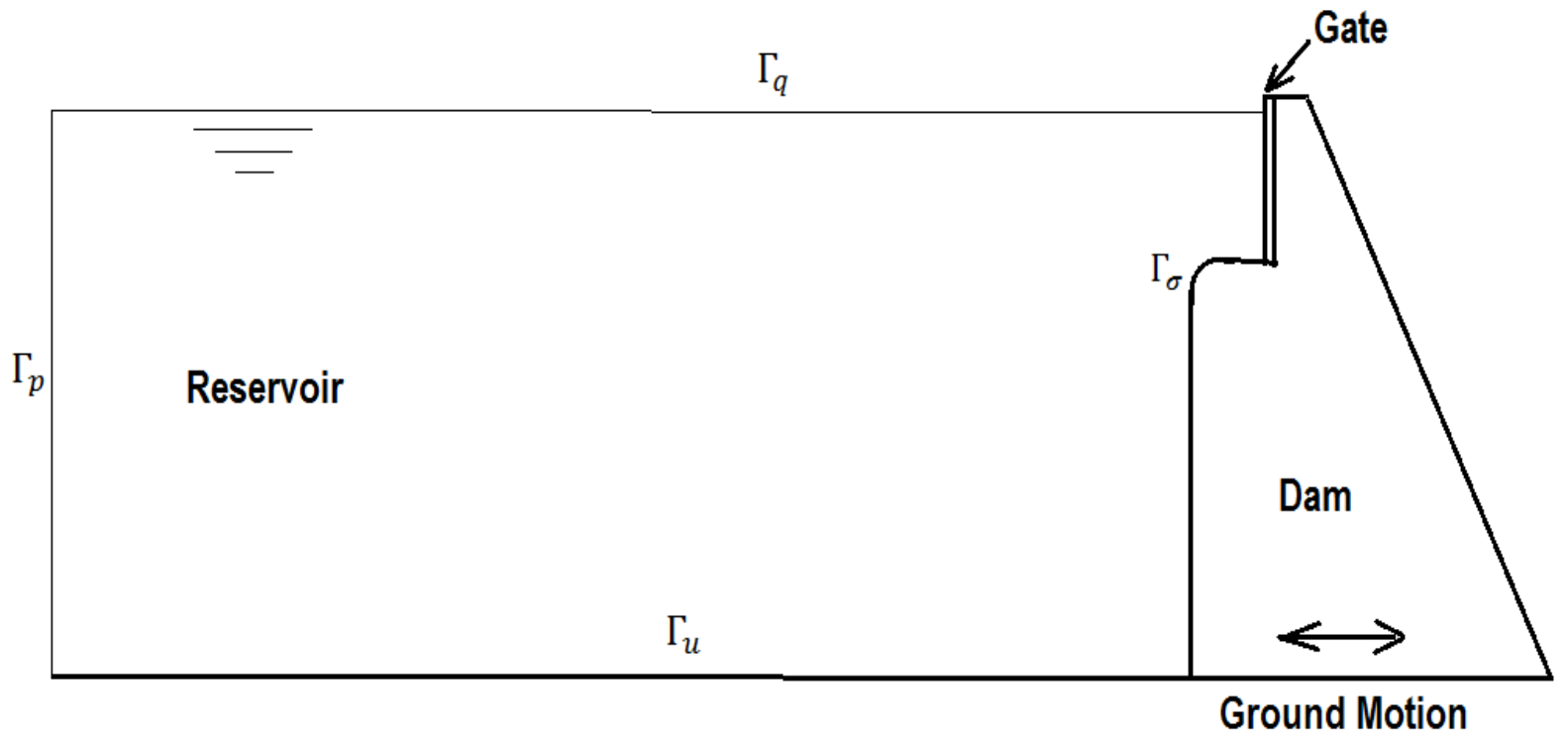
# Size of Radial Gates

- Spillway radial gates exist in a variety of sizes, with gates up to 50-feet in width common
- Failure of one or more spillway gates could exceed the downstream safe channel capacity or impact recreationalists downstream

# Reservoir Water Level

- The reservoir water level on spillway gates is a key parameter
- The water level affects the loading on the gates
- The water level will determine the uncontrolled release if one or more gates fail
- Likelihood of various reservoir levels can typically be estimated from historical reservoir exceedance curves
- Gate loads drop significantly with reduction in head on gate; varies with $h^2$

# Hydrodynamic Loads



# Seismic Hazard

- Most radial gates have reserve capacity beyond the stress levels created by full reservoir loads
- The level of seismic loading in combination with the reservoir level at the time of an earthquake will determine if the gate arms are overstressed and if so to what level

# Mechanics of Pin Friction

- Pin friction is usually at its peak when gate is loaded under full reservoir and gate is initially opened
- When spillway radial gate opened, friction at the trunnion pin is transferred as bending moment into the gate arms
- If trunnion lubrication is not provided or if moisture can access the trunnion pin, corrosion can occur and increase friction over time
- Typical trunnion pin friction values provided in Tables VII-1-1 (as designed) and VII-1-2 (failed bushing)
- Larger diameter trunnion pins will result in more load being transferred to gate arms

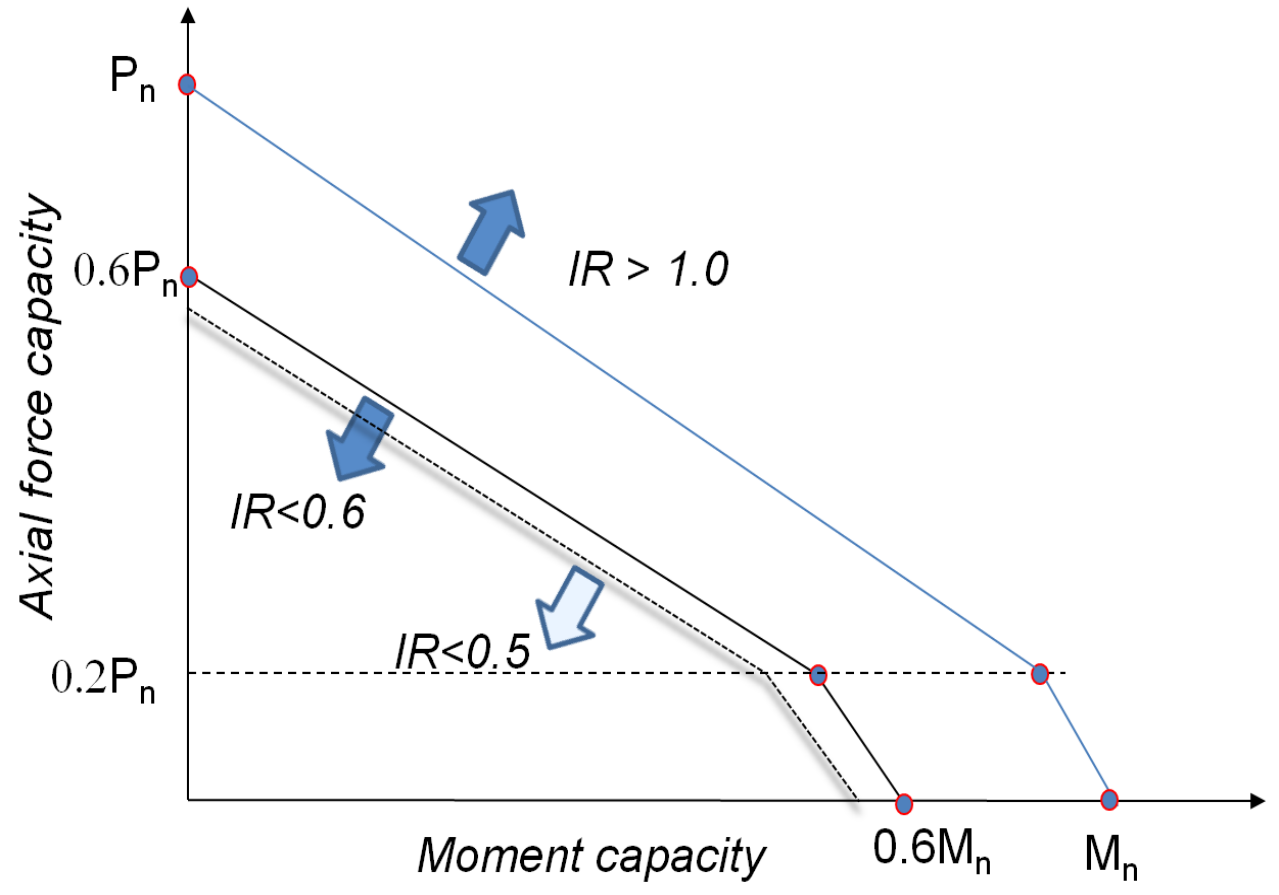
# Interaction Ratio (Eq. VII-1-1)

$$IR = \frac{P_u}{P_n} + \frac{8}{9}\left(\frac{M_{ux}}{M_{nx}} + \frac{M_{uy}}{M_{ny}}\right) \qquad for\ \frac{P_u}{P_n} \geq 0.2$$

$$IR = \frac{P_u}{2P_n} + \left(\frac{M_{ux}}{M_{nx}} + \frac{M_{uy}}{M_{ny}}\right) \qquad for\ \frac{P_u}{P_n} < 0.2$$

$P_u$ – required axial strength
$P_n$ – the available axial strength equals the nominal compressive strength
$M_u$ – required flexural strength
$M_n$ – the available flexural strength equals the nominal flexural strength

# Interaction Ratios for Radial Gates



# Number of Gates

- Multiple spillway gates on a given project will typically increase the probability of gate failure under seismic loading, with a variety of possible outcomes
- Multiple spillway gate failures also create the potential for a large breach outflow and the potential for higher loss of life
- For spillway with multiple gates under normal operations, failure is most likely to be limited to one gate – especially if failure occurs during routine exercising of gates

# Maintenance of Spillway Gates

- Gates that are well maintained can usually be relied upon to have their original design capacity at the time of an earthquake
- If the 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

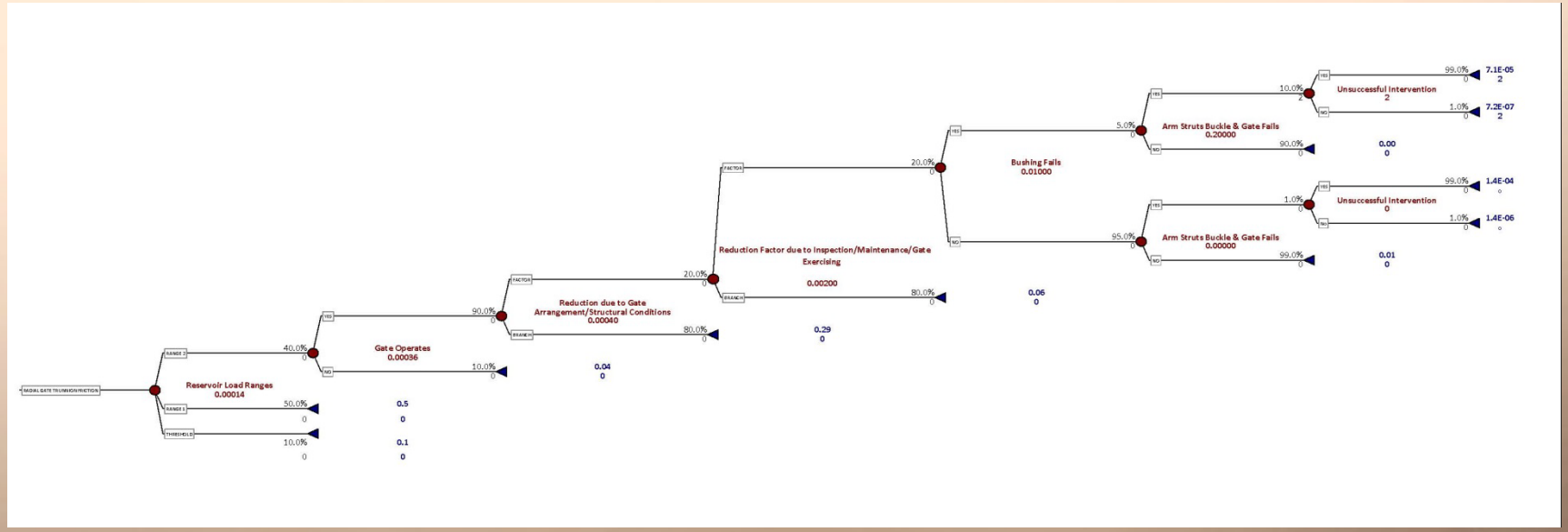
# Hoist Ropes and Chains
# Gate Binding

- Other mechanisms can lead to inoperable spillway gates
- Mechanisms may not lead to gate failure and uncontrolled release but could lead to reduced spillway capacity that could contribute to dam overtopping or other failure modes
- If gates are well maintained and exercised regularly chance of inoperable gate is reduced
- Inspections should focus on wear or corrosion of wire ropes and chains and their connections to gates/hoists as well as plumbness of walls/piers
- Exercising gate will verify gate can travel freely in opening

# Trunnion Friction Radial Gate Failure

- For most radial gates, trunnion pin friction has not been found to be a problem for gate overloading
- Pin frictional movement typically accounted for in gate design
- Pin friction typically represents a relatively small and manageable load
- Larger, older designed radial gates with deficient pin design and lack of hub stiffening and/or arm bracing may be vulnerable

# Example Event Tree
# Normal Operational Conditions
# (Figure VII-1-10)



# Structural Analysis

- Finite element model of gate is typically created and can evaluate stresses in all gate members
- Interaction ratio is critical parameter to evaluate – reflects buckling potential
- Trunnion pin friction can be varied in sensitivity studies; event tree considers as designed and failed bushing

# Interaction Ratio (Eq. VII-1-1)

$$IR = \frac{P_u}{P_n} + \frac{8}{9}\left(\frac{M_{ux}}{M_{nx}} + \frac{M_{uy}}{M_{ny}}\right) \qquad for\ \frac{P_u}{P_n} \geq 0.2$$

$$IR = \frac{P_u}{2P_n} + \left(\frac{M_{ux}}{M_{nx}} + \frac{M_{uy}}{M_{ny}}\right) \qquad for\ \frac{P_u}{P_n} < 0.2$$

$P_u$ – required axial strength
$P_n$ – the available axial strength equals the nominal compressive strength
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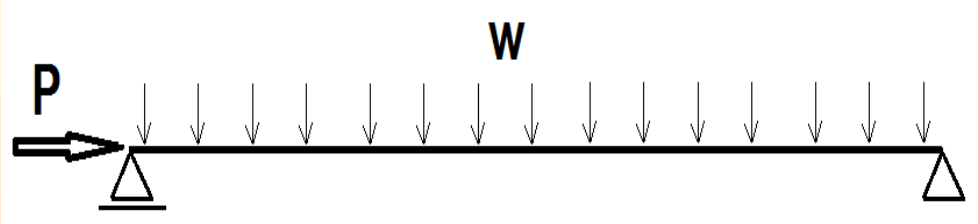
# Second-order effects




Results of second-order (S-O) analysis for a 28-ft long horizontal W14x48 arm strut bent about the weak axis considering self-weight of the member.

| Second-order (S-O) | Axial Force, P[kips] | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 30 | 60 | 90 | 101 | 105 |
| Moment [kip-in] | 55.5 | 72.5 | 105 | 182 | 252 | 293 |
| Max. deflection [in] | 0.44 | 0.57 | 0.81 | 1.45 | 1.99 | 2.31 |
| IR (Eq.VII-1-1) with S-O effect | 0.05 | 0.30 | 0.56 | 0.86 | 1.00 | 1.07 |
| IR (Eq.VII-1-1) without S-O effect | 0.05 | 0.28 | 0.51 | 0.74 | 0.83 | 0.86 |

# Gate Failure Response 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 |

| Table VII-1-6 Reduction Factor Considerations Related to Gate Arrangement/Condition | |
|---|---|
| **Condition** | **Considerations** |
| Age of Gate and Frequency of Gate Operations | Older gates (more than 50 years old) will be more vulnerable to failure given:<br>• fatigue in the gate structure members during operational life of the structure and<br>• potential for increased trunnion pin friction over time. |
| Complexity of the Gate Arm Frame Assembly | Gates with more members may be more vulnerable to failure due to an increased number of connections and the increased potential for one or more of the critical members to have defects which could lead to the failure of the whole gate structure. |
| Fracture Critical Members | Fracture critical members are defined as members whose failure would lead to a catastrophic failure of the gate. Gates with multiple fracture critical members are more vulnerable to catastrophic failure. |
| Fatigue of the Gate Members | Cyclic loading of the gates members may lead to fatigue of the fracture critical members or their connections during operational life of the gate. Gates with multiple fracture critical members and with longer operational life and higher operational frequency, or that have a history of vibration during operation are more vulnerable to failure of their members. |
| Welded Connections | Welded connections can be more vulnerable to undetected cracking, during operational life of the gate. |
| Age of Coatings | Coatings that are older are more likely to have localized failures that could lead to corrosion and loss of material. |

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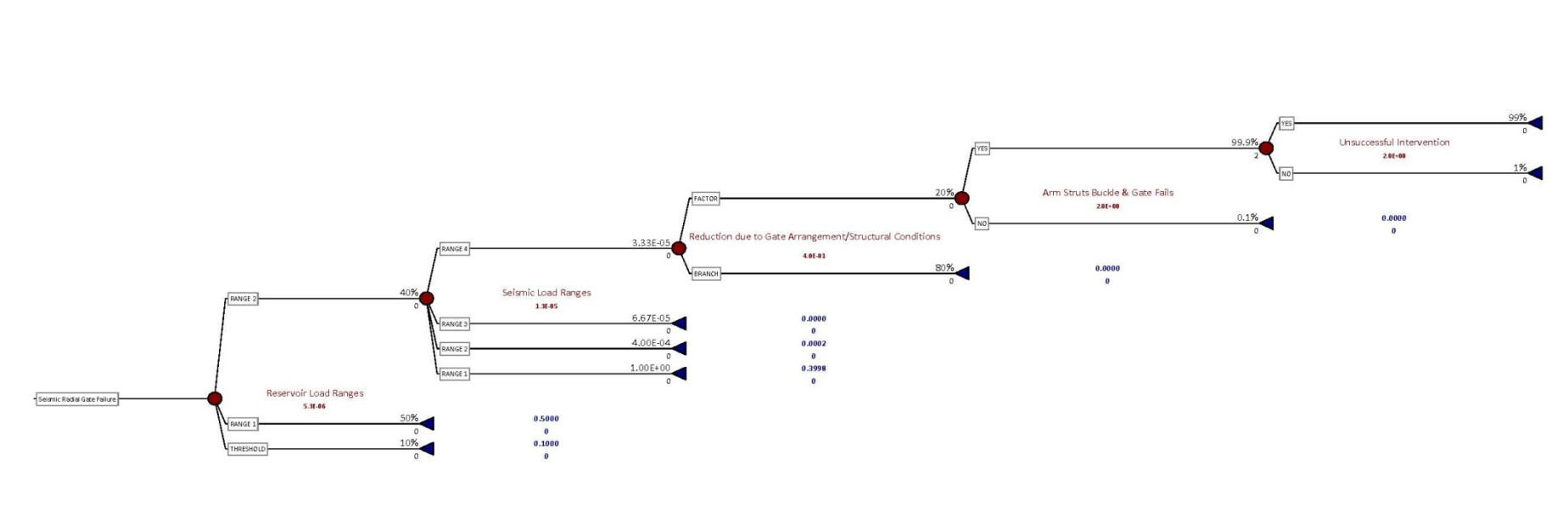
# Reduction Factor due to Gate Inspections/Maintenance/Exercising

- Reduction factor of between 0.1 and 1.0 should be selected by the risk team
- Ideally gates should be exercised annually and thoroughly inspected every three years. If this is the case, and no adverse conditions are found, the team should consider a value of 0.1
- If the gates are not exercised (either as a matter of O&M practice or as part of flood operations) or inspected, a value of 1.0 should be considered.

# Base Failure Rate

- Reclamation has 314 spillway radial gates
- About 20,000 gate years of operation (as of 2015)
- Folsom radial gate failure in 1995 is the only failure that has occurred
- Base failure rate = 5 E-05
- Event tree results are generally consistent with rate
- For IR between 0.6 and 0.7, a small chance of a failed bushing and reduction factors both estimated at 0.3, annualized failure probability can be as high as 9 E-05 to 9 E-04
- For IR < 0.6, annualized failure probability less than 1 E-05 and may be less than 1 E-06

# Event Tree – Seismic Radial/Tainter Gate (Figure VII-3-2)



# Reservoir Load Ranges

- Typically chosen to represent a reasonable breakdown of larger reservoir range from normal reservoir water surface (near the top of the gate) and an elevation in the lower half of the gate, in which stresses are not a concern
- Usually 3 to 4 ranges, with 5 to 10 foot increments
- Select load range boundaries where there is a change in response
- Historical reservoir elevations used to generate probabilities for ranges

# Seismic Load Ranges

- Typically chosen to provide a reasonable breakdown of the maximum earthquake loads from the max seismic load analyzed to a threshold earthquake load (0.1 to 0.3g)
- Typically results in 4 to 6 seismic load ranges
- Select load range boundaries where there is a change in response
- Probabilities for seismic load ranges determined from seismic hazard curves

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# Conditional Failure Probabilities

- Given the seismic and reservoir loading, conditional failure probabilities are determined
- Gate arms are usually the most critical members and failure would be initiated by buckling of arms
- Interaction ratio considers the axial and bending stresses and is used to evaluate buckling potential
- Bracing of gate arms reduces the unsupported length of gate arms

# Interaction Ratio (Eq. VII-1-1)

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| 0.9 to 1.0 | 0.9 to 0.99 |
| > 1.0 | 0.9 to 0.999 |

# Single Gate Failure Probability

| Res. El. | Acceleration at Trunnion Pin | | | |
|---|---|---|---|---|
| | 0.25g | 0.5g | 1.0g | 2.0g |
| 466 | 4590<br><br>0.005 | 5650<br><br>0.05 | 8300<br>0.95<br>0.95 | 13800<br>1.4<br>0.999 |
| 458 | 3320<br><br>- | 4200<br><br>0.001 | 6400<br>0.81<br>0.20 | 10200<br>1.1<br>0.999 |
| 450 | 2054<br><br>- | 2530<br><br>- | 3720<br>0.6<br>.001 | 6100<br>0.9<br>0.9 |
| 434 | 600<br><br>- | 760<br><br>- | 1200<br><br>- | 2000<br><br>.001 |

Gate load in kips
Combined stress ratio
Estimated failure probability of single gate

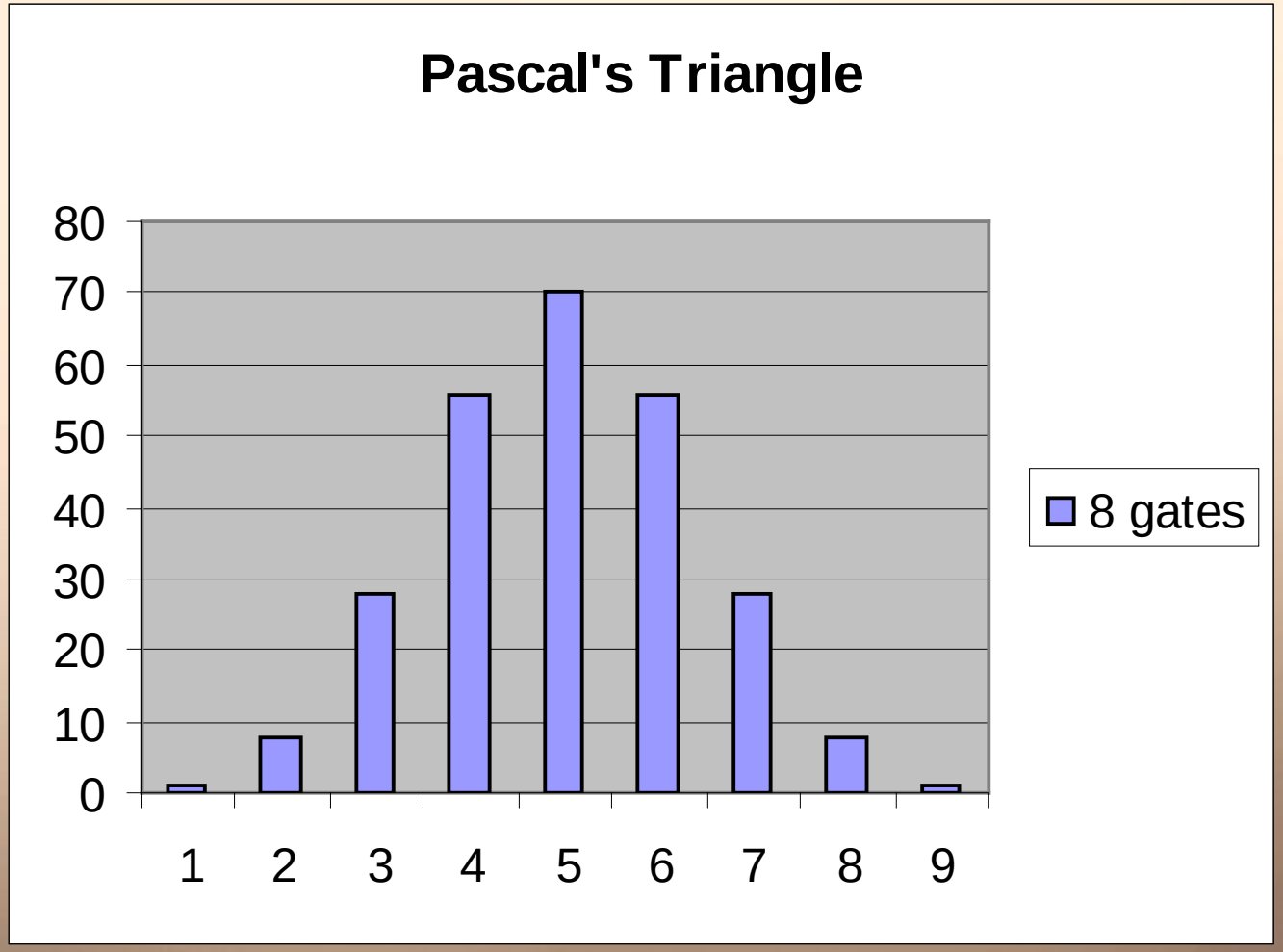
# Pascal's Triangle

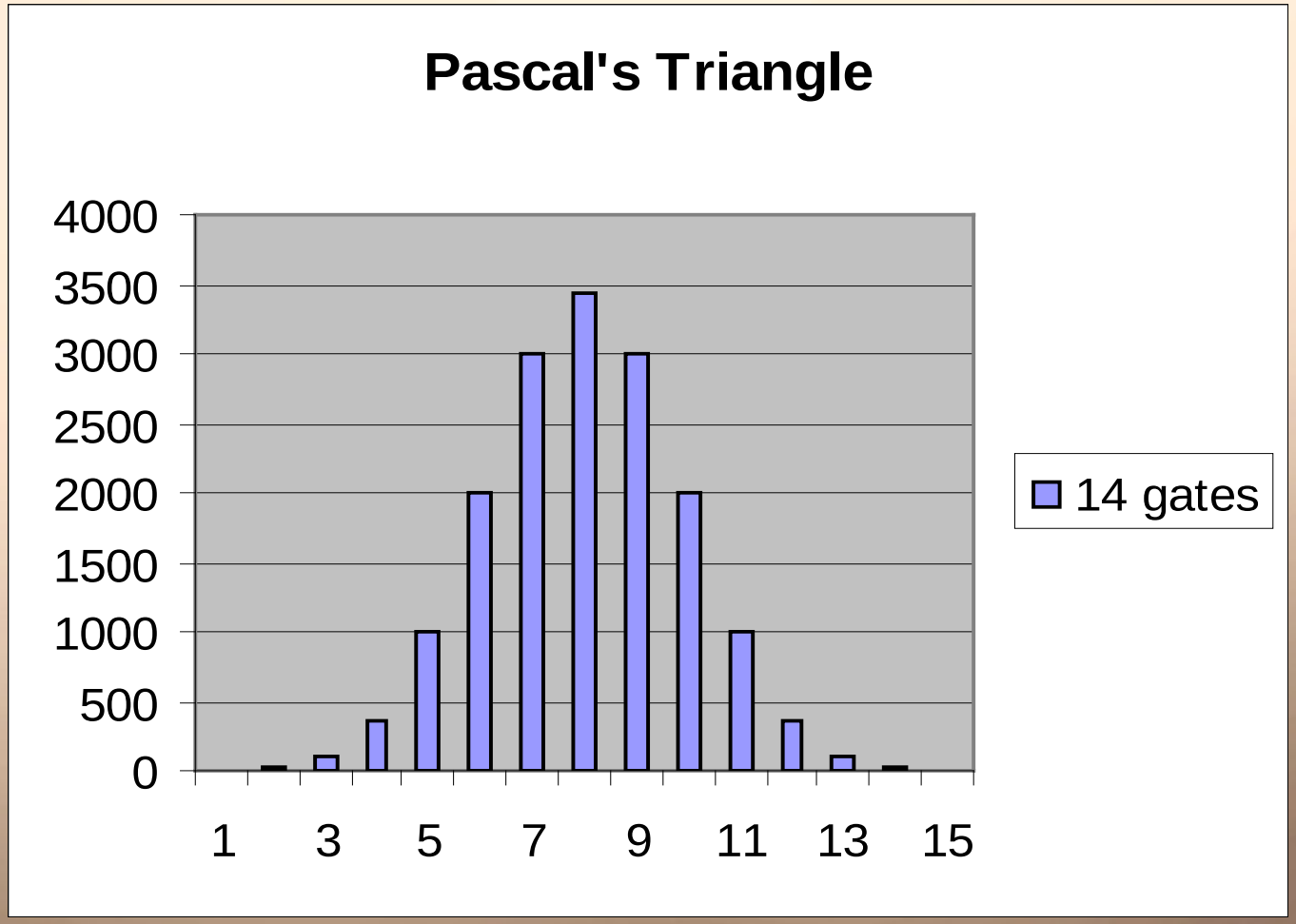
- If a spillway has eight gates and a failure of one or more gates occurs there are 255 possible combinations
- Pascal's Triangle identifies the combinations for each outcome (1 gate failing, 2 gates failing, etc.)
- The coefficients can be used to calculate the probability of each outcome, assuming the gates are independent
- $P_2 = 28(P)^2(1-P)^6$

# Pascal's Triangle

| Number of Gates | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | |
| 1 | | | | | | | | | | | | | | 1 | | 1 | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | 1 | | 2 | | 1 | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | 1 | | 3 | | 3 | | 1 | | | | | | | | | | | |
| 4 | | | | | | | | | | | 1 | | 4 | | 6 | | 4 | | 1 | | | | | | | | | | |
| 5 | | | | | | | | | | 1 | | 5 | | 10 | | 10 | | 5 | | 1 | | | | | | | | | |
| 6 | | | | | | | | | 1 | | 6 | | 15 | | 20 | | 15 | | 6 | | 1 | | | | | | | | |
| 7 | | | | | | | | 1 | | 7 | | 21 | | 35 | | 35 | | 21 | | 7 | | 1 | | | | | | | |
| 8 | | | | | | | 1 | | 8 | | 28 | | 56 | | 70 | | 56 | | 28 | | 8 | | 1 | | | | | | |
| 9 | | | | | | 1 | | 9 | | 36 | | 84 | | 126 | | 126 | | 84 | | 36 | | 9 | | 1 | | | | | |
| 10 | | | | | 1 | | 10 | | 45 | | 120 | | 210 | | 252 | | 210 | | 120 | | 45 | | 10 | | 1 | | | | |
| 11 | | | | 1 | | 11 | | 55 | | 165 | | 330 | | 462 | | 462 | | 330 | | 165 | | 55 | | 11 | | 1 | | | |
| 12 | | | 1 | | 12 | | 66 | | 220 | | 495 | | 792 | | 924 | | 792 | | 495 | | 220 | | 66 | | 12 | | 1 | | |
| 13 | | 1 | | 13 | | 78 | | 286 | | 715 | | 1287 | | 1716 | | 1716 | | 1287 | | 715 | | 286 | | 78 | | 13 | | 1 | |
| 14 | 1 | | 14 | | 91 | | 364 | | 1001 | | 2002 | | 3003 | | 3432 | | 3003 | | 2002 | | 1001 | | 364 | | 91 | | 14 | | 1 |

**Figure 4 - Pascals's Triangle for Muptiple Gate Failure Probability Coefficients**


Pascal's Triangle
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
8 gates


Pascal's Triangle
4000
3500
3000
2500
2000
1500
1000
500
0
1
3
5
7
9
11
13
15
14 gates

# Virginia Lottery - 1992

- Lottery involved picking 6 numbers from 1 to 44
- Pascal's Triangle indicates that there are 7,059,052 ways of choosing 6 numbers from a group of 44
- Lottery jackpot was $27 million
- Australian investors realized that if they bought all the possible combinations they would be guaranteed in winning at least a share of the jackpot
- In previous 170 times the lottery was held – no winner 120 times, 1 winner 40 times, 2 winners just 10 times

# Virginia Lottery - 1992

- Investors bought tickets at 125 retail outlets starting 72 hours before deadline
- At the deadline they purchased just 5 million out of the 7,059,052 tickets
- Despite this, the consortium won and was the only winner

from Mlodinow 2008

# Failure Probability Estimates

| Probability for Single Gate Failure → | | 0.001 | 0.05 | 0.16 | 0.94 |
|---|---|---|---|---|---|
| **No. of Gates Failing** | **Equation for "x" Gates Failing** | **Probability for "x" Gates Failing** | **Probability for "x" Gates Failing** | **Probability for "x" Gates Failing** | **Probability for "x" Gates Failing** |
| 0 | $1P^0(1-P)^8$ | 0.992 | 0.663 | 0.248 | 1.68E-10 |
| 1 | $8P^1(1-P)^7$ | 0.008 | 0.279 | 0.378 | 2.10E-08 |
| 2 | $28P^2(1-P)^6$ | 2.78-05 | 0.051 | 0.252 | 1.15E-06 |
| 3 | $56P^3(1-P)^5$ | 5.57E-08 | 0.005 | 0.096 | 3.62E-05 |
| 4 | $70P^4(1-P)^4$ | 6.97E-11 | 0.001 | 0.023 | 0.001 |
| 5 | $56P^5(1-P)^3$ | 5.58E-14 | 1.50E-05 | 0.003 | 0.009 |
| 6 | $28P^6(1-P)^2$ | 2.79E-17 | 3.95E-07 | 0.001 | 0.070 |
| 7 | $8P^7(1-P)^1$ | 7.99E-21 | 5.94E-09 | 1.80-05 | 0.311 |
| 8 | $1P^8(1-P)^1$ | 1.00E-24 | 3.91E-11 | 4.29E-07 | 0.610 |
| Total | | 0.008 | 0.337 | 0.752 | 1 |

# Consequences

- Consequences are a function of the number of gates that fail and the reservoir water surface at the time of failure
- For a failure probability estimate based on a single gate failure, there are a number of outcomes that can occur with multiple gates
- A weighted average loss of life estimate can be calculated

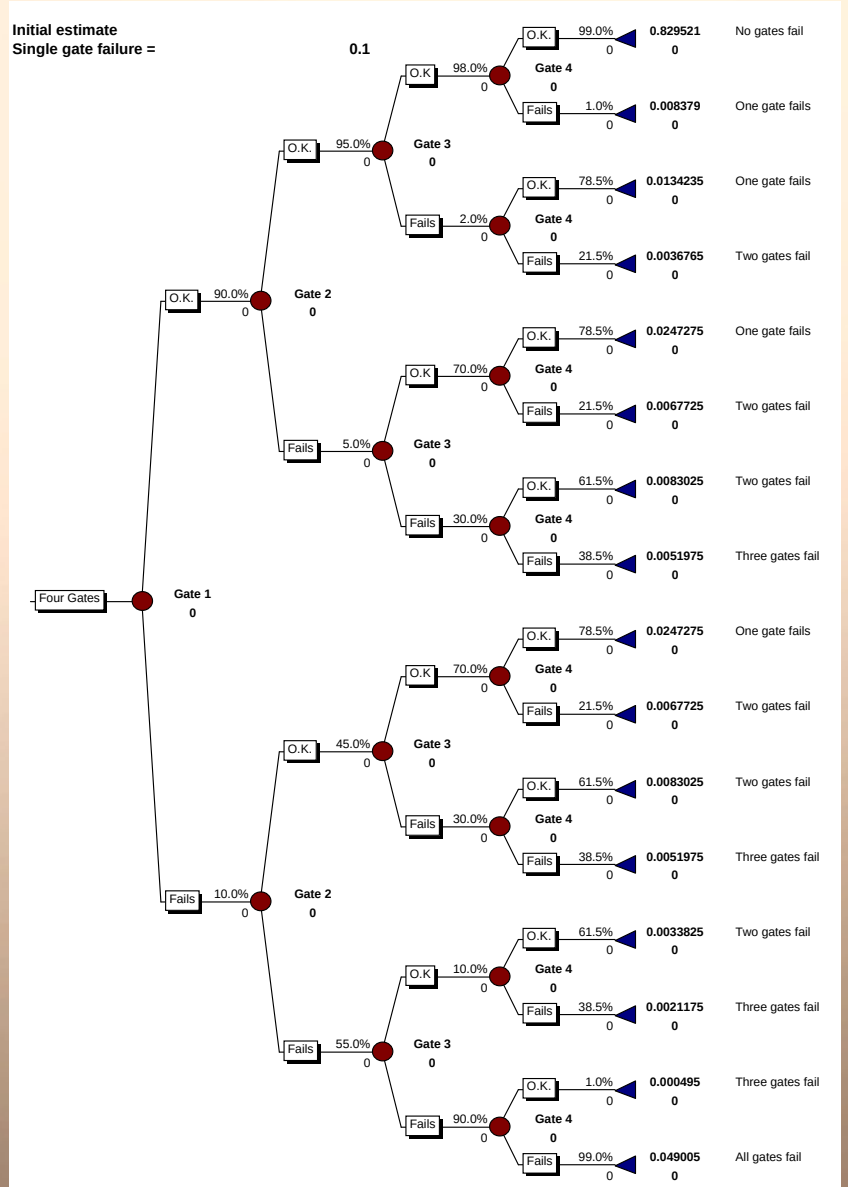
# Weighted Avg Loss of Life

| Number of Gates Failing | Probability of Failure Equations | Probability ($P_x$) of (x) Gates Failing | Expected Value Loss of Life | Loss of Life for (x) Gates Failing x ($P_x$) |
|---|---|---|---|---|
| 1 | $P_1 = 8(P)^1(1-P)^7$ | 0.378 | 8 | 3.022 |
| 2 | $P_2 = 28(P)^2(1-P)^6$ | 0.252 | 16 | 4.029 |
| 3 | $P_3 = 56(P)^3(1-P)^5$ | 0.096 | 23 | 2.206 |
| 4 | $P_4 = 70(P)^4(1-P)^4$ | 0.023 | 30 | 0.685 |
| 5 | $P_5 = 56(P)^5(1-P)^3$ | 0.003 | 147 | 0.512 |
| 6 | $P_6 = 28(P)^6(1-P)^2$ | 0.001 | 164 | 0.054 |
| 7 | $P_7 = 8(P)^7(1-P)^1$ | 1.80E-05 | 181 | 0.003 |
| 8 | $P_8 = 1(P)^8(1-P)^0$ | 4.29E-07 | 201 | 8.63E-05 |
| **Totals** | | **0.752** | **Weighted ave = 14 people** | **10.512** |

# Independence vs. Dependence

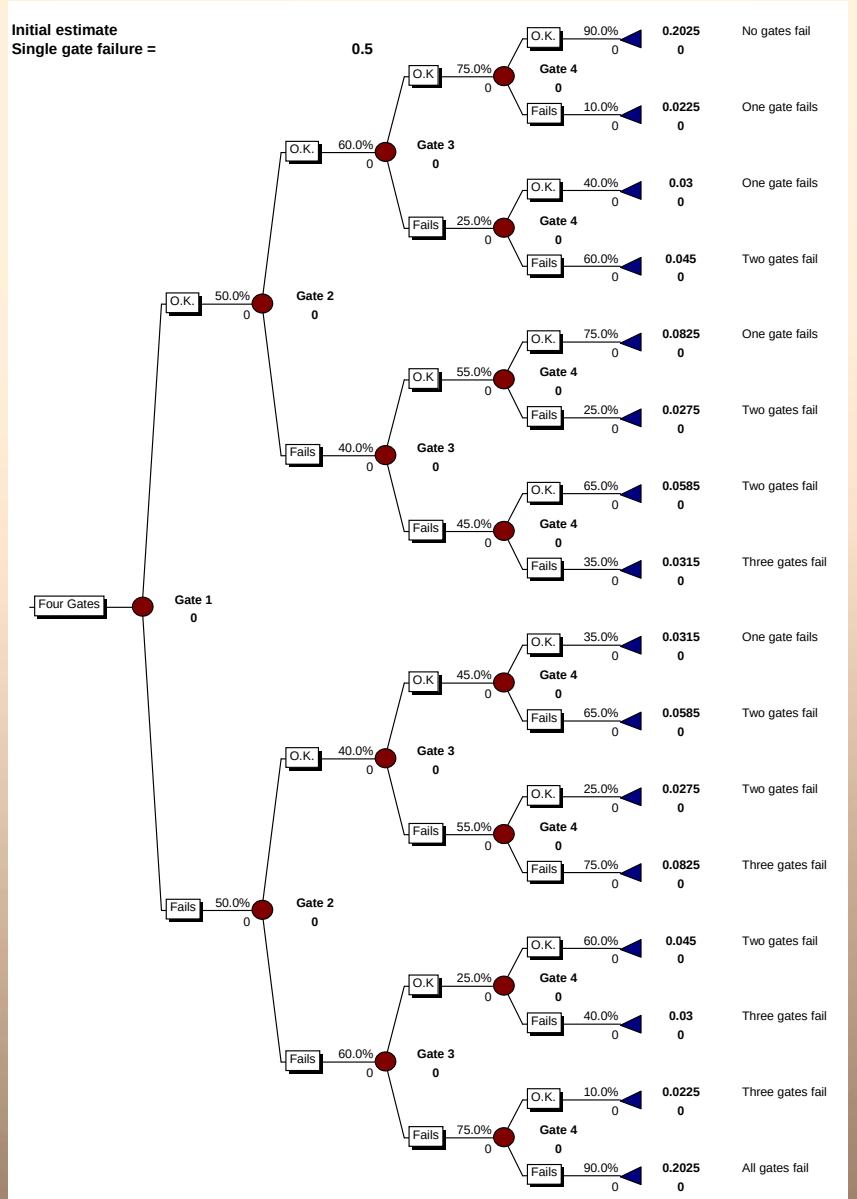
- The approach outlined assumes that the gates are independent of each other
- If one or more gate failures are considered, there is not a recognition that a failure or multiple failures may be symptomatic of a factor that would affect all the gates (the gate analysis was grossly in error; the steel properties of the gate arms were much different than what was assumed, etc.)
- Example is provided in Best Practices chapter on evaluating dependency of gates, using an “updating approach” – this issue should be given some thought and impacts evaluated
- Overall the results are believed to be reasonable

# Updating Event Tree for 4 Radial Gates, Initial P = 0.1




| Pascal's Triangle | | | Tree | |
|---|---|---|---|---|
| No gates fail | $1*P^0*(1-P)^4$ = | 0.6561 | No gates fail = | 0.8295 |
| One gate fails | $4*P^1*(1-P)^3$ = | 0.2916 | One gate fails = | 0.0713 |
| Two gates fail | $6*P^2*(1-P)^2$ = | 0.0486 | Two gates fail = | 0.0372 |
| Three gates fail | $4*P^3*(1-P)^1$ = | 0.0036 | Three gates fail = | 0.0130 |
| Four gates fail | $1*P^4*(1-P)^0$ = | 0.0001 | Four gates fail = | 0.0490 |
| One or more | | 0.3439 | One or more = | 0.1705 |

# Updating Event Tree for 4 Radial Gates, Initial P = 0.5




| Pascal's Triangle | | | Tree | |
|---|---|---|---|---|
| No gates fail | $1*P^0*(1-P)^4$ = | 0.0625 | No gates fail = | 0.2025 |
| One gate fails | $4*P^1*(1-P)^3$ = | 0.25 | One gate fails = | 0.1665 |
| Two gates fail | $6*P^2*(1-P)^2$ = | 0.375 | Two gates fail = | 0.2620 |
| Three gates fail | $4*P^3*(1-P)^1$ = | 0.25 | Three gates fail = | 0.1665 |
| Four gates fail | $1*P^4*(1-P)^0$ = | 0.0625 | Four gates fail = | 0.2025 |
| One or more | | 0.9375 | One or more = | 0.7975 |

# Conclusions

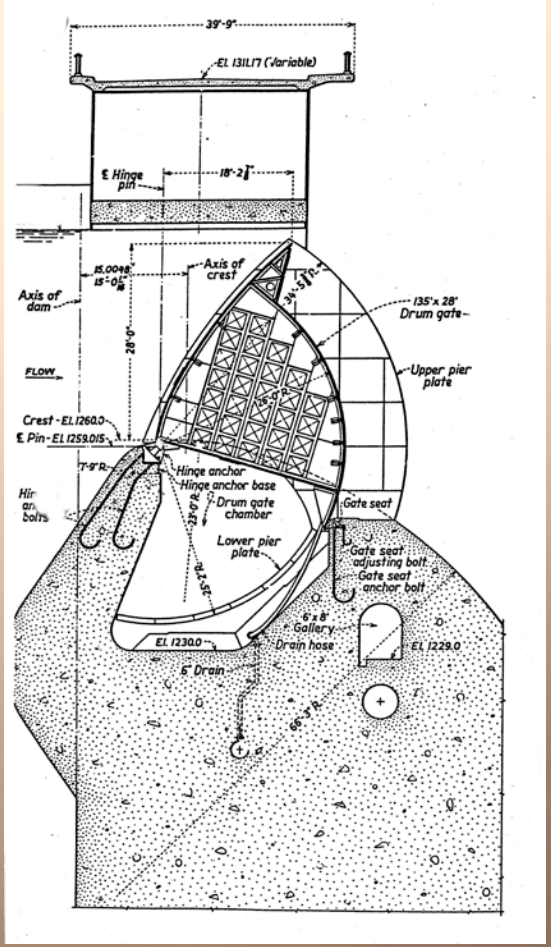
- Spillway gates may be significantly overstressed for large earthquake loads
- Gate failure can be sudden with little in the way of mitigating factors
- Probabilistic methods can be used to convert failure estimate for a single gate to the probability of multiple gate failure and loss of life from gate failure

# Key Concepts – Other Gate Failures

- Spillway Gate Failure could lead to incresed flow downstream and could lead to loss of life and economic impacts.
- Failure of gates in Navigation Locks and Dams could lead to a loss of service or loss of pool.
- For High Hazard Navigation Dams, failure of a gate could result in loss of life.

# 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

- Inadvertent 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 fragility)
- Drum gates have been filled with styrofoam to prevent inadvertent lowering, but this limits the ability to inspect and maintain

# Reclamation Experience

| Dam | Completion Year | Years of Service | No. of Gates | Gate-Years of Operation |
|---|---|---|---|---|
| Arrowrock | 1915 | 100 | 6 | 600 |
| Black Canyon | 1924 | 91 | 3 | 273 |
| Tieton | 1925 | 90 | 6 | 540 |
| Guernsey | 1927 | 88 | 2 | 176 |
| Easton | 1929 | 86 | 1 | 86 |
| Hoover | 1936 | 79 | 8 | 632 |
| Grand Coulee | 1942 | 73 | 11 | 803 |
| Friant* | 1944 | 71 | 3 | 213 |
| Shasta | 1945 | 70 | 3 | 210 |
| Total | | | | 3533 |

* Two drum gates replaced

# Two Reclamation Incidents

- Guernsey Dam (Wyoming)
  - 1986
  - Lowering of drum gate on South spillway
  - d/s flows within 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

# Black Canyon Diversion Dam

- Not counted as an incidents since discovered during routine exercising and inspection
- Gate 3 was lowered 1.5 ft but could not be raised
- Lowered another 0.5 ft but still could not be raised
- Reservoir lowered, discovered one drain line had become unthreaded from swivel

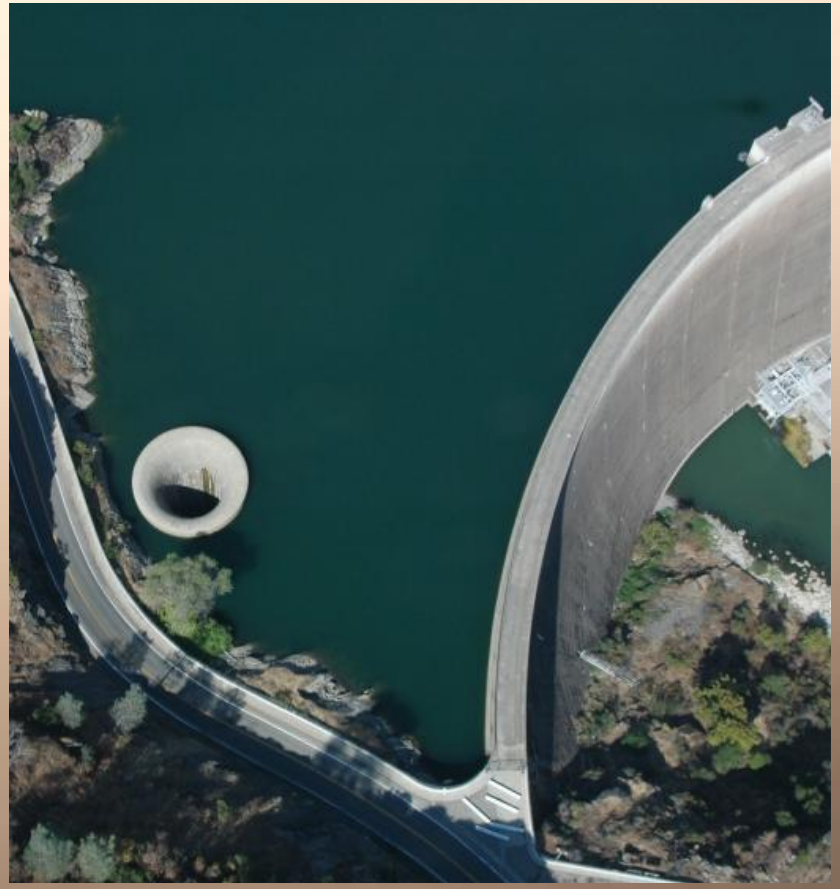
- Gate 3 – 13 of 17 hinge pins found to be fractured
- Bushings re-bored and re-aligned, new hinge pins

# Base Frequency

- 2 incidences in 3533 gate years of operation
- Annual Probability of Failure of 6 X 10-4
- Adjust up or down based on site specific adverse and favorable factors

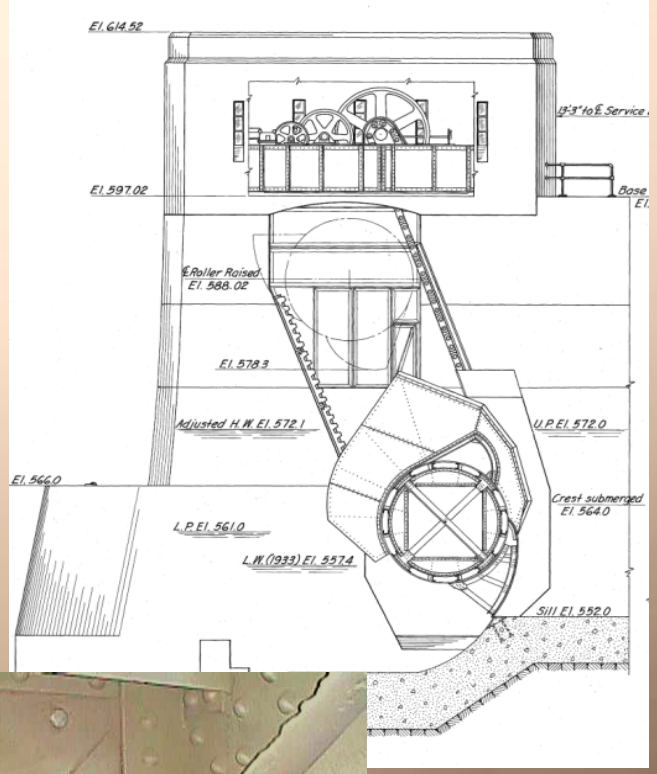
# Ring Gates/Morning Glory Spillways

- Ring gates similar to drum gates, but circular gate floats in circular chamber (on morning glory spillway)
- Morning glory spillways designed for crest control
- Can shift to throat control if design discharge exceeded (discharge curve not valid at higher flows)
- Not much can be done about debris blockage in tunnels until flood flows subside.



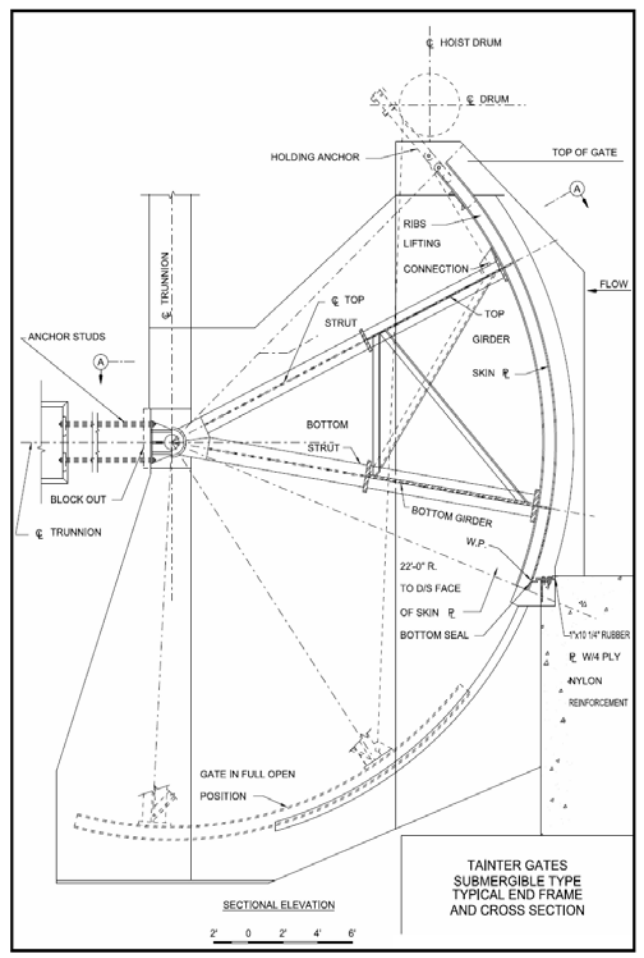
# Roller Gates

- Used in older, lower head navigation locks with wide pier to pier distance.
- Horizontal steel cylinder, usually riveted.
- Significant vibration during lowering of gate has changed operation of dam at certain locations.
- Original gate design from the 1930's did not consider additional loading due to ice or seismic event.
- Fatigue cracking has been seen at end frames and at welded details used for repairs or strengthening.
- Redundant structures.



# Submergible Tainter Gate

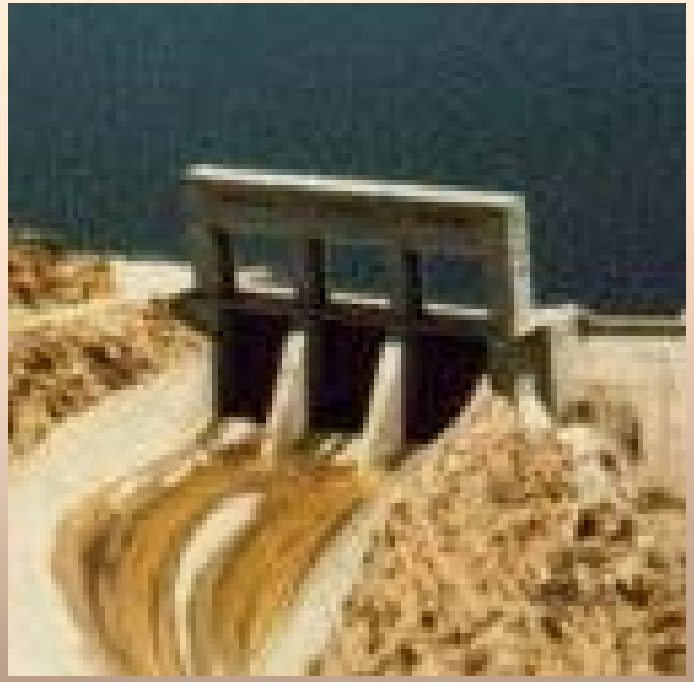
- Similar vulnerabilities of Non-surmersible Tainter gates.
- Lowering could lead to excessive vibration and fatigue cracking should be considered.



# Vertical Lift Gates

- Used both in Nav 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

# Hoist Houses



# 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.
- Crackign 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.

# Miter Gates

- Most common gate in USACE navigation locks.
- Gates are vertically or horizontally framed.
- History of fatigue cracking at USACE dams.
- 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.

# 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 immmediate 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

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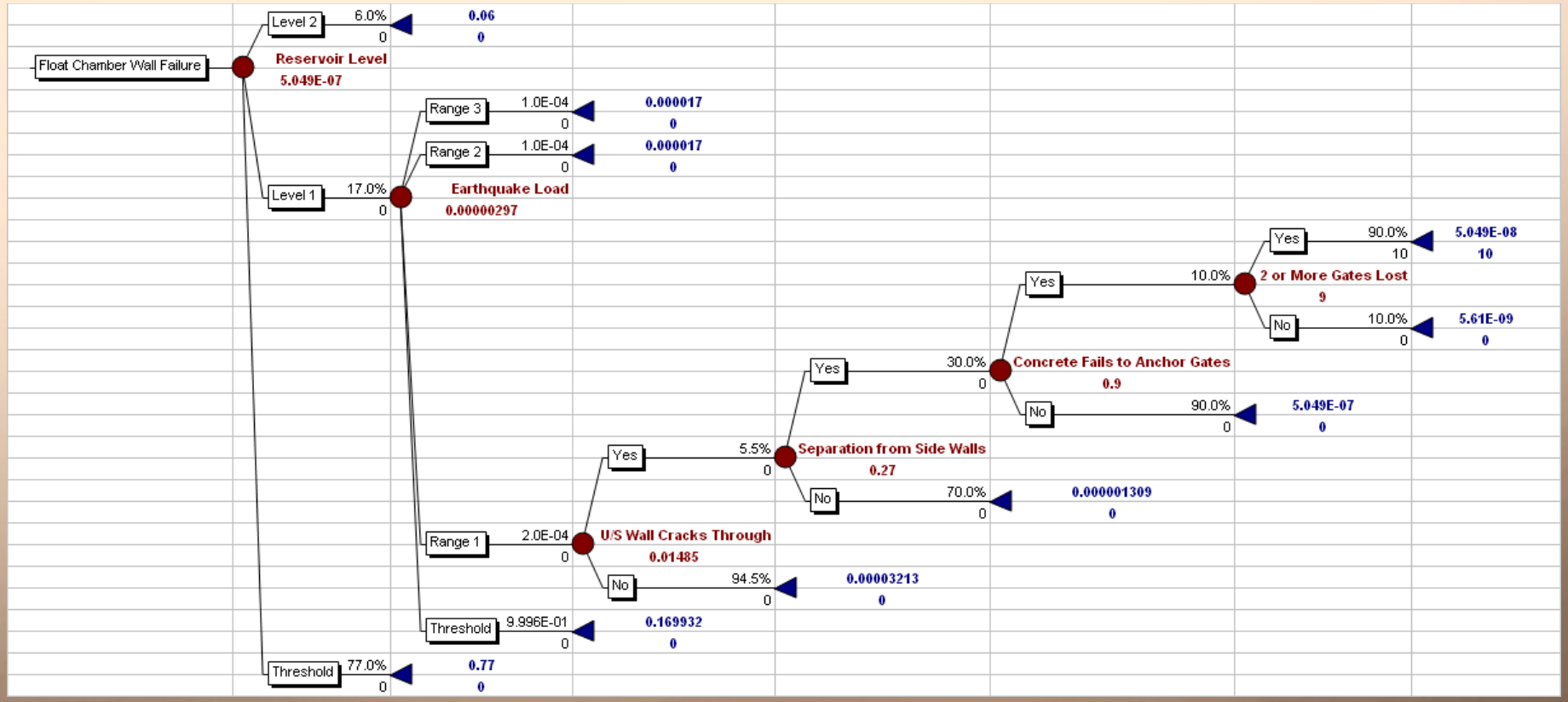
# Other Failure Scenarios

- Think through how they could fail and properly define/describe failure mode
- Set up event tree
- Estimate nodal probabilities using subjective probability

# Example Potential Failure Mode

- *With the reservoir high on the drum gates, a large earthquake hits the site that causes large seismic response and cracking through the unreinforced concrete near the base of the upstream float chamber walls. Additional cracking separates the upstream walls from the side walls. The upstream walls with gates still attached at the hinge pin, move into the float chambers. Buoyant forces are sufficient to displace the gates and attached concrete to the point where the gate is no longer effectively retaining water. Failure of two or more gates exceeds the safe downstream channel capacity threatening the campground and small community directly downstream of the dam.*

# Event Tree for Float Chamber Wall Cracking and Failure



# Cresta Dam Drum Gate Failure

# Description of Failure

- Summer mid-afternoon left side drum gate began to drop uncontrollably
- EAP initiated on dropping reservoir/rising tailwater alarm
- 20-30 minutes to drop completely
- Downstream water level rose from 1.6’ to 15’ in 40 minutes
- Maximum downstream discharge ~ 15,100 cfs
- No fatalities

# Conclusions Re: Gate Failure

- 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

# Exercise 1 – Trunnion Pin Friction

- Consider a spillway with two radial gates, each 34.5 feet high by 51 feet wide. The reservoir is at the normal pool elevation (3 feet below the top of the gates in the closed position) at least two months of every year. Structural analyses of the gates have been performed with the reservoir at the normal pool elevation and assuming a trunnion friction coefficient of 0.1 (based on the manufacturer's recommended value for the bushings). The critical interaction ratio (IR) for this condition is 0.6. If the bushings were to fail, the friction coefficient could increase to 0.3 (assume a 1 percent change that this happens). With the increased friction, the IR will increase to 0.8. The trunnion pins have a self-lubricating bushing and the gates are exercised annually and thoroughly inspected every three years. Assume that there are no adverse factors listed in **Table VII-1-5** that apply to the gates and that unsuccessful intervention in the event of gate failure will be very likely. Estimate the expected annual failure probability for gate failure during the annual exercising of the gates, which typically occurs when the reservoir is full.

# Possible Exercise 1 Solution

- Load probability is 1.0 since reservoir reaches full pool every year.
- Gate operates probability is assumed to be 0.99, since gates are exercised annually when pool is full.
- Reduction Factor Due to Gate Arrangement/Condition – 0.1
- Reduction Factor Due to Inspections/Exercise – The gates are exercised annually and inspected every 3 years - 0.1
- Conditional Failure Probability Based on Interaction Ratio – From Table VII-1-7:
  - For as designed condition (0.99 probability of condition; critical IR = 0.6) – estimate of 0.001
  - For failed bushing condition (0.01 probability of condition; critical IR = 0.8) – estimate of 0.1
- The annual probability of failure is estimated to be **2E-05**

# Exercise 2 – Drum Gate

- Consider a dam with two 30-foot-high by 50-foot-long drum gates. Electronically controlled float chamber inlet and outlet valves have been installed so that the gates can be remotely operated from a control center 30 miles away. A curve relating valve flow to opening is used to control the gates. Due to the availability of parts and sizes of the piping, the outlet valves have twice the capacity of the inlet valves. The drum gates were installed just after WWII. The seals have been replaced, but no other maintenance has been performed. The seals are again leaking, but the leakage is variable depending on the time of year. There is a campground about 100 yards downstream of the dam adjacent to the right river bank. In groups of two to four, discuss the possible vulnerabilities of the gates.

# Possible Exercise 2 Solution

- Drain lines are old; if one fails, a gate could fill with water and inadvertently drop
- Gates are old and have not been painted/ maintained; failure of a weld or portion of the skin plate could result in filling and dropping of a gate
- Outlet valve can let out more water than can be let in; if outlet valve is accidentally opened, a gate would drop
- Remote operation means gates are operated without visual confirmation of proper position; if there is a glitch, it may not be detected
- Float chamber level is controlled by valve flow and does not account for seal leakage; if leakage is large, gate may slowly drop
- The gates are large; if one drops it could result in life-threatening flows at the campground