Field Evaluation of Trunnion Friction Using Strain Gages

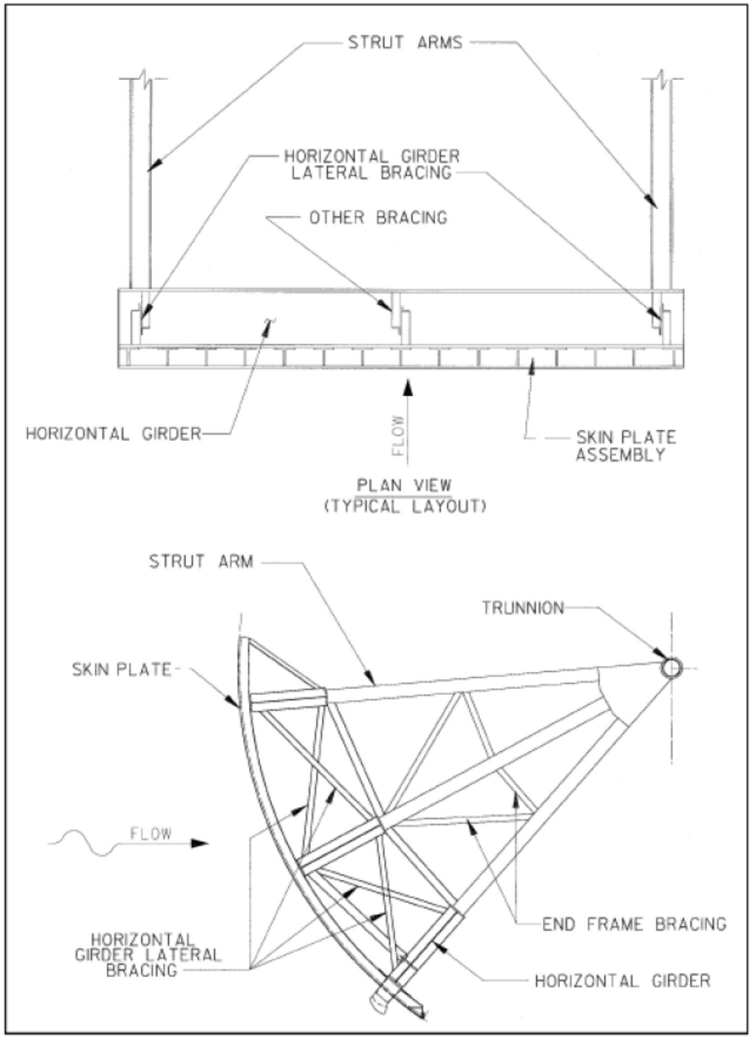
PUGET SOUND ENERGY

- Tainter Gate Overview
- Upper Baker Dam Trunnion Friction Evaluation
- Chief Joseph Dam Trunnion Friction Evaluation
- Summary

PUGET SOUND ENERGY

Tainter Gate Overview

- Most common type of gate for a spillway crest
- Favorable hydraulic discharge characteristics from curved shape
- Economical
  - Simplicity
  - Light Weight
  - Low Hoist Capacity
- Hydrostatic loads transferred through the trunnion
- Terminology



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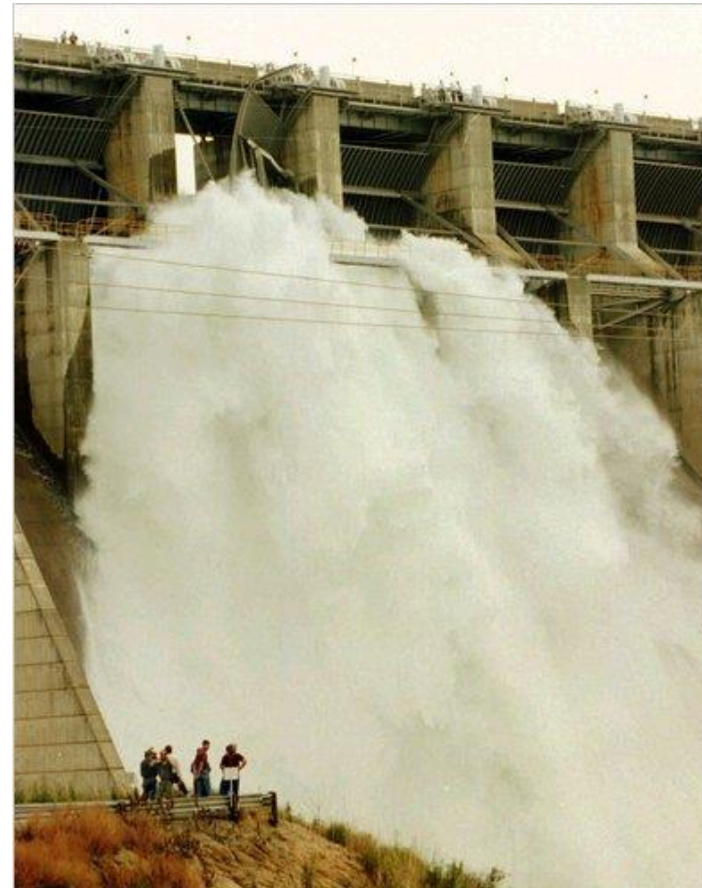
Trunnion Friction Background

- 1995 Folsom Dam Gate Failure.
- Failure mode due to excessive friction
- Coefficient of Friction $\mu = 0.3$
  - USACE Design / Retrofit ETL 1110-2-584

    - Trunnion pin friction, Ft. During opening or closing of gates, friction loads exist around the surface of the trunnion pin between the bushing and the pin and at the end of the hub between the hub bushing and side plate (yoke plate for yoke mounted pins). These friction loads result in a trunnion friction moment Ft about the pin that must be considered in design. The friction moment is a function of a coefficient of friction, the trunnion reaction force component R that acts normal to the surface of the pin (parallel to the pier face), and the radius of the pin. The friction moment at the end of the hub is a function of a coefficient of friction, the trunnion reaction force component Rz that acts normal to the end of the pin (normal to the pier face), and the average radius of the hub. A coefficient of friction of 0.3 shall be used. This is a reasonable value that applies for any bushing material that may be slightly worn or improperly maintained and includes effects thrust washer friction and bearing misalignment.

  - FERC (0.3 in the absence of a measured value)
- Reliable design/retrofit
- Doesn't address safety of existing gates.
- Need for realistic value



PUGET SOUND ENERGY

Upper Baker Dam

- Puget Sound Energy
- 3 Spillway Gates
- Self Lubricating - Lubrite
- 1999 Hands-on Inspection by HDR
- 2009 Hands-on Inpspection & Laser Deflection Testing by MWH/Extreme Access
    - 5-Year Trunnion Friction Monitoring

PSE PUGET SOUND ENERGY

Upper Baker Dam

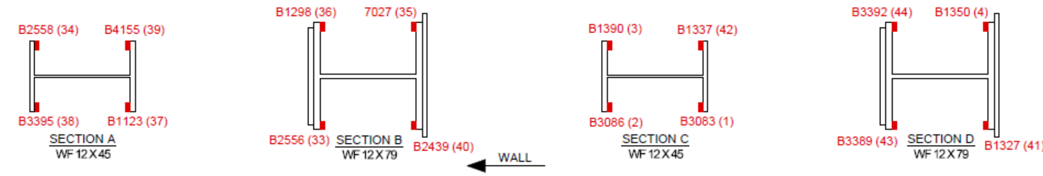
- Strengthened following 2009 Inspection & Analysis for Maximum Credible Earthquake
- No Maintenance (Self-Lubricating)
- Routine Exercise - Weekly
- 2014 Strain Gage Testing by BDI, Inc
  - 16 strain transducers
  - 2 rotation sensors
  - 2 torque sensors
  - Amp sensor

PSE PUGET SOUND ENERGY

Upper Baker Dam - Instrumentation

SENSOR LEGEND

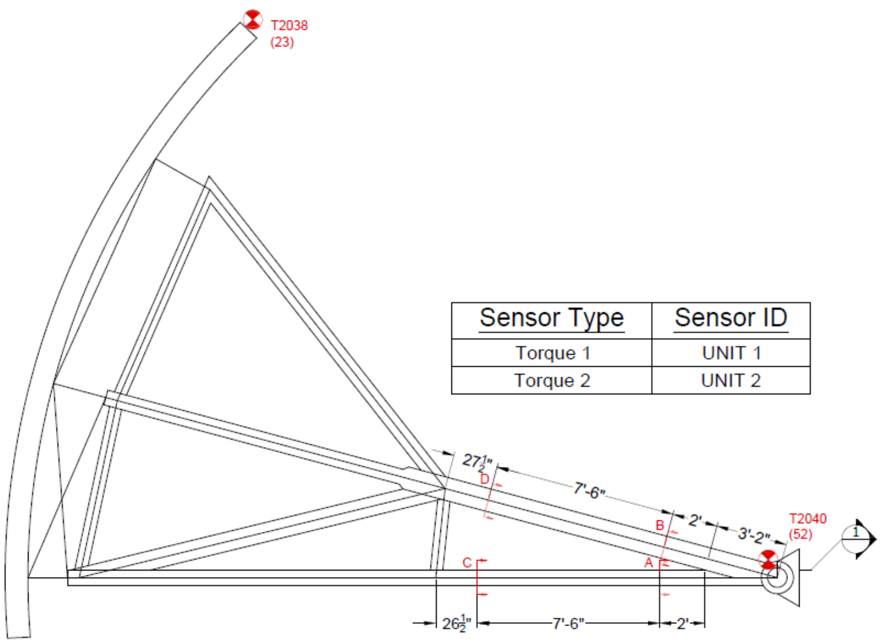
- STRAIN SENSOR (16)
- ROTATION SENSOR (2)



CROSS-SECTIONS

SCALE: N.T.S

NOTES:
- INSTRUMENTED CROSS SECTIONS ARE DRAWN PERPENDICULAR TO THE LENGTH OF EACH BEAM LOOKING TOWARDS PIN.
- EDGE OF STRAIN SENSORS WERE ALIGNED WITH EDGE OF FLANGE.
- ALL GAGES WERE MOUNTED TO FACES STRIPPED OF PAINT.
- SECTIONS A-A AND B-B WERE LOCATED 2'-0" FROM THE EDGE OF THE STRUT WELD CONNECTION.
- SECTIONS C-C AND D-D WERE BE LOCATED 7'-6" FROM SECTIONS A-A AND B-B.
- TRUNNION ROTATION SENSORS WERE MOUNTED ON TRUNNION BRACKET AS CLOSE TO THE TRUNNION HUB AS POSSIBLE.
- SKIN PLATE ROTATION SENSORS WERE MOUNTED AS NEAR TO THE TOP AS POSSIBLE.
- TORQUE SENSORS WERE MOUNTED ON OPPOSITE SIDES OF THE PINNION GEAR SHAFT.



Sensor Type	Sensor ID
Torque 1	UNIT 1
Torque 2	UNIT 2

TESTING PLAN:
- STARTED WITH THE GATE IN THE CLOSED POSITION AND WATER LEVELS AT NORMAL OPERATION CONDITIONS.
- BEGAN DATA COLLECTION, RAISED THE GATE APPROXIMATELY ONE FOOT AND HELD THERE UNTIL DATA WAS STABLE.
- LOWERED THE GATE APPROXIMATELY 6 INCHES AND HELD THERE UNTIL DATA WAS STABLE.
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- RAISED THE GATE APPROXIMATELY ONE FOOT AND HELD THERE UNTIL DATA WAS STABLE.
- LOWERED THE GATE BACK TO CLOSED POSITION AND STOPPED DATA COLLECTION.

NOTE: THREE TESTS WERE RUN TO ENSURE QUALITY DATA WAS COLLECTED.
NOTE: MAX HEIGHT OF GATE SHOULD NOT HAVE EXCEEDED 18 INCHES.

GATE 3 - SOUTH ARM ELEVATION

SCALE: N.T.S

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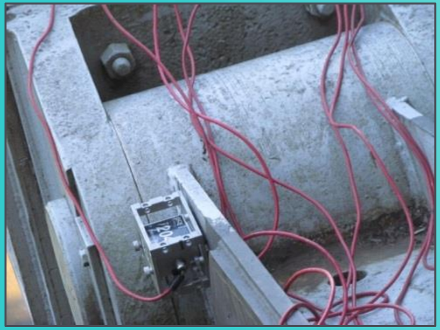
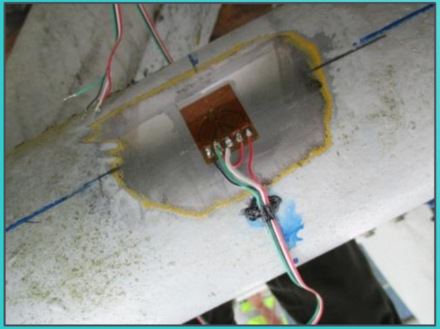
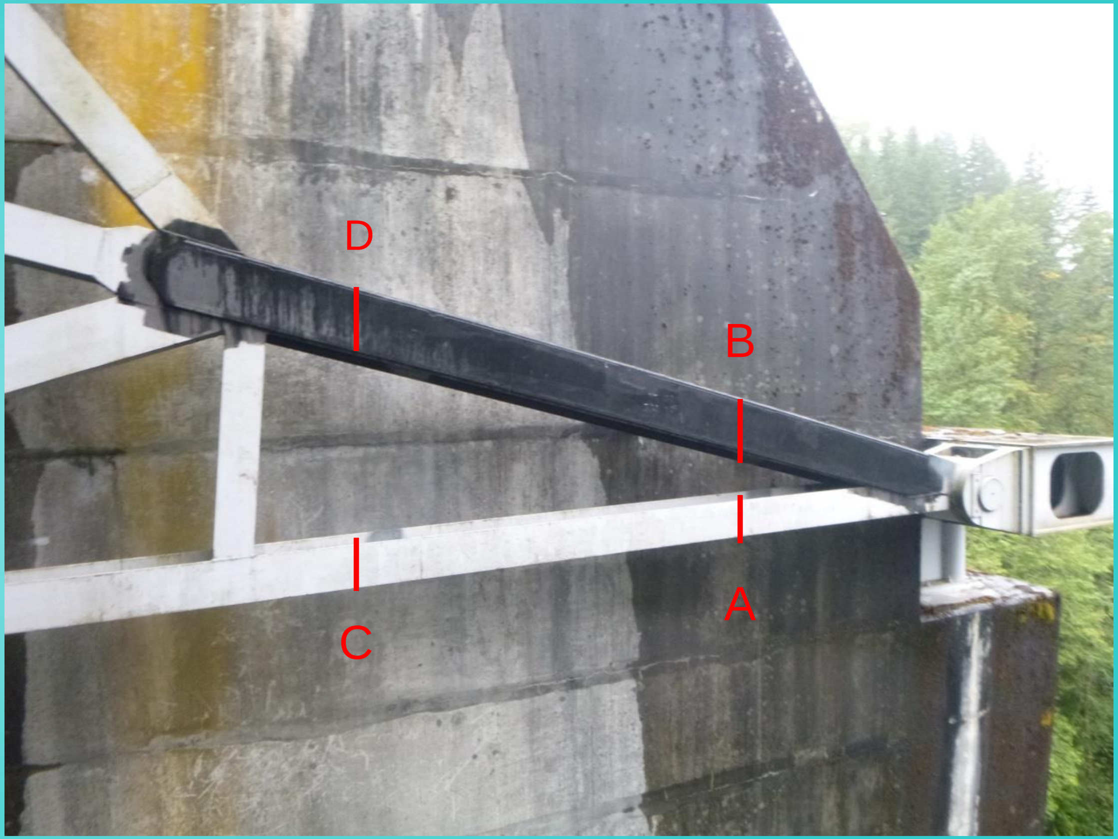
Upper Baker Dam – Instrumentation

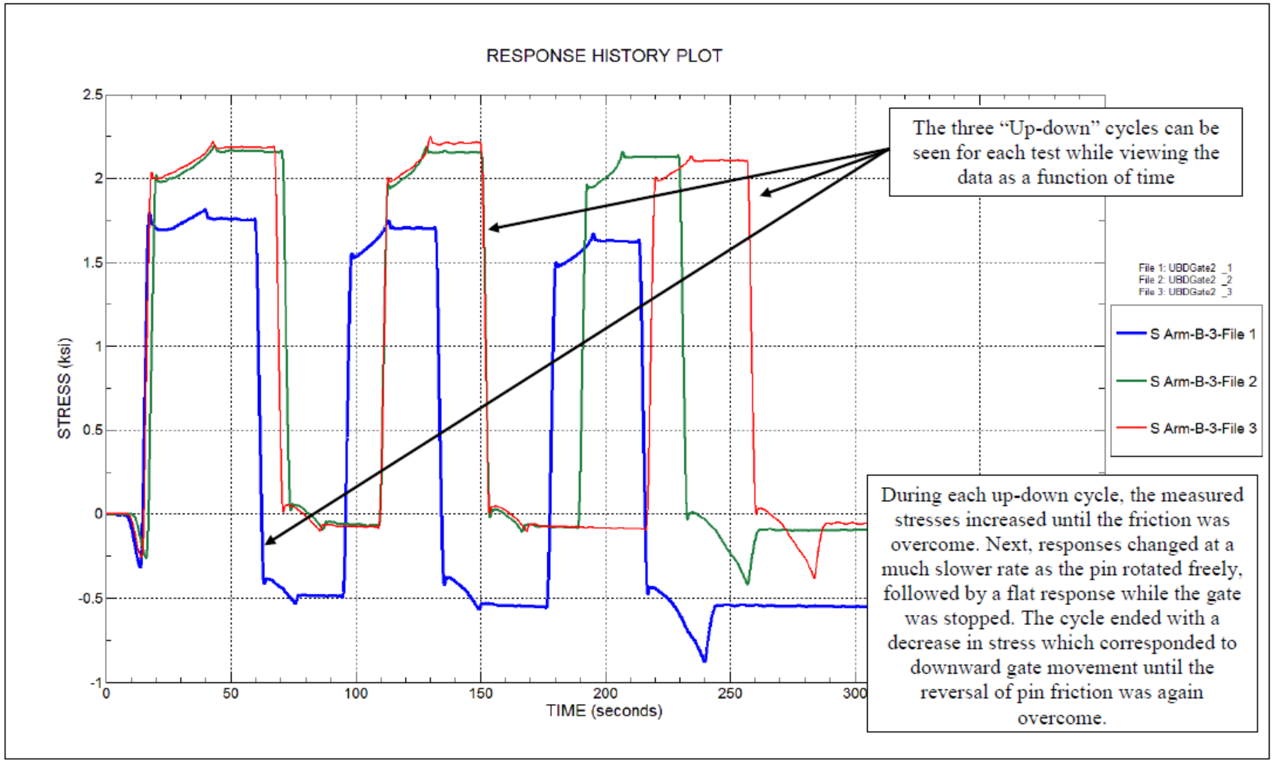






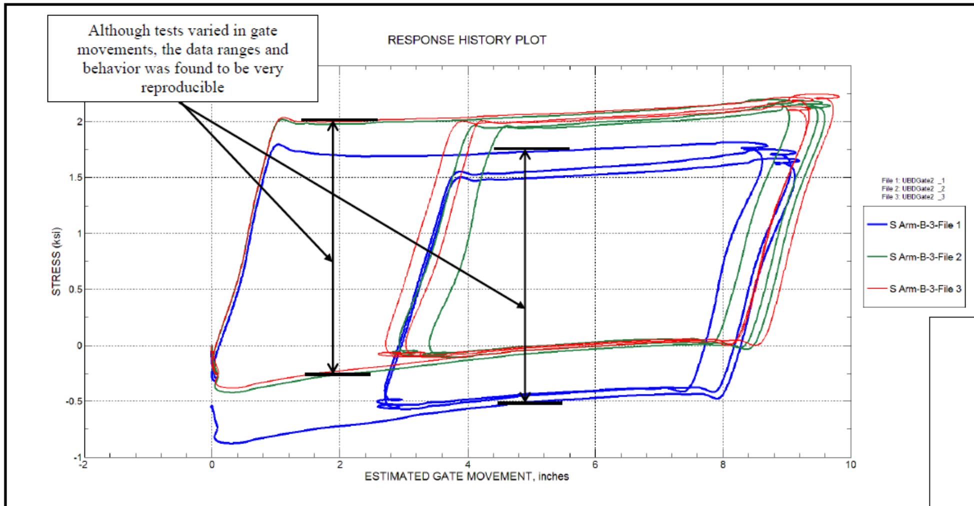
Upper Baker Dam - Instrumentation

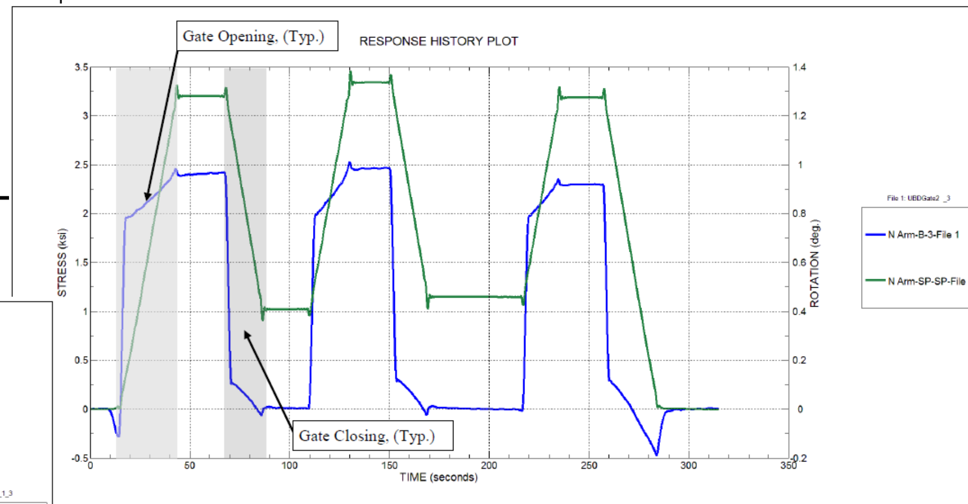
- 3 series of “Up-Down” spill tests
- Each test included 3 sets of direction reversal
- Direction reversal consisted of lifting the gate until friction was broken, pausing, then lowering until friction was broken again

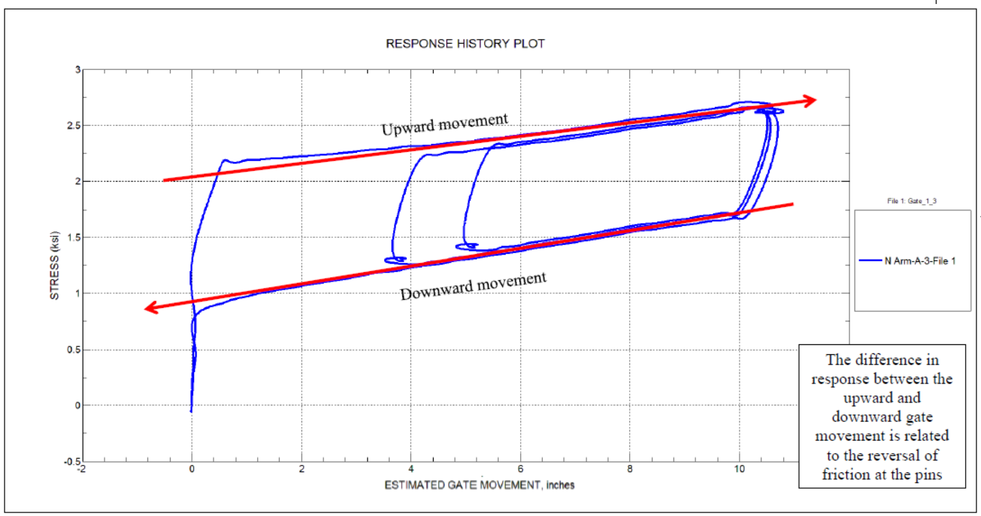


PUGET SOUND ENERGY

Upper Baker Dam - Instrumentation

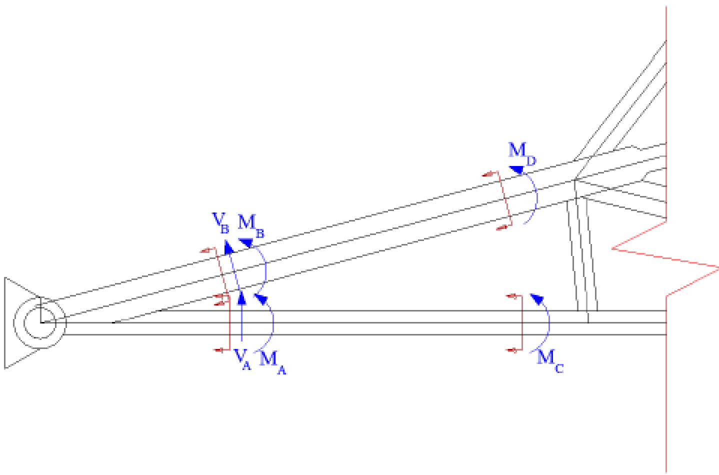




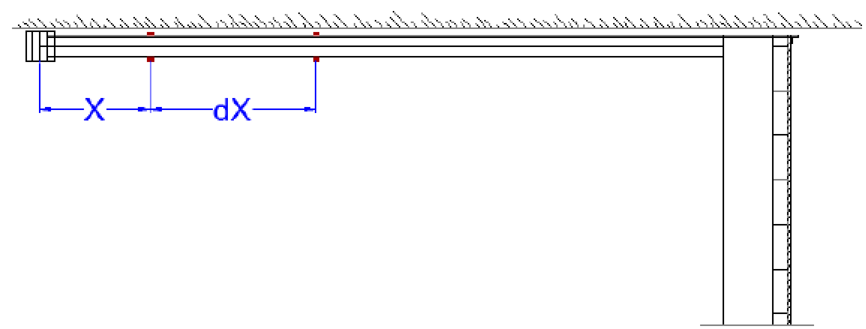


PSE PUGET SOUND ENERGY

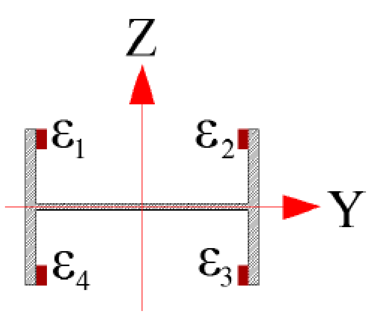
Upper Baker Dam - Instrumentation



Elevation View of Gate Arm



Plan view of Gate Arm



Typical Strut Cross-section

$$M_Y = M_A = M_B = M_C = M_D = \frac{E[(\varepsilon_3 + \varepsilon_4)/2 - (\varepsilon_1 + \varepsilon_2)/2]S_Y}{2}$$

$$\Delta M_{BOTTOM} = M_A - M_C$$

$$\Delta M_{TOP} = M_B - M_D$$

$$V_A = \frac{(\Delta M_{BOTTOM})}{dX}$$

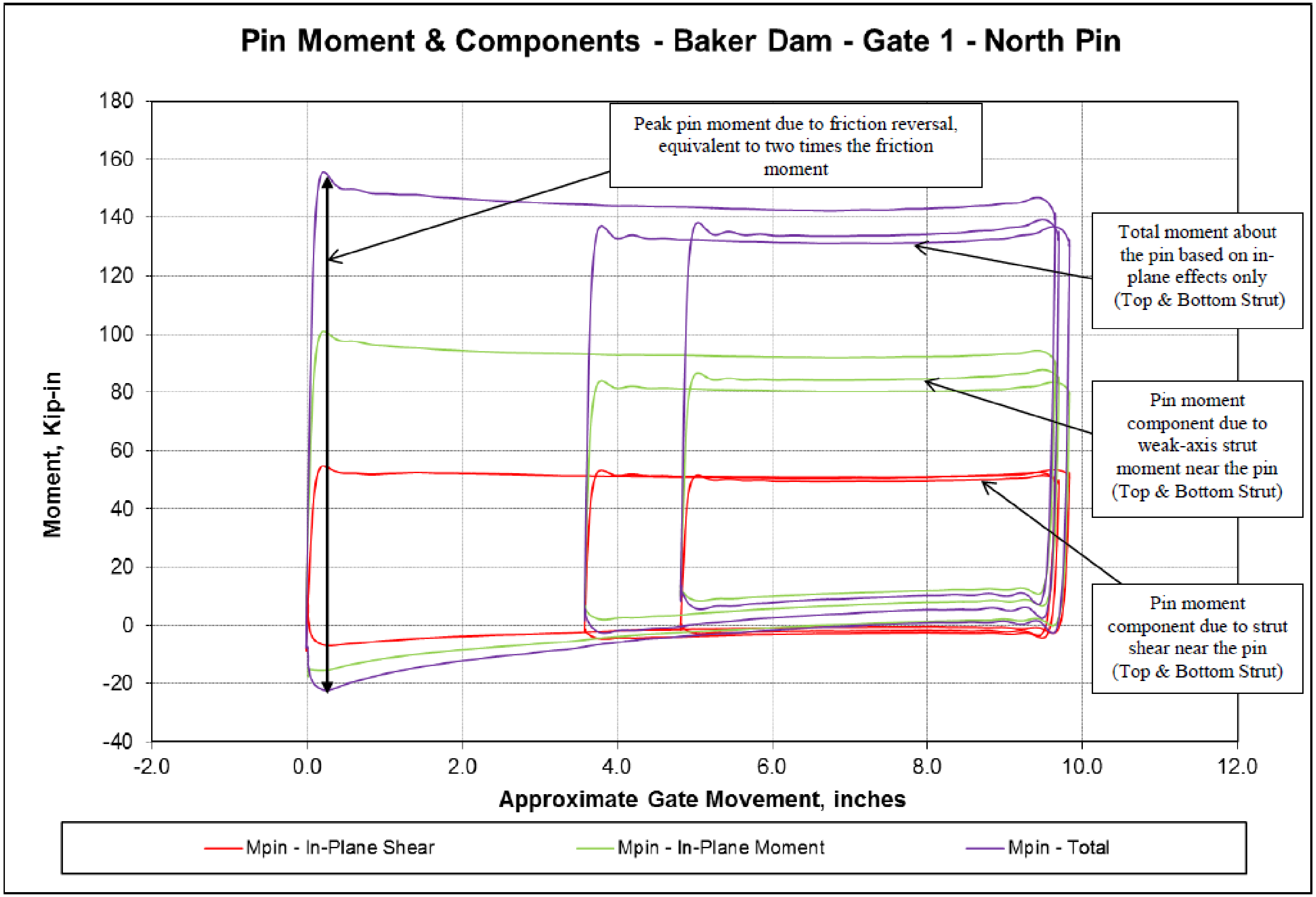
$$V_B = \frac{(\Delta M_{TOP})}{dX}$$

$$\sum M_o = 0$$

$$M_{PIN} = X(V_A + V_B) + (M_A + M_B)$$

PUGET SOUND ENERGY

Upper Baker Dam - Instrumentation



PUGET SOUND ENERGY

Upper Baker Dam – Friction Results

- All friction coefficients below 0.3
- Results compared with 2009 Laser deflection test
- 2010 strength analysis: safe up to $\mu = 0.40$

	2014 Strain Gage Results – Reservoir Elevation 722.0		2009 Laser Deflection Results – Reservoir Elevation 718.0	
Gate	Arm Designation	Maximum Friction Coefficient	Arm Deflection	Friction Coefficient
Gate 1	North Pin	0.09	0.25	0.18
	South Pin	0.15	0.38	0.23
Gate 2	North Pin	0.16	0.63	0.33
	South Pin	0.17	0.38	0.23
Gate 3	North Pin	0.07	0.25	0.18
	South Pin	0.29	0.51	0.28

PUGET SOUND ENERGY

Upper Baker Dam - Comparison

- Did not take laser deflection measurements in 2014 for direct comparison
  - Reservoir elevation not significantly different
  - Laser deflection could verify strain gage results if already instrumenting the gate
- 2009 friction varied between 0.18 and 0.33 (range of 0.15)
- 2014 friction varied between 0.07 and 0.29 (range of 0.22)
- Wider range of friction values with strain gages.
  - Resolution of laser measurements versus strain gage
  - Methodology or instrument installation issues
  - Change in friction or just change in measurement technique

PUGET SOUND ENERGY

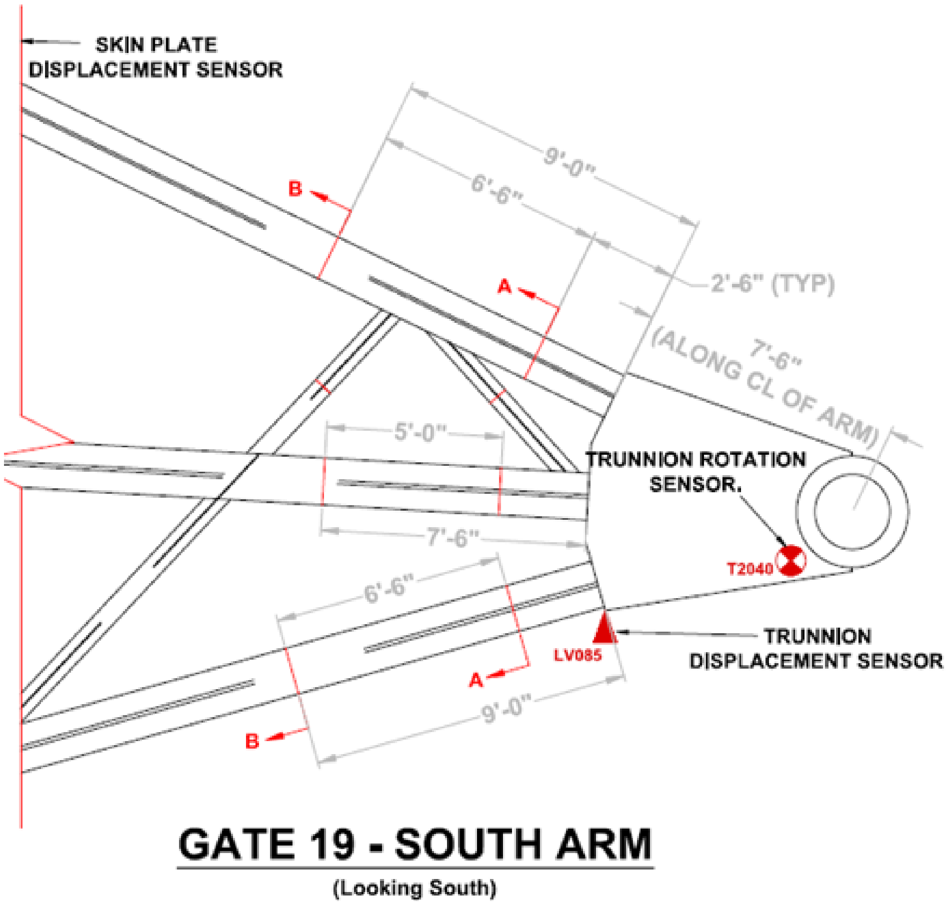
Chief Joseph Dam

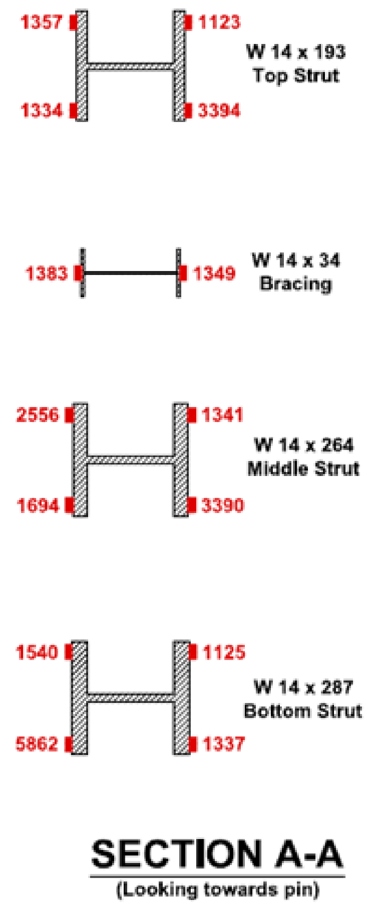
- US. Army Corps of Engineers – Seattle District
- 19 spillway gates
- Lubrite "or equivalent"
- 3 gates instrumented in 2012 by HDR & BDI, Inc.

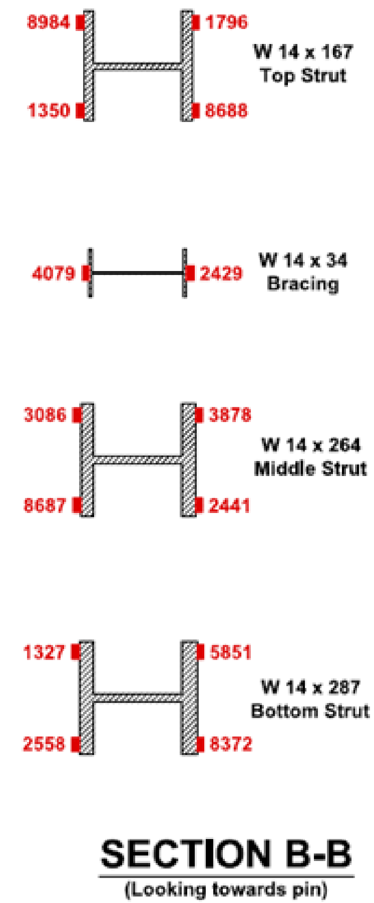
- Additional instrumentation required due to gate arm design:
  - 28 strain transducers
  - 2 displacement sensors
  - 1 rotation sensor
  - 1 Torque sensor @ pinion gear

PSE PUGET SOUND ENERGY

Chief Joseph Dam - Instrumentation







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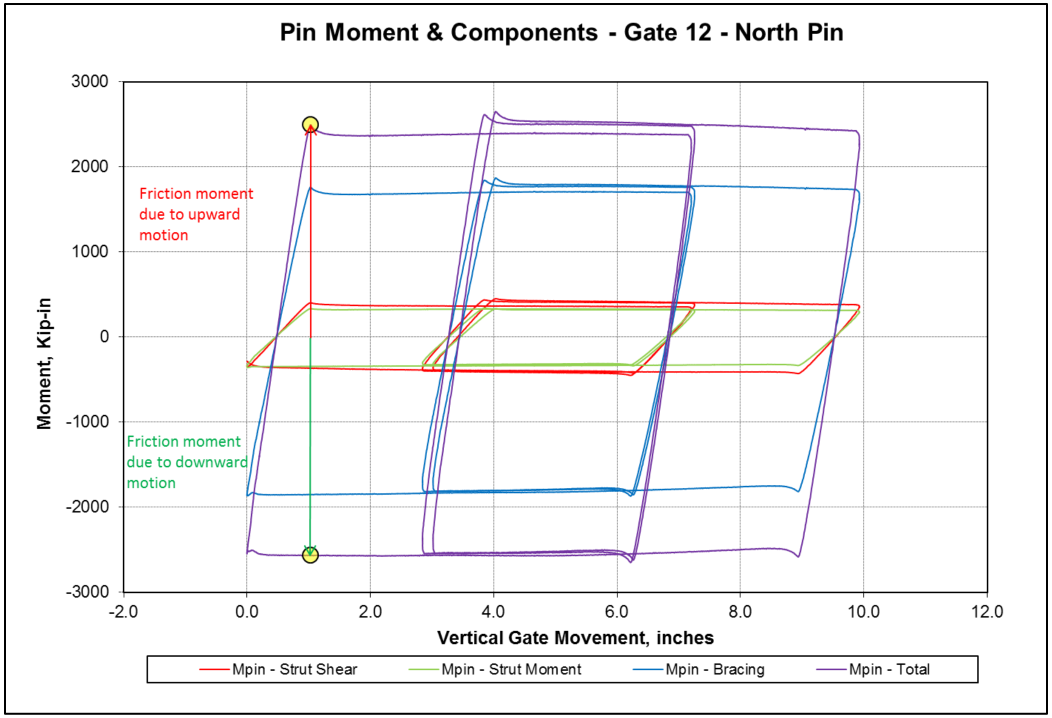
Chief Joseph Dam – Friction Results



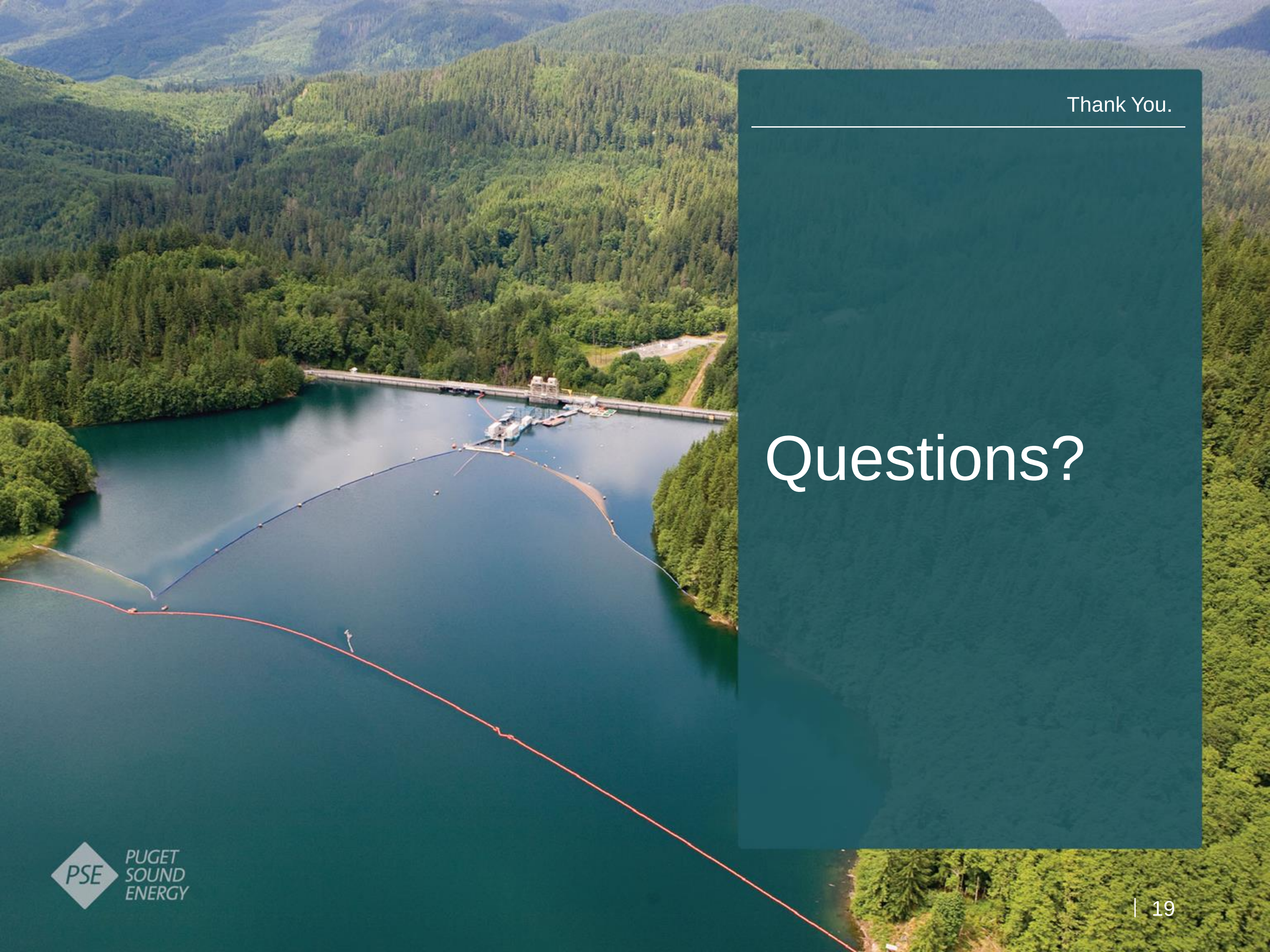
Gate	Arm	Friction Coefficient
Gate 4	North Pin	0.11
	South Pin	0.12
Gate 12	North Pin	0.11
	South Pin	0.11
Gate 19	North Pin	0.13
	South Pin	0.11

- Consistency between tested gates across spillway
- Finite Element Analysis of gates for trunnion friction coefficient of 0.3
- Fit for Service Evaluation with measured friction coefficients

PUGET SOUND ENERGY

Summary

- Consider comparison of instrumentation methods
- Standardized testing not currently documented
- Accuracy, Precision, Resolution
- Multiple performance measures
  - Pinion torque
  - Cable tension
  - Hoist Power
- It isn't just trunnion friction…
- Follow the load path, remember the big picture



Thank You.

Questions?

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