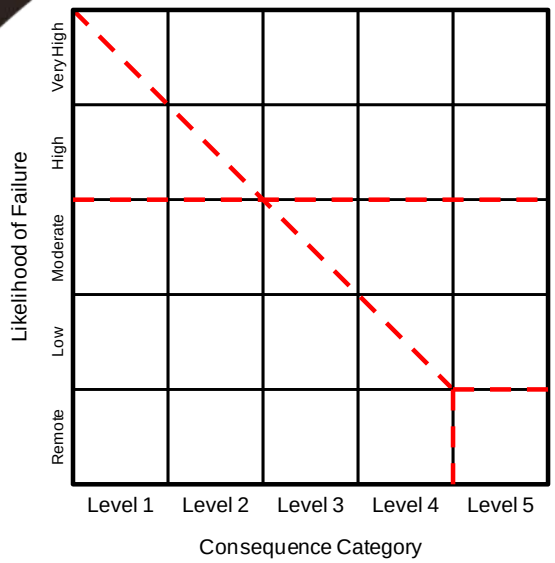
Best Practices in Dam and Levee Safety Risk Analysis

I-3 and I-4. Potential Failure Modes and Semi-Quantitative Risk Analysis

13 April 2015



RECLAMATION
Managing Water in the West

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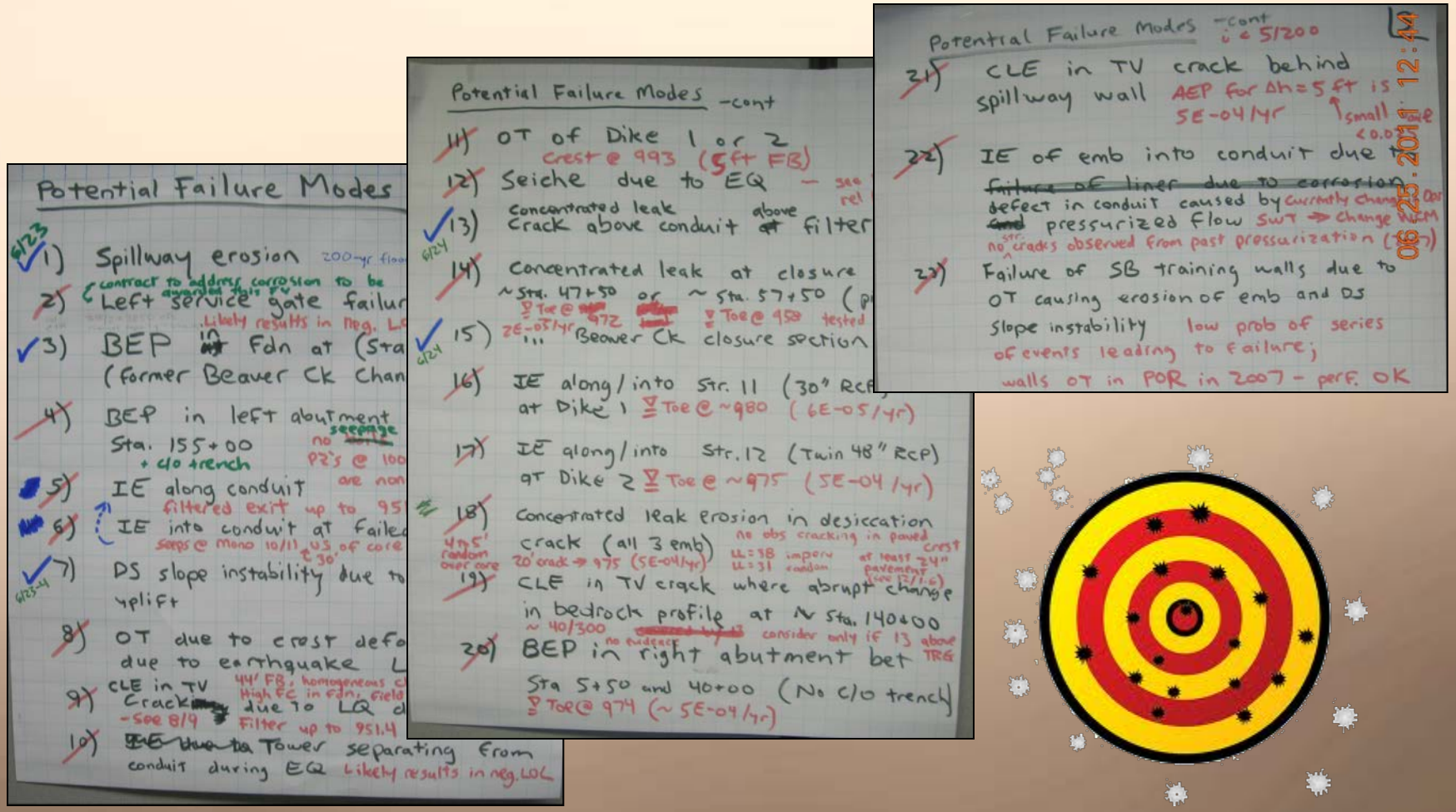
Overview of Process

- Collect and review all available background information.
- Conduct a brief site visit focused on vulnerabilities.
- Review loading conditions and baseline consequences.
- Brainstorm potential failure modes.
  - Categorize as risk-drivers or non-risk-drivers.
- Discuss, evaluate, and classify risk for risk-drivers.
  - Document justification for non-risk-drivers.
- Document major findings and key background information (i.e., “build the case”).

Key Concepts

- Perform with diverse team.
- Take a fresh look.
- Review background material diligently (by more than one qualified engineer).
- Involve operating personnel in the potential failure modes discussions.
- Think beyond traditional analyses.

Brainstorming



Describing Risk-Driver

- Three elements of a risk-driver potential failure mode description are:
  - The Initiator (e.g. reservoir load, deterioration/aging, misoperation/malfunction, earthquake)
  - The Failure Mechanism (<u>including location and/or path</u>) (step-by-step progression)
  - The Resulting Impact on the Structure (e.g., rapidity of failure, breach characteristics)

Example 1

Example 1 (cont.)

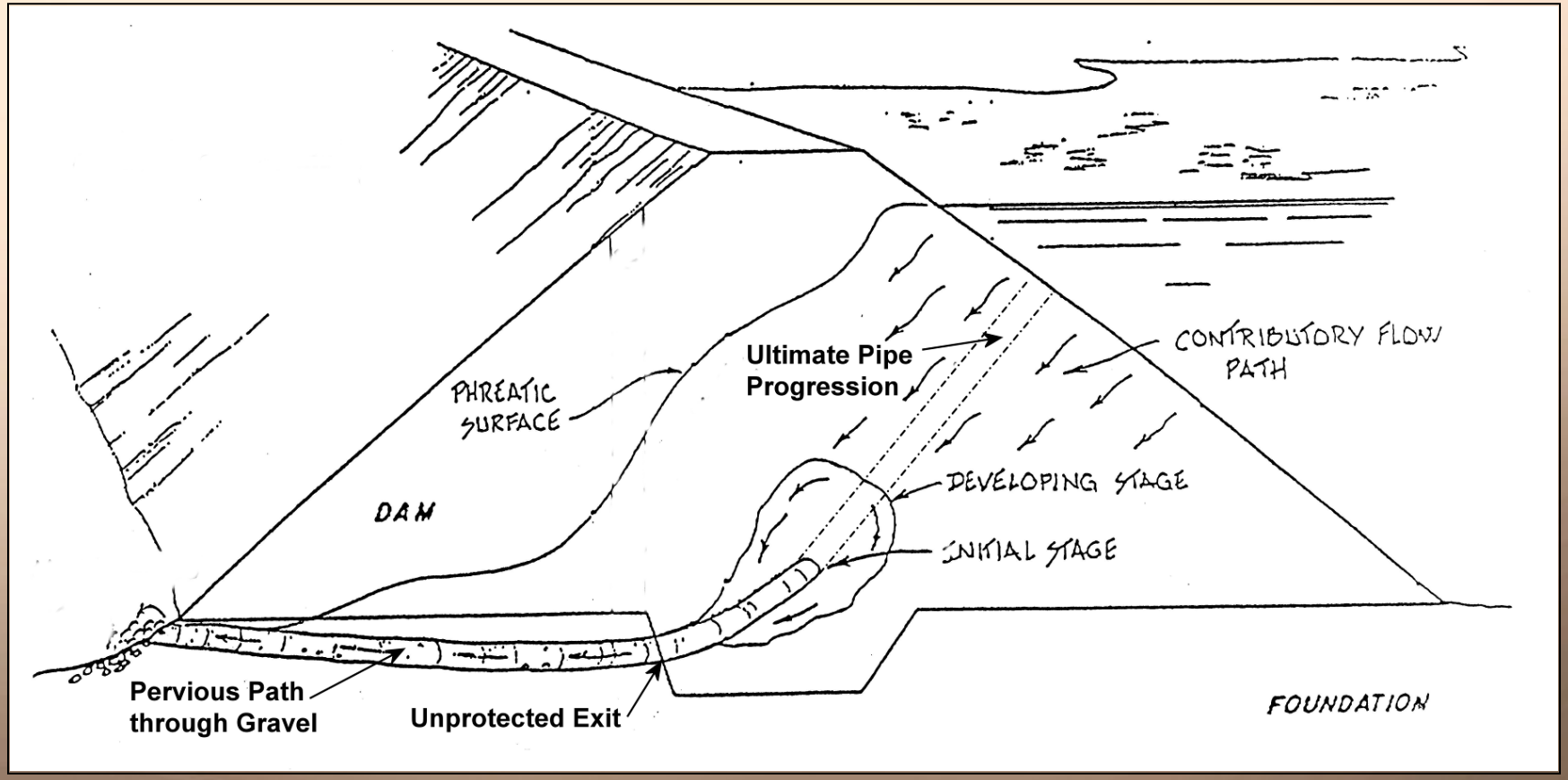
Example 1 (cont.)

Example 1 (cont.)

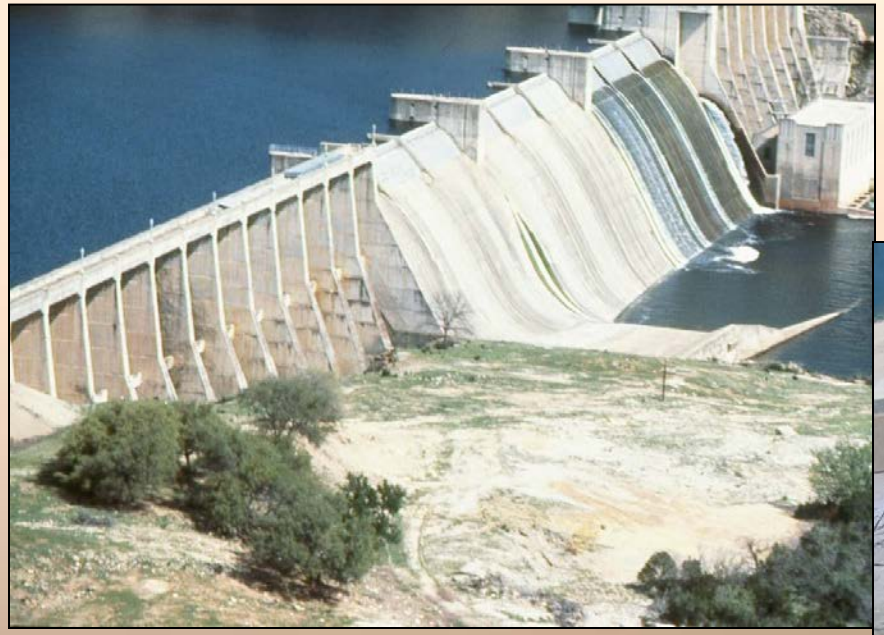
- Unedited (insufficient detail): Piping from the embankment into the foundation

- Edited: During a period of high reservoir elevation, piping of the embankment core initiates at the gravel foundation interface in the shallow cutoff trench near Station 2+35 (where problems with the sheet pile and sinkhole occurred). Material might or might not exit at the toe of the dam. Backward erosion occurs until a "pipe" forms through the core exiting upstream below the reservoir level. Rapid erosion enlargement of the pipe occurs until the crest of the dam collapses into the void, and the dam erodes down to the rock foundation.

Example 1 (cont.)



Example 2



Review of geology indicated dam is founded on horizontally-bedded shale and clay seams

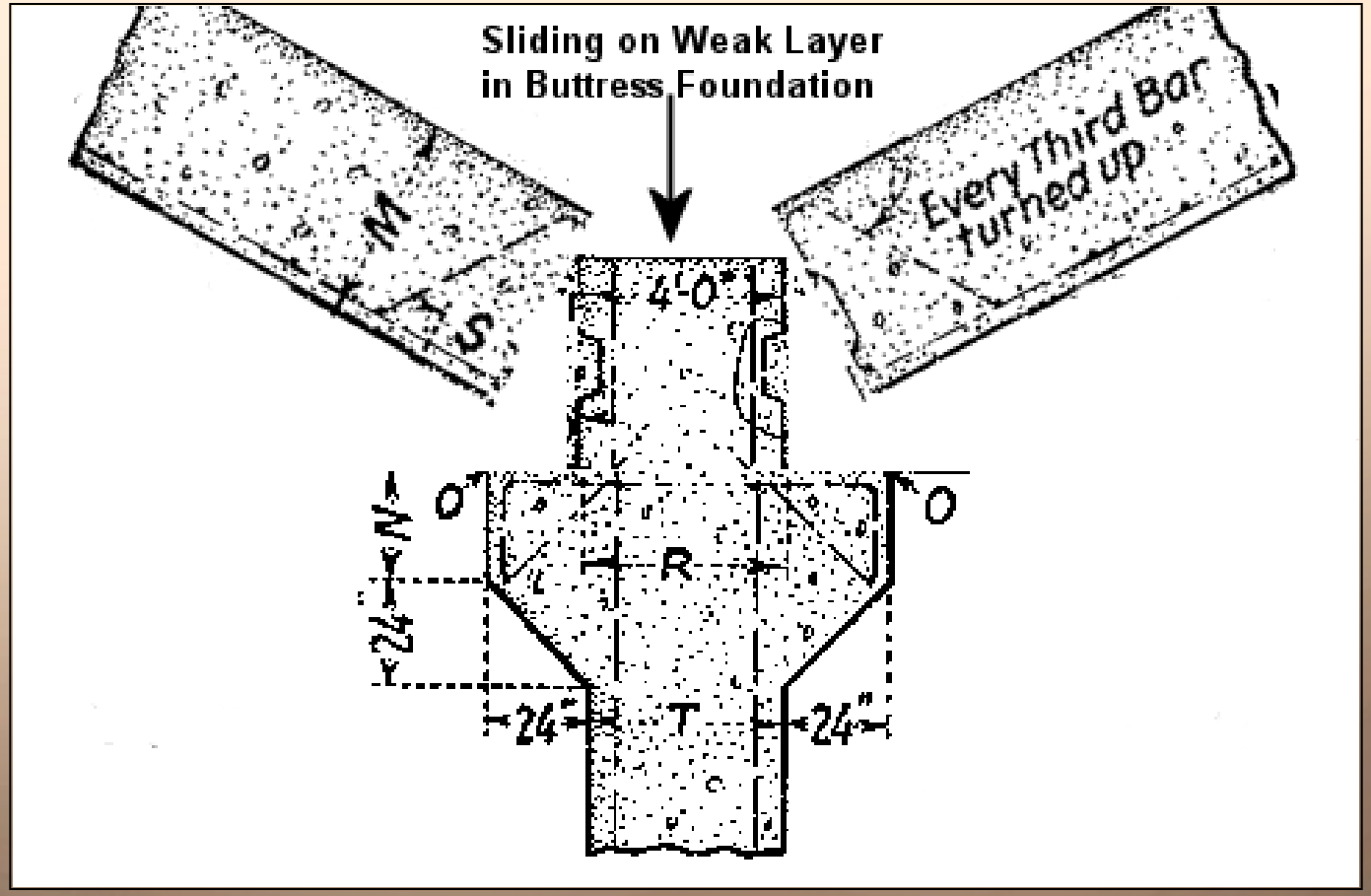
Surveying results indicated the dam had moved several inches since monitoring began

Example 2 (cont.)

- Unedited (insufficient detail): Sliding of the concrete dam foundation

- Edited: As a result of high reservoir levels and (1) a continuing increase in uplift pressure on the old shale layer slide plane, or (2) a decrease in shearing resistance due to gradual creep on the slide plane, sliding of the buttresses initiates. Major differential movement between two buttresses takes place causing the deck slabs to be unseated from their simply supported condition on the corbels. Breaching failure of the concrete dam through two bays quickly results followed by failure of adjacent buttresses due to lateral water load.

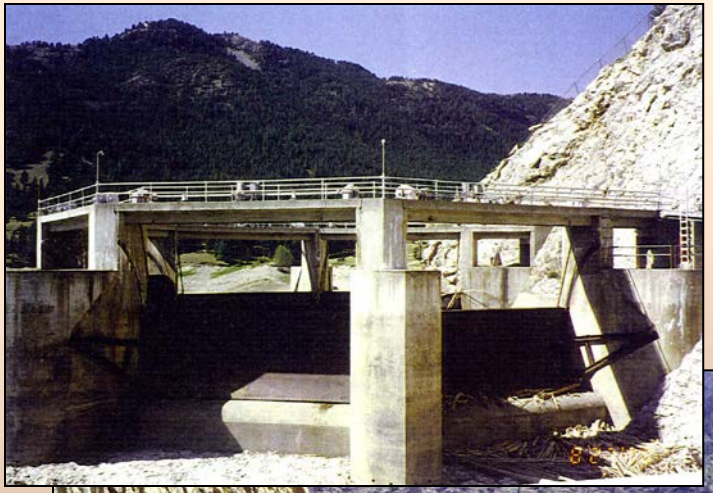
Example 2 (cont.)

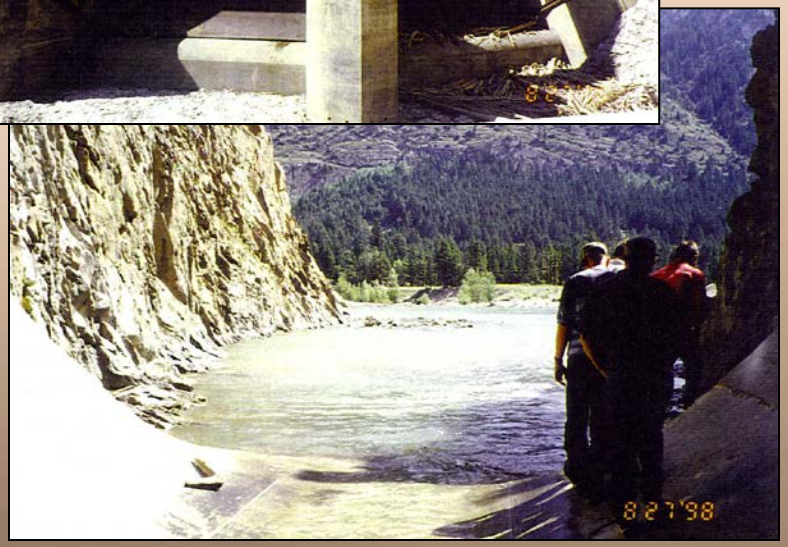


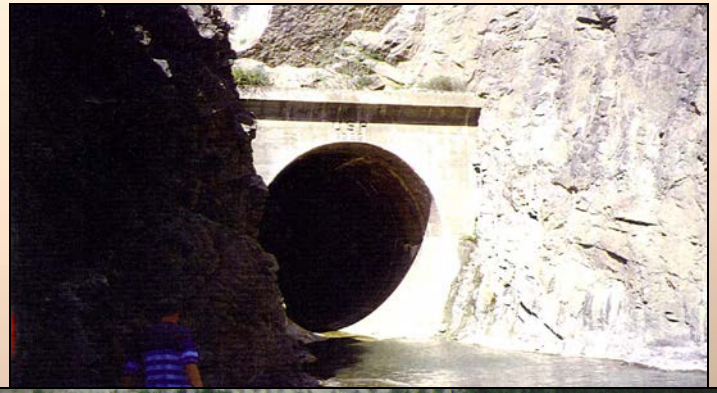
Example 3

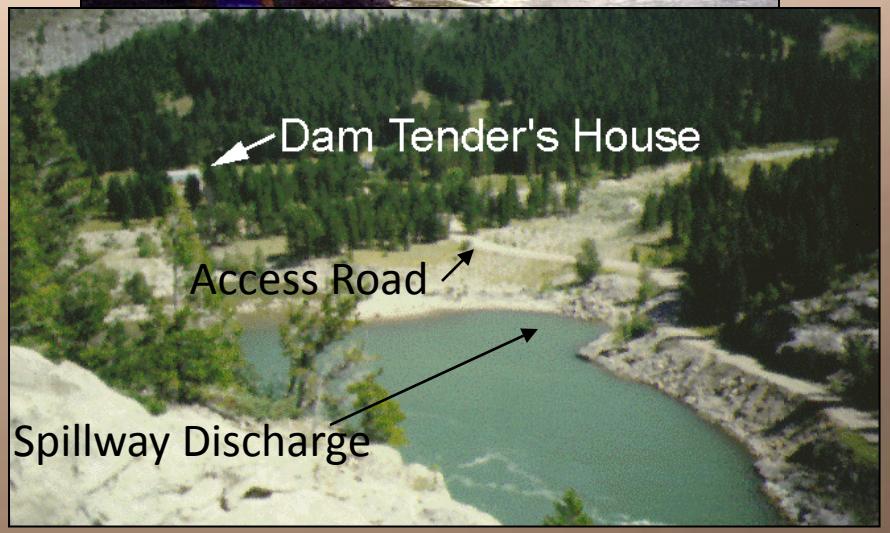
- An embankment dam has a gated spillway crest for passing flood flows. Of the six gates, one can be remotely operated from the power control center to pass normal flows. The remaining five gates must be operated manually from a control house on top of the spillway hoist deck. If a single gate is opened completely, the main access road is inundated. A limit switch keeps the remotely operated gate from opening more than half way without on-site intervention. The limit switch failed in 1994 and the road was washed out. The only other access to the spillway gate deck is a rough 4-wheel-drive road from the reservoir side that becomes muddy and treacherous when it rains.

Example 3 (cont.)









Example 3 (cont.)

- Unedited (insufficient detail): Dam overtopping due to gate operation failure

- Edited: During a large flood, releases in excess of those that can be passed through the automated gate are required. The limit switch on the automated gate fails (occurred in 1994) due to a loss in communications and the gate opens fully wiping out the only access road. An operator is deployed to the site, but cannot make it to the gate operating controls. The release capacity of the single automated gate is insufficient, and the dam overtops, eroding down to the stream level.

Potential Failure Mode Analysis

For each potential failure mode:

- List adverse or “more likely” factors
- List favorable or “less likely” factors
- Flesh them out so they can be understood by others and years down the road (ask, “why did we say that?,” and write down the answer)
- Perform an evaluation of the potential risk – suggest using semi-quantitative approach described in next section.

Adverse "More Likely" Factors

- The gravel alluvium *in contact with the embankment core on the downstream side of the cutoff trench* is similar to the transition zones which do not meet *modern "no erosion"* filter criteria *relative to the core base soil*.
- The gravel alluvium may be internally unstable*, leading to erosion of the finer fraction through the coarser fraction and even worse filter compatibility with the core*.
- The reservoir has never filled to the top of joint use*; it has only been within 9 feet of this level; most dam failures occur at high reservoir levels; the reservoir would fill here for a 50 to 100-year snow pack (based on reservoir exceedance probability curves from historical operation).*
- The core can sustain a roof or pipe*; the material was well compacted (to 100 percent of laboratory maximum), and contains some plasticity (average Plasticity Index ~ 11).*
- There is likely a *significant seepage* gradient *from the core* into the *downstream* gravel foundation*, as evidenced by the hydraulic piezometers installed during original construction (and since abandoned)*.
- *It is likely that* all flow through the foundation cannot be observed *due to the thickness and pervious nature (transmissivity) of the alluvium.*

Favorable or "Less Likely" Factors

- Very little seepage is seen downstream*; the weir at the downstream toe, which records about 10 gal/min at high reservoir when there is no preceding precipitation, indicating the core is relatively impermeable; these flow rates may be too small to initiate erosion.*
- The core material is well compacted *(to 100 percent of laboratory maximum)* and has some plasticity *(average Plasticity Index ~ 11), both of which reduce its susceptibility to erosion.*
- N*o benches were left in the excavation profile that could cause cracking and the abutments were excavated to smooth slopes less than 2H:1V.*
- *If erosion of the core initiates,* the gravel alluvium may plug off before complete breach occurs *(see criteria for "some erosion" or "excessive erosion", Foster and Fell, 2001).*

Review Consequences of Failure

- If the dam were to breach by this mechanism, at risk would be a highway, a railroad, two bridges, farmhouses, a gas pumping station, an aggregate plant, a barley mill, a transmission line, and the town of Tannerville. There is little recreation activity downstream of the dam. The flood wave would spread out into the wider valley by the time it reaches the population centers. The total population at risk is estimated at about 1,400.

- The embankment is constructed of well compacted material with a moderate PI and the alluvium is mostly cohesionless sand, a moderately fast erosion breach would likely occur down to bedrock.

- (But, don't rule out a potential failure mode with low consequences if it has a high likelihood of occurrence.)

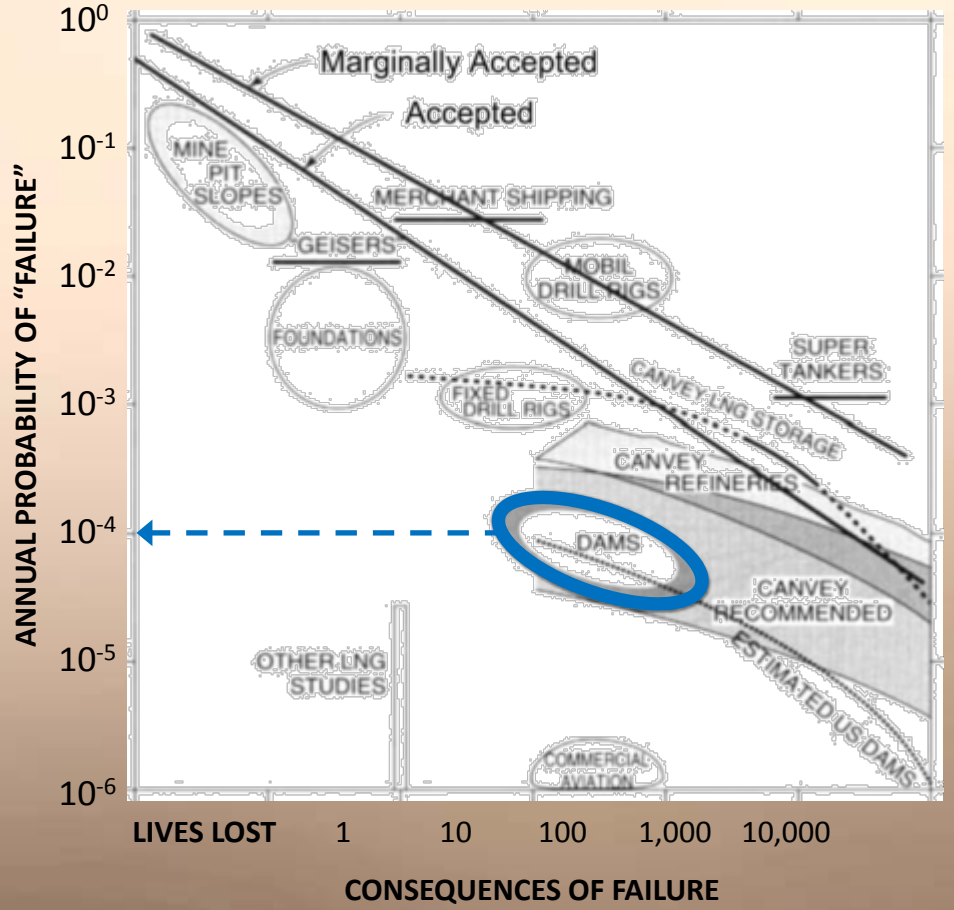
Consequences Study

- Ideally, there will be a consequences study to help guide the team.
- Sometimes there will not be such a study.
- Even when there is a consequences study, the results may not adequately reflect the failure modes being considered.
- The team must critically review the consequences study and make adjustments as appropriate.

Screening

- The risk for each risk-driver potential failure mode can be screened at this point using the semi-quantitative approach described next.

Historical Failure Rates for Semi-Quantitative Dam Safety Assessments



- APF ~ 1 in 10,000/year
- Whitman and Baecher (1981)
- Von Thun (1985) 1.4E-04
- Hatem (1985) 2.6E-04
- M.K. Engineers (1988)
- Foster et al. (1998, 2000)
  - Built before 1950: 3.6E-04
  - Built after 1950: 1.6E-04
  - All Dams: 2.0E-04
- Douglas et al. (1998)

Failure Likelihood Categories for Dams

- Remote: Annual failure likelihood more remote than 1/1,000,000. Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood.
- Low: Annual failure likelihood from 1/100,000 to 1/1,000,000. Cannot be ruled out, but no compelling evidence to suggest it has occurred or that flaw exists that could lead to initiation.
- Moderate: Annual failure likelihood from 1/100,000 to 1/10,000. Flaw exists; key evidence weighted more heavily toward “less likely” than “more likely.”
- High: Annual failure likelihood from 1/10,000 to 1/1,000. Flaw exists; key evidence weighted more heavily toward “more likely” than “less likely.”
- Very High: Annual failure likelihood more frequent (greater) than 1/1,000. Direct evidence or substantial indirect evidence to suggest it has initiated or is likely to occur in near future.

Consequences

- Per Graham (1999), consequences are related to:
  - Population at risk
  - Flood severity (inundation/trans-boundary issues)
  - Warning time
  - Understanding of the flood severity
- Clarity and availability of evacuation routes also important
- Consider when identifying order of magnitude type consequences

Inland Navigation Projects

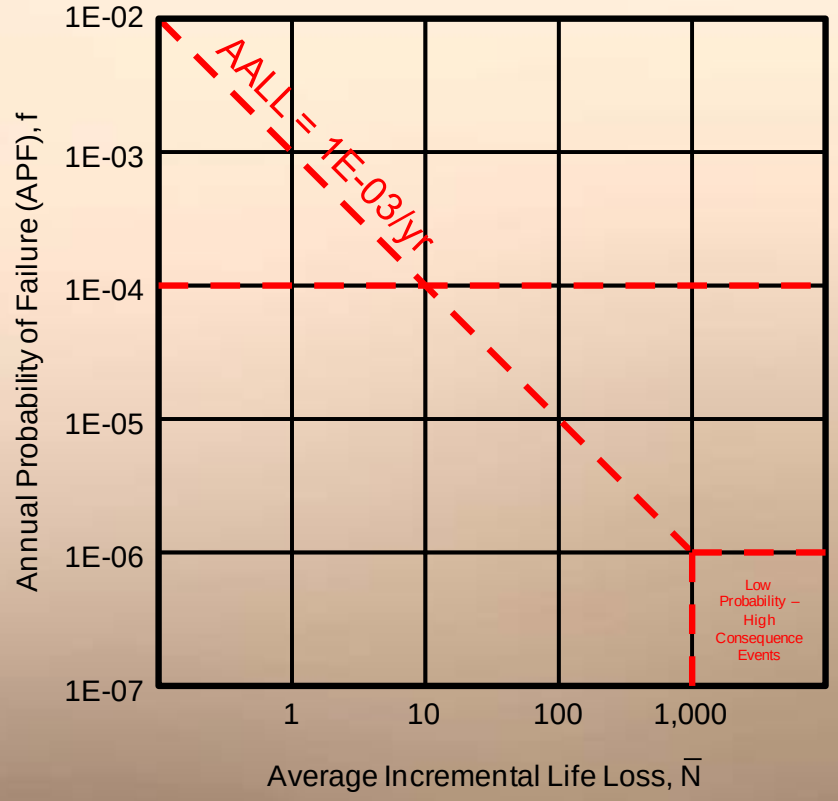
- Loss of navigable pool or lock closure may have significant economic consequences but little to no flood risk (such as life safety risk due to breach).
  - Failure is per event, but all events are not equal (i.e., duration of outage can vary significantly).
  - Assess the upstream economic consequences due to loss of navigable pool or lock closure.

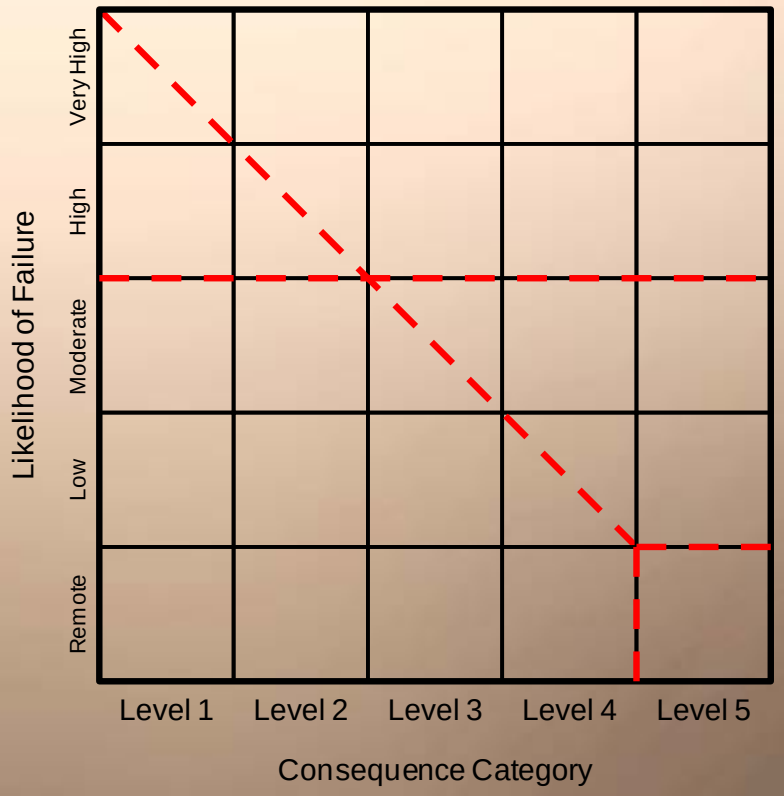
Consequence Categories

Consequence Level	Consequences	
	Incremental Life Loss	Economic Loss [3]
0	(See Note 1)	N/A
1	(See Note 2)	Less than $10M
2	1 to 10	$10M to $100M
3	10 to 100	$100M to $1B
4	100 to 1,000	$1B to $10B
5	> 1,000	More than $10B

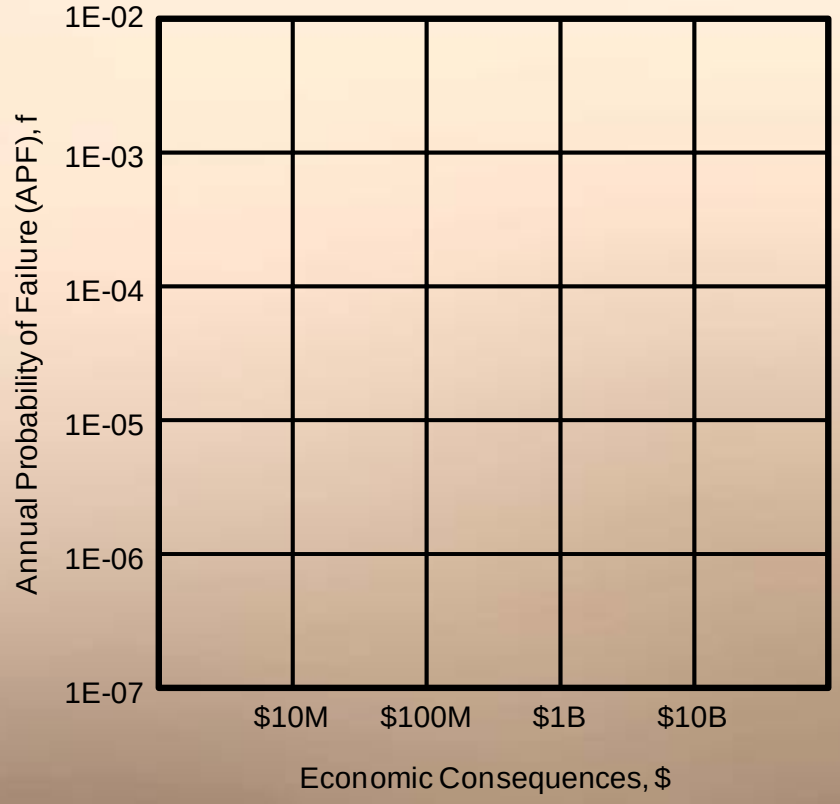
[1]No significant impacts to downstream population other than temporary minor flooding of roads or land adjacent to river.
[2]Although life-threatening flows are released and people are at risk, loss of life is unlikely.
[3]Costs associated with disruption to navigation traffic and water supply, flood damage to property, damage to structures along the navigation pool from loss of pool, and disruption to industry and facilities dependent on navigation. These are not intended to be equated to the life loss categories to arrive at a value for human life.

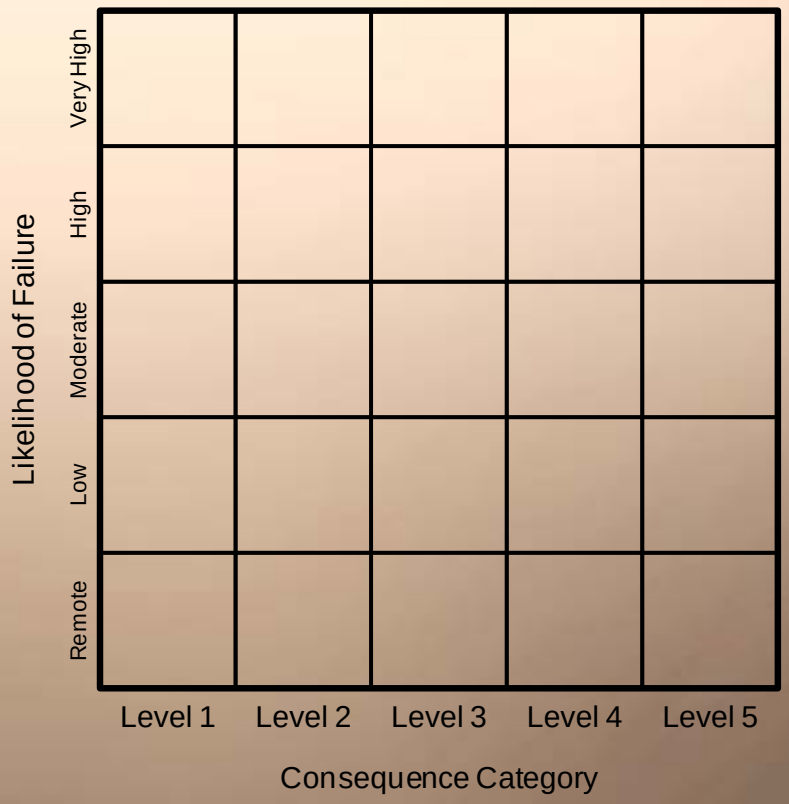
Incremental Life Safety Risk Matrix for Dams





Incremental Economic Risk Matrix for Dams





Confidence

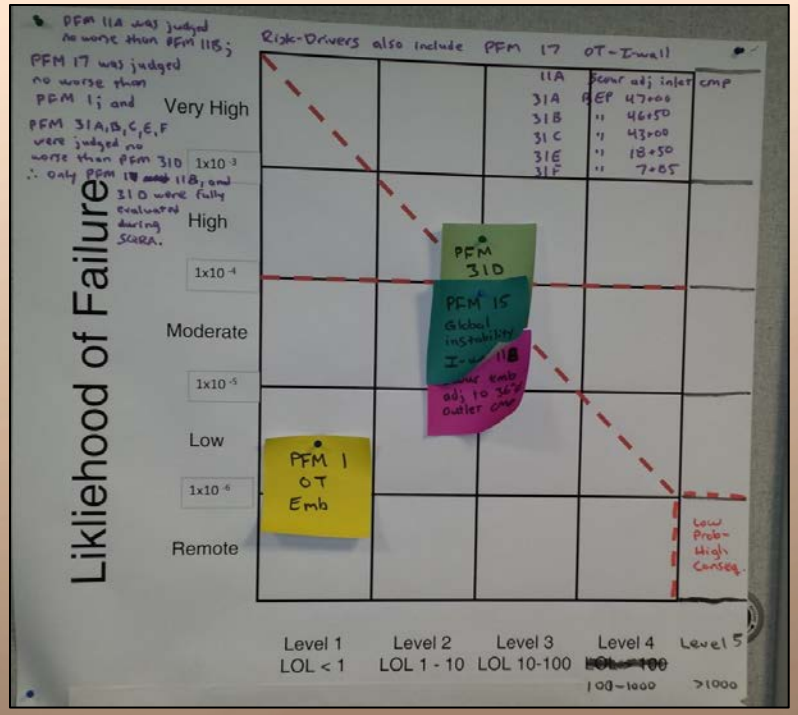
- High: The team is confident in the order of magnitude for the assigned category and, it is unlikely that additional information would change the estimate.
- Low: The team is not confident in the order of magnitude for the assigned category, and it is entirely possible that additional information would change the estimate.
- Moderate: The team is relatively confident in the order of magnitude for the assigned category, but key additional information might possibly change the estimate.

Discussion of Risk-Driver PFMs

- Document pertinent background information.
- Assign classification for likelihood of failure and confidence; provide rationale.
- Assign classification for consequences and confidence; provide rationale.
- Discuss possible recommendations for additional monitoring, risk-reduction, data, or analysis.

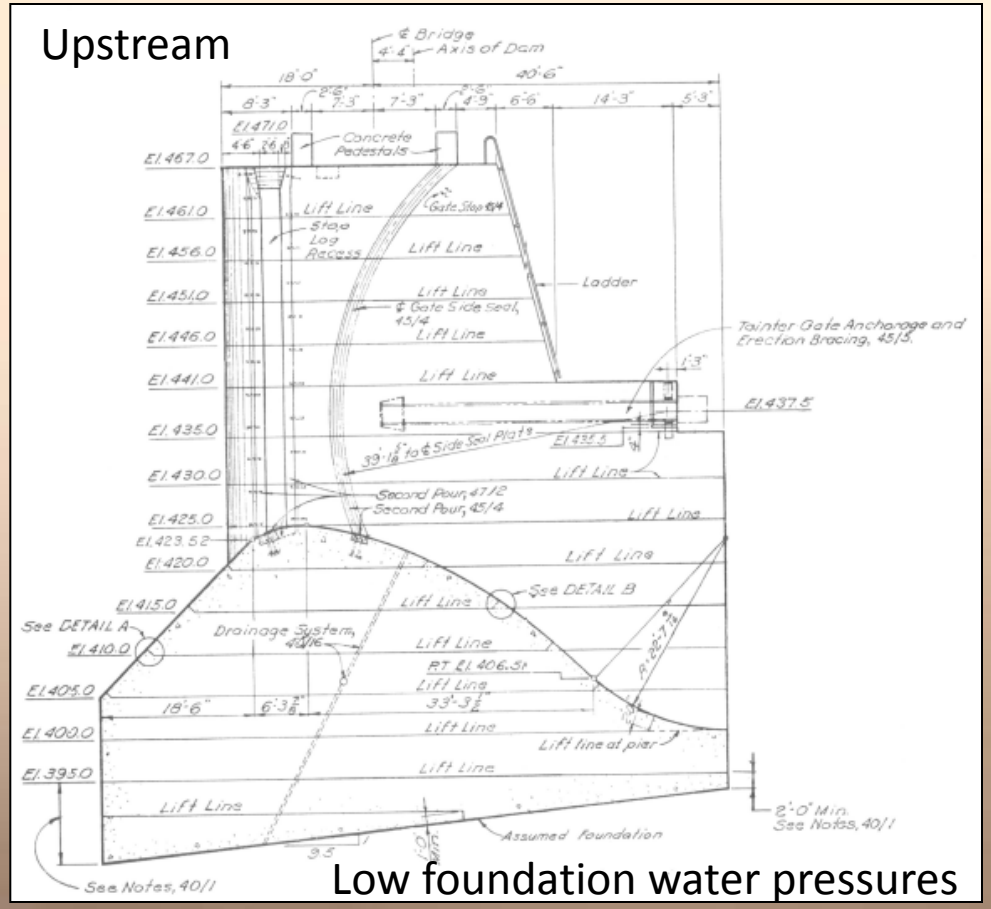
Results

- List each failure mode on a “Post-It Note” and place it on a large blank incremental risk matrix on the wall.
  - Different colors can help differentiate different structures or elements.



Example

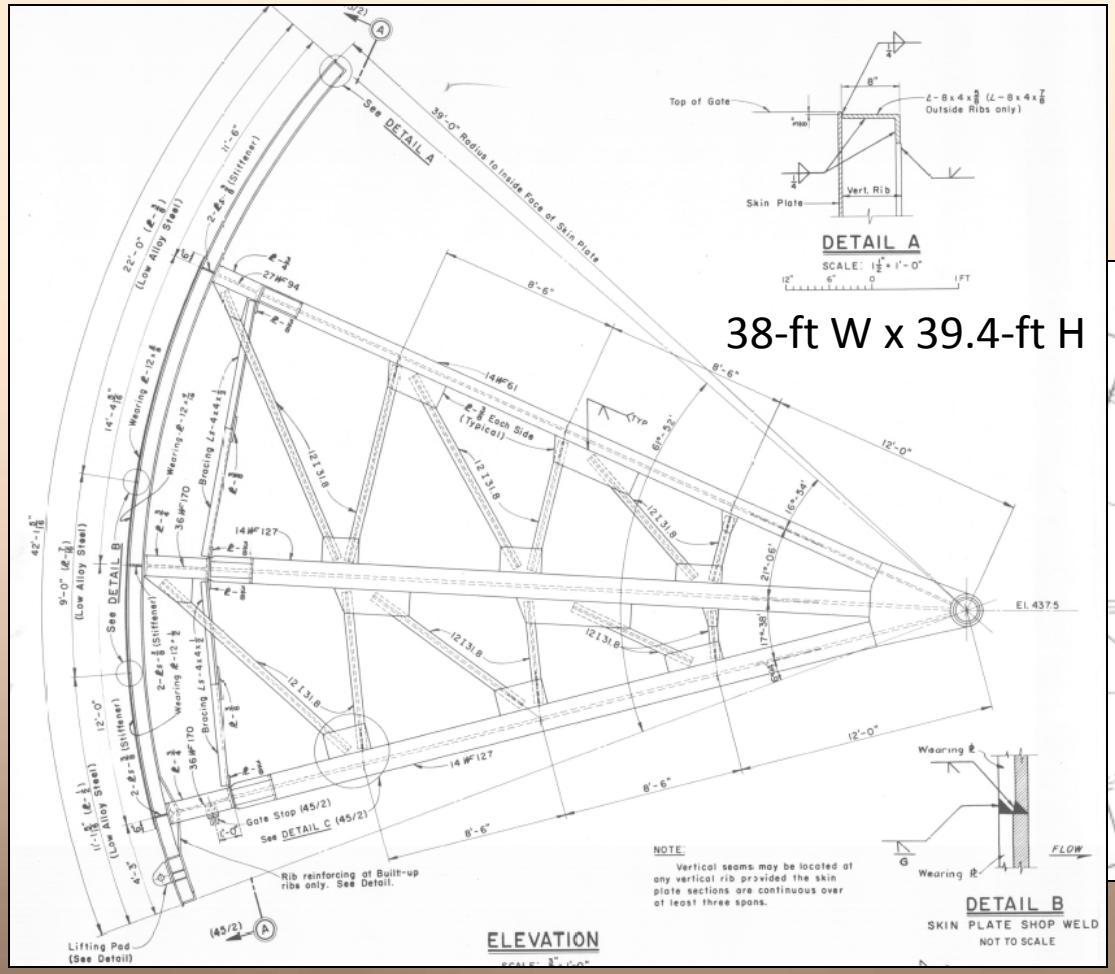
Concrete Spillway Section



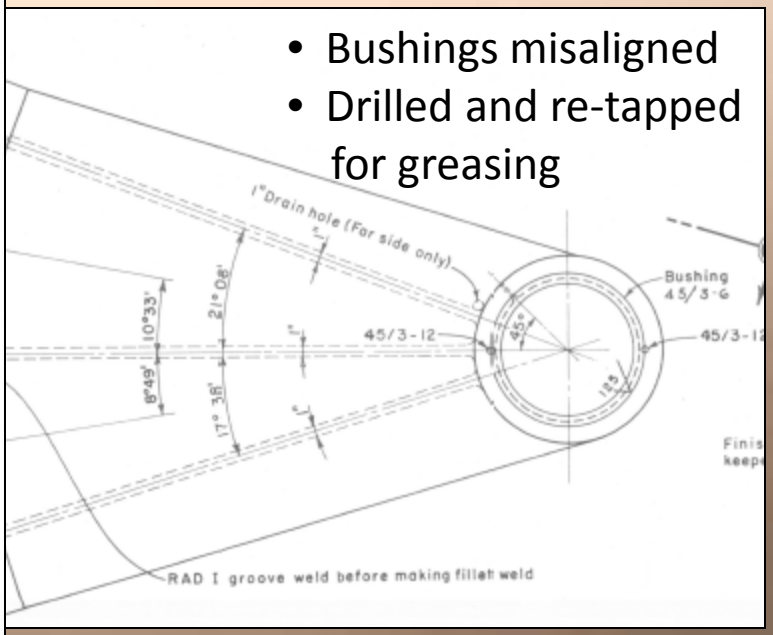
Low foundation water pressures

Note upstream dipping excavation

Tainter Gates



38-ft W x 39.4-ft H



- Bushings misaligned
- Drilled and re-tapped for greasing

Risk-Driver Potential Failure Mode

- Buckling of Tainter gate arm due to trunnion friction during initial opening
  - Failure likelihood: Moderate but low confidence
    - Problems with bushings, original design analysis shows combined stress ratio approaching 1 without friction, no trunnion friction analyses have been performed.
    - O&M staff has kept bushings lubricated (tipped scale to unlikely side).
    - Recommend SOP for trunnion lubrication and possibly trunnion friction analysis/measuring trunnion friction.

Risk-Driver Potential Failure Mode

- Buckling of Tainter gate arm due to trunnion friction during initial opening
  - Consequences: Level 1 with high confidence
    - Failure of one gate within channel capacity.
    - Only population at risk might be fishermen.
    - Short distance to safety.

Solutioned Limestone Treatment in Cutoff Trench Excavation

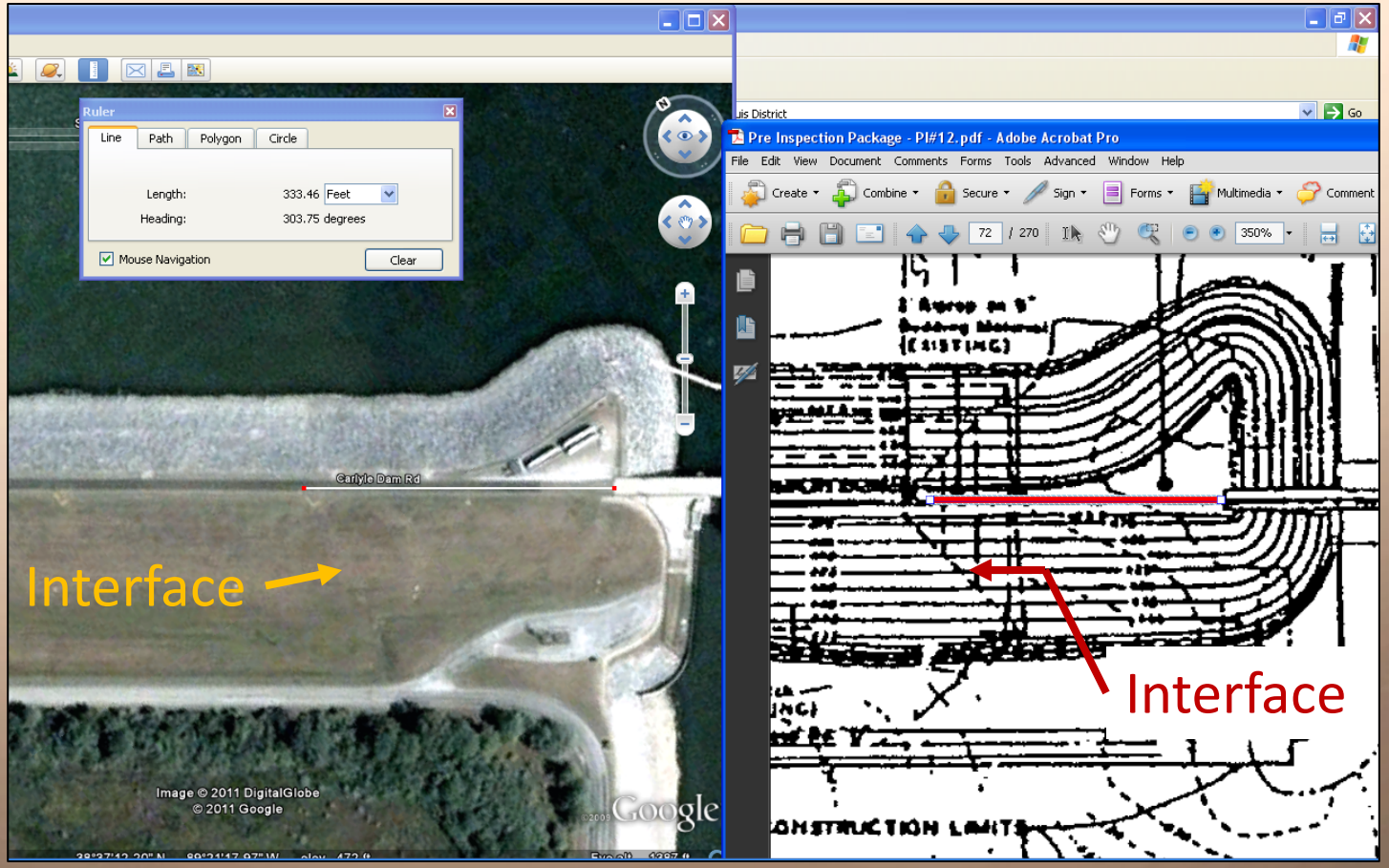
Risk-Driver Potential Failure Mode

- Erosion of foundation soils and embankment into and through solutioned joints
  - Failure likelihood: Low to moderate with moderate confidence
    - Foundation treatment in cutoff trench was good.
    - Uncertainties with geology, pressures, and gradients downstream of the cutoff trench, along with difficulties in monitoring led to dual classification.
    - Recommend possible additional piezometers.

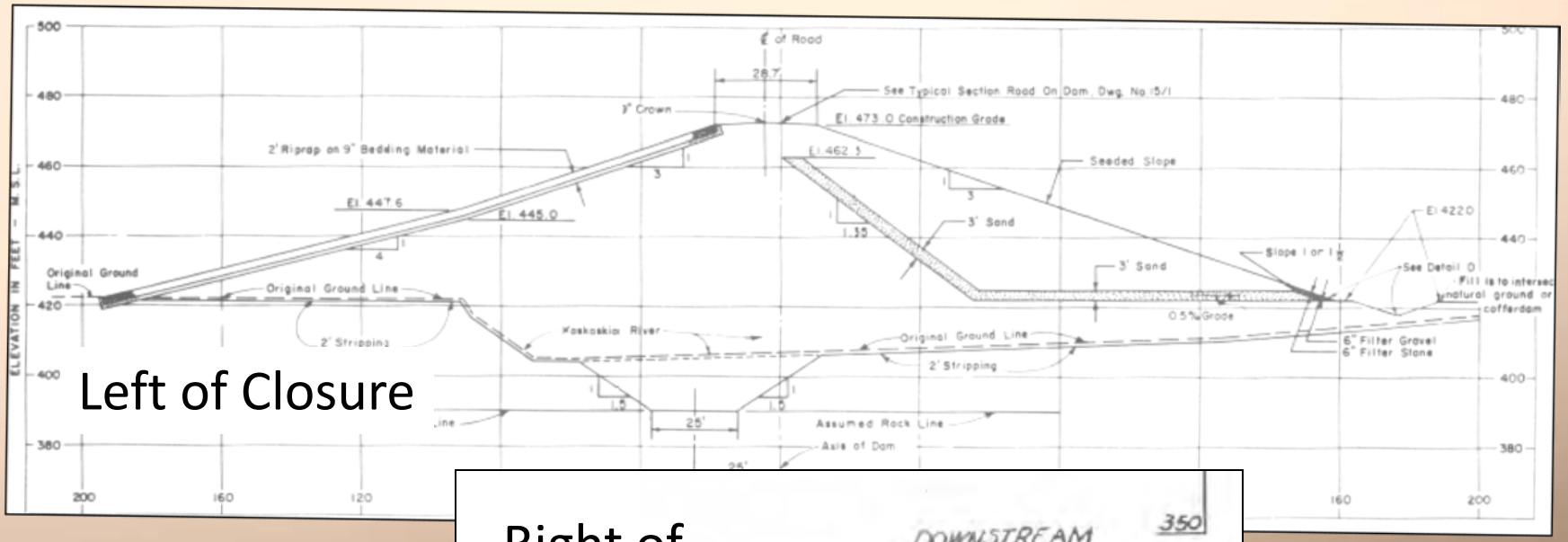
Risk-Driver Potential Failure Mode

- Erosion of foundation soils and embankment into and through solutioned joints
  - Consequences: Level 2 with high confidence
    - Life-threatening flows could be released.
    - Failure mode would take some time to develop due to soil plasticity; evacuation could be effective.
    - Only a few structures on the edge of town would be inundated.

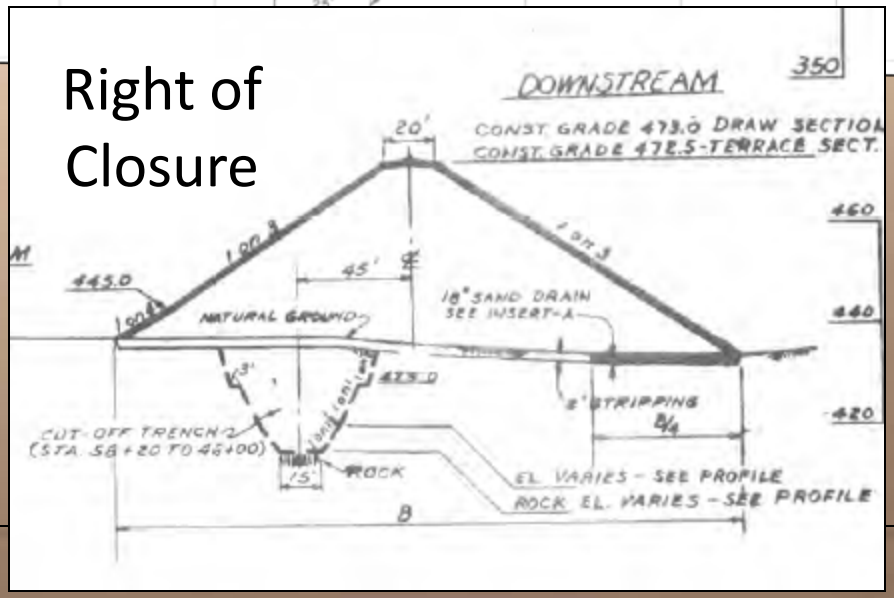
Phase 1 / 3 Embankment Interface



Embankment Sections



Left of Closure



Right of Closure

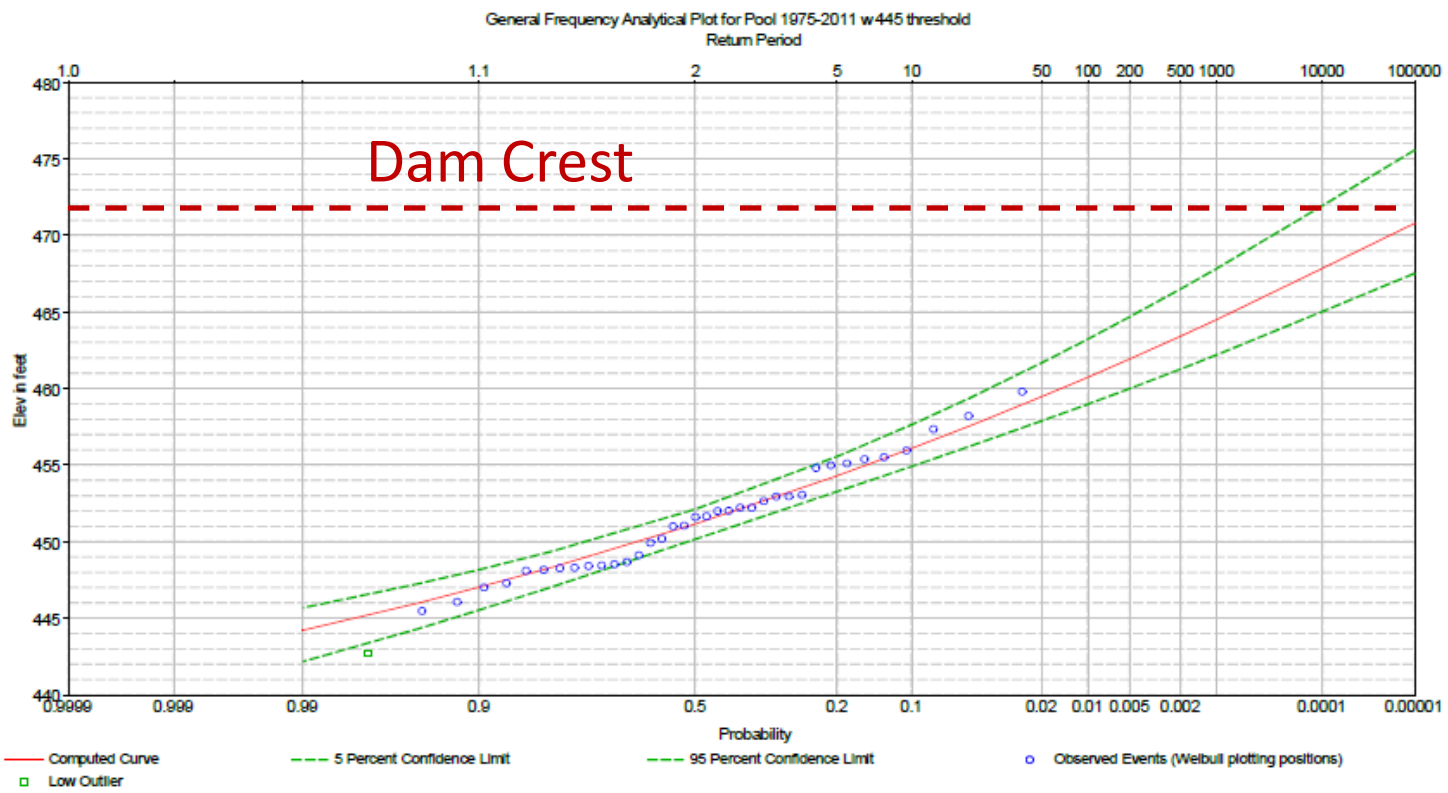
Risk-Driver Potential Failure Mode

- Internal erosion along defect between Phase 1 and Phase 3 embankments
  - Failure likelihood: High but low confidence
    - Phase 1 exposed up to 5 years.
    - Nothing in specifications to indicate special treatment.
    - Discontinuity in internal drainage/filter details.
    - Wet spots on downstream face in this area.
    - Recommend additional exploration (possible trenching, piezometers)

Risk-Driver Potential Failure Mode

- Internal Erosion Along Defect between Phase 1 and Phase 3 Embankments
  - Consequences: Level 2 with high confidence
    - Life-threatening flows could be released,
    - Failure mode would take some time to develop due to soil plasticity; evacuation could be effective.
    - Only a few structures on the edge of town would be inundated.

Stage-Frequency Curve



General Frequency Analytical Plot for Pool 1975-2011 with 445 Threshold

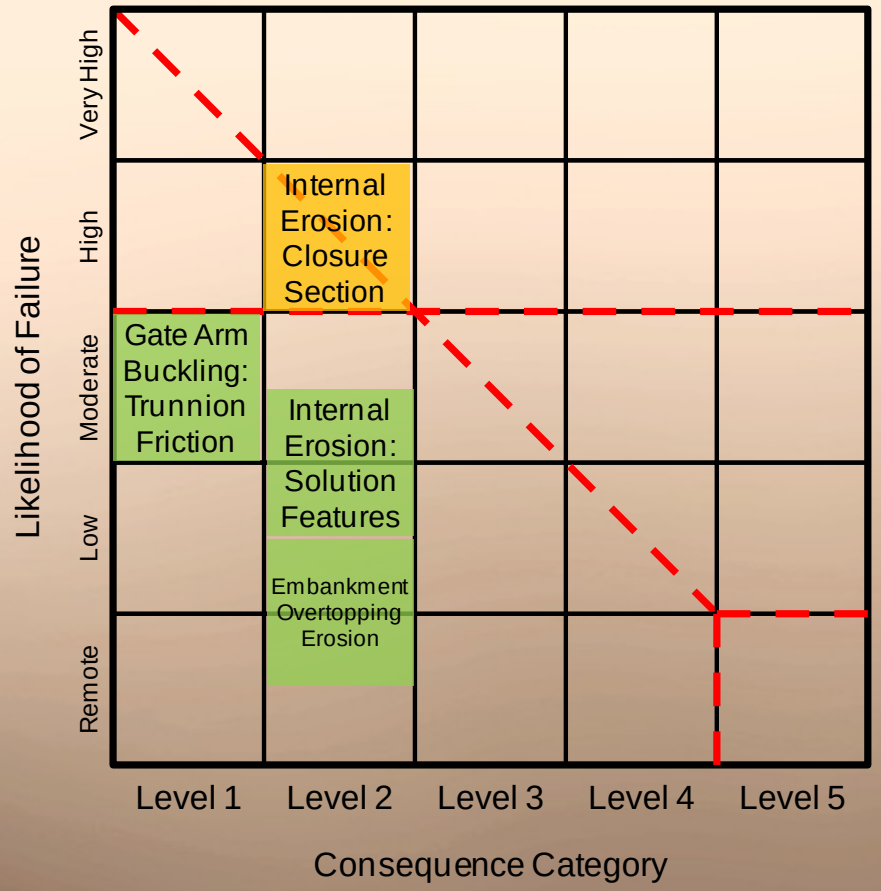
Risk-Driver Potential Failure Mode

- Flood overtopping erosion
  - Failure Likelihood: Low to remote with moderate confidence
    - Overtopping flood has low AEP (~1 in 100,000/yr).
    - Methodology used for flood-frequency plot simplified; a more detailed study could show different results.

Risk-Driver Potential Failure Mode

- Flood overtopping erosion
  - Consequences: Level 2 with moderate confidence
    - Flows would be life-threatening due to the large volume of water released.
    - Inundation boundary estimated to be slightly larger than under normal conditions.
    - Should be good warning.
    - Uncertainties relate to location of breach and how quickly it would develop.

Risk Matrix
(Incremental Consequences)



Confirm and Prioritize recommendations based on risk.

Take Away Points

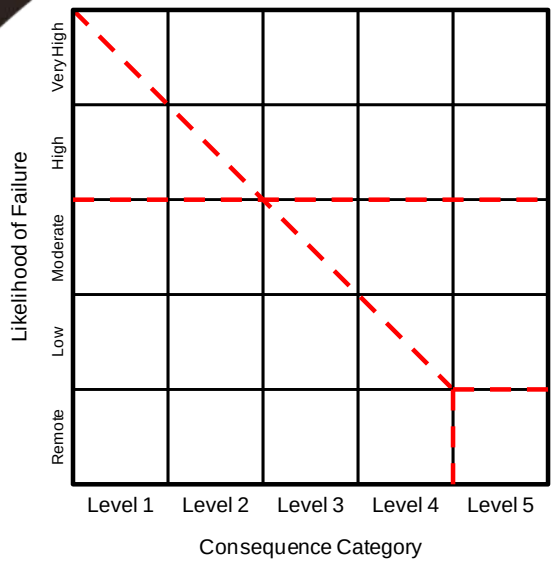
- Potential Failure Mode Analysis is the first and most important step in Risk-Informed Decision Making.
- If this isn't done right, the rest doesn't matter.
- Review all background material.
- Include operations personnel.
- Think beyond traditional analyses.

Conclusions

- Potential failure modes analysis, assigning likelihood and consequence categories, and plotting on an incremental risk matrix provide a relevant risk categorization system.
- Using a risk matrix to conduct qualitative or semi-quantitative risk assessments is a useful and quick means to prioritize dam safety activities, especially to determine where higher level studies would be beneficial.

Questions, Comments, or Discussion

Thank you for your attention.



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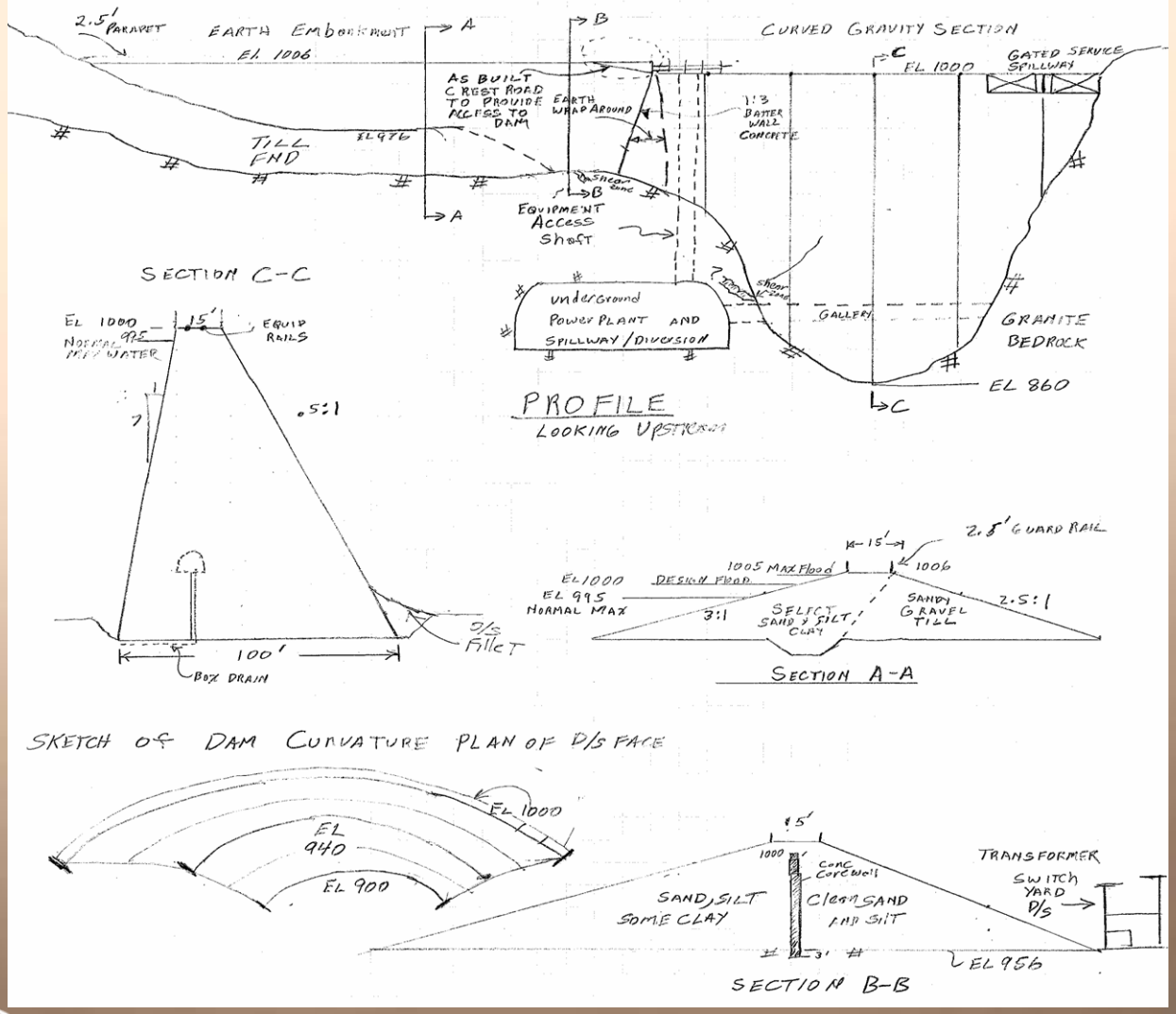
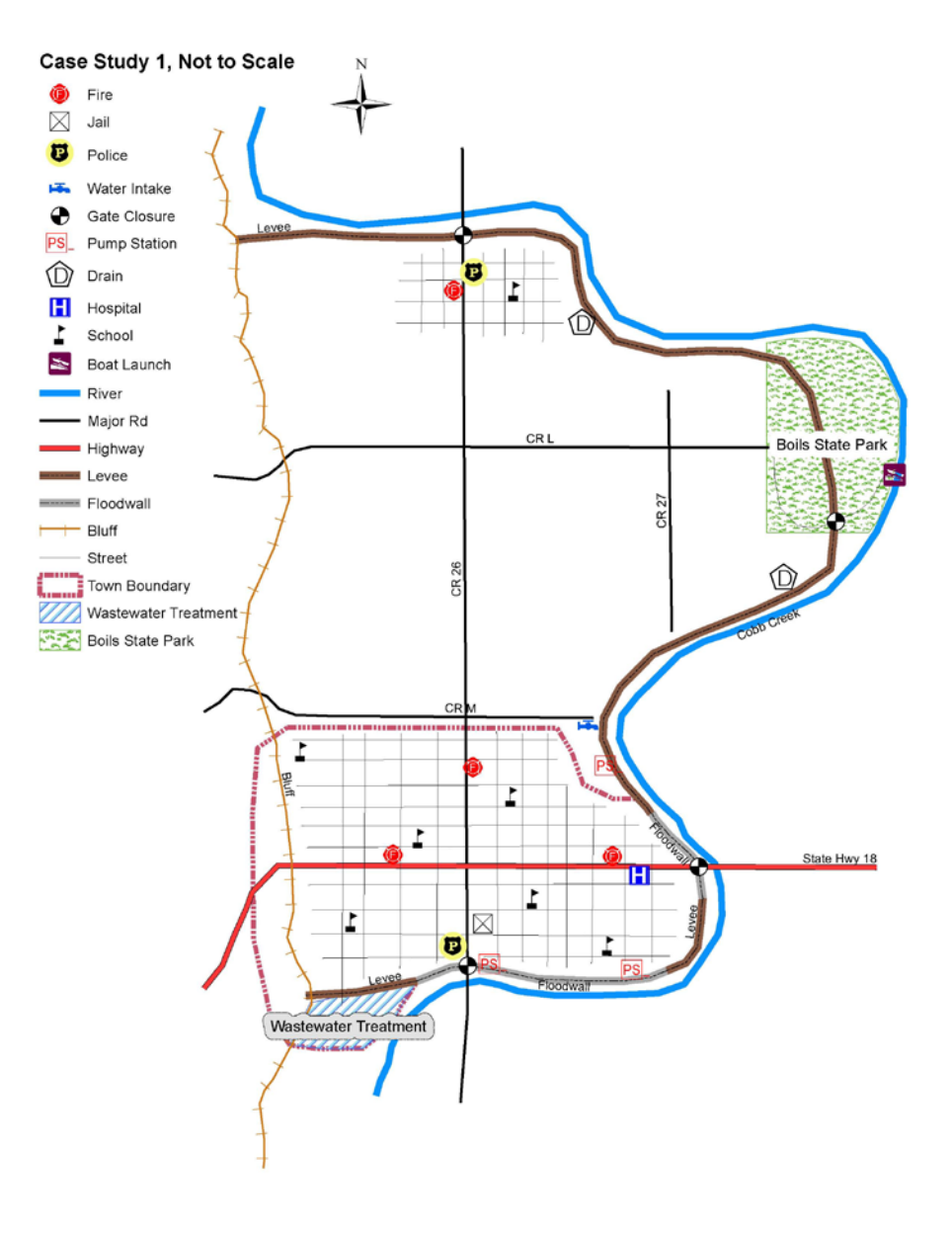
Evans Creek Dam and Power Plant

Sketch of Profile and Cross Sections



Use Evans Creek example if audience is mostly interested in dam safety rather than levee safety

Cobb Creek Levee



Use Cobb Creek example if audience is primarily interested in levee safety rather than dam safety

Practice Session 1: Identify and Describe a Potential Failure Mode

1. Read hand out material and examine sketch.

2. In groups of two or three, propose potential failure modes; agree on a viable/credible candidate potential failure mode.

3. Develop a potential failure mode description that can be clearly understood by a reader in 5 years.

Practice Session 2: Potential Failure Mode Analysis

For the potential failure mode you previously described:

- Identify more likely / adverse factors.
- Identify less likely / favorable factors.
- Classify the potential failure mode according to its semi-quantitative likelihood and consequences category; provide a confidence and rationale for each (Evans Creek only).
- Rank the potential failure modes from most critical to least critical (Cobb Creek only).
- Plot the potential failure mode(s) on the risk matrix.
- Identify potential interim risk reduction measures, monitoring, analyses, and/or data needs.

Possible Exercise Solution (Evans Creek Dam)

- Potential Failure Mode 1: Piping of sand and silt from embankment founded on rock
  - Failure likelihood: Low to moderate
    - There is no direct or indirect evidence (e.g., observed movement of fines, sinkholes) to suggest this potential failure mode is likely. Therefore, the evidence is weighted toward unlikely.
    - However, with the unprotected seepage exit, high seepage volumes, and inability to detect fines movement some weight must be given to the potential for it to develop.

Potential Exercise Solution (Evans Creek Dam)

– Consequences: Level 2

- It is expected that this potential failure mode will take some time to develop due to the presence of the concrete core wall, and there will be indications that it is in progress (e.g., slumping on the downstream face) so that there should be time to initiate warnings.
- Although the embankment represents a small height of the dam, downstream property damage is likely, and life loss is possible due to difficulties in warning and evacuating all exposed individuals.

Possible Exercise Solution (Evans Creek Dam)

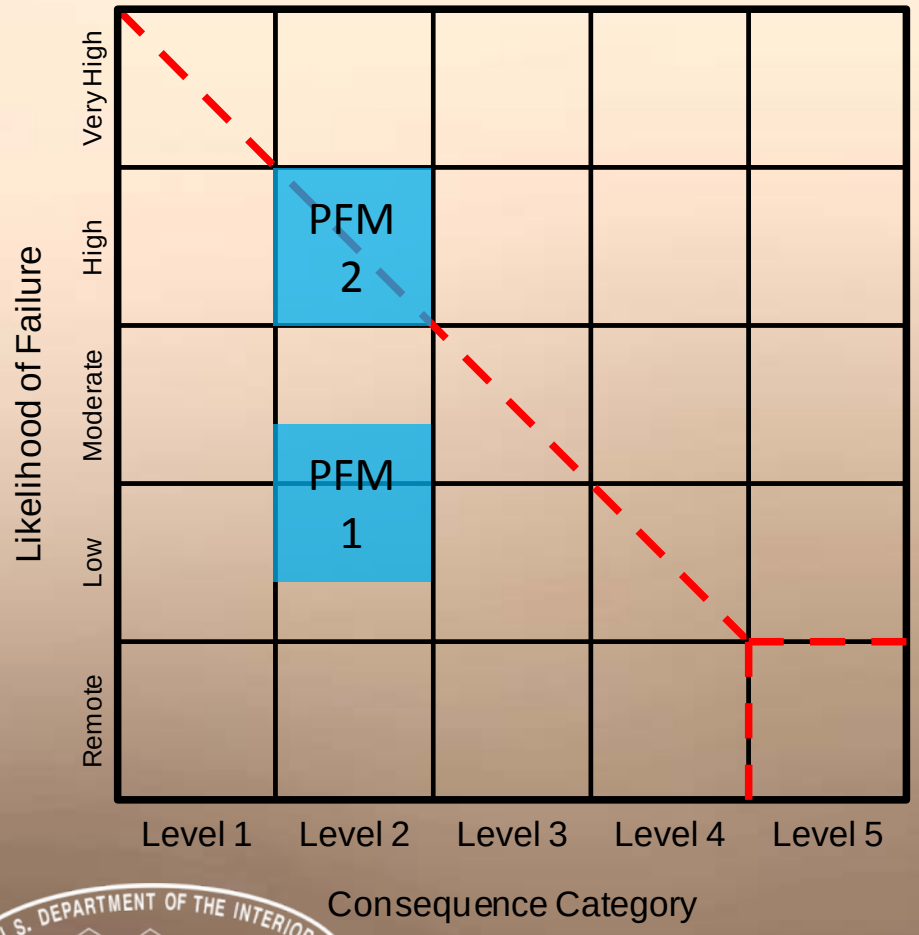
- Potential Failure Mode 2: Overtopping erosion of embankment adjacent to concrete section
  - Failure likelihood: High
    - A flood with an ACE of somewhat less than 1/7,500 would likely cause failure.

Potential Exercise Solution (Evans Creek Dam)

– Consequences: Level 2

- It is expected that this potential failure mode will take some time to develop due to the presence of the concrete core wall, and there will be indications that it is in progress (such as slumping on the downstream face) so that there should be time to initiate warnings.
- Even though the embankment represents a small height of the dam, downstream property damage is likely, and loss of life is possible due to difficulties in warning and evacuating all exposed individuals.

Potential Exercise Solution (Evans Creek Dam)

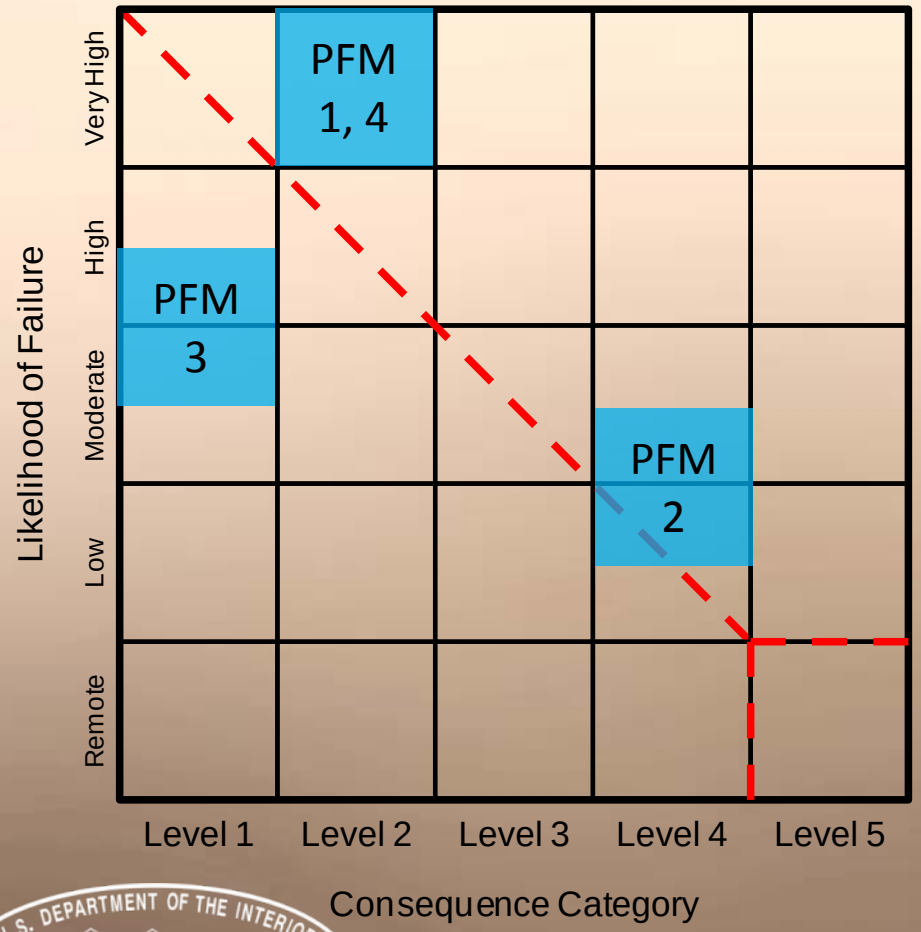


<u>Risk-Driver PFMs</u>

PFM 1: Piping of sand and silt from embankment founded on rock

PFM 2: Overtopping erosion of embankment adjacent to concrete section

Potential Exercise Solution (Cobb Creek Levee)



Risk-Driver PFMs

PFM 1: Backward erosion piping through the foundation at Boils State Park

PFM 2: Misoperation/malfunction of Highway 17 closure

PFM 3: Collapse of CMP drainage pipe

PFM 4: 1000-year flood occurs

Note: PFM 2 is the highest risk due the incremental life loss potential, but PFM 4 and PFM 1 have higher failure likelihood (but with lower incremental life loss).