RISK ASSESSMENT FOR DAMS AND LEVEES

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Outline

- Dams and Levees
- Decisions
- Screening
- Non-Routine
- Example
- Conclusion

Critical Risk Integral

$$\int beer = happiness$$

Dams vs. Levees

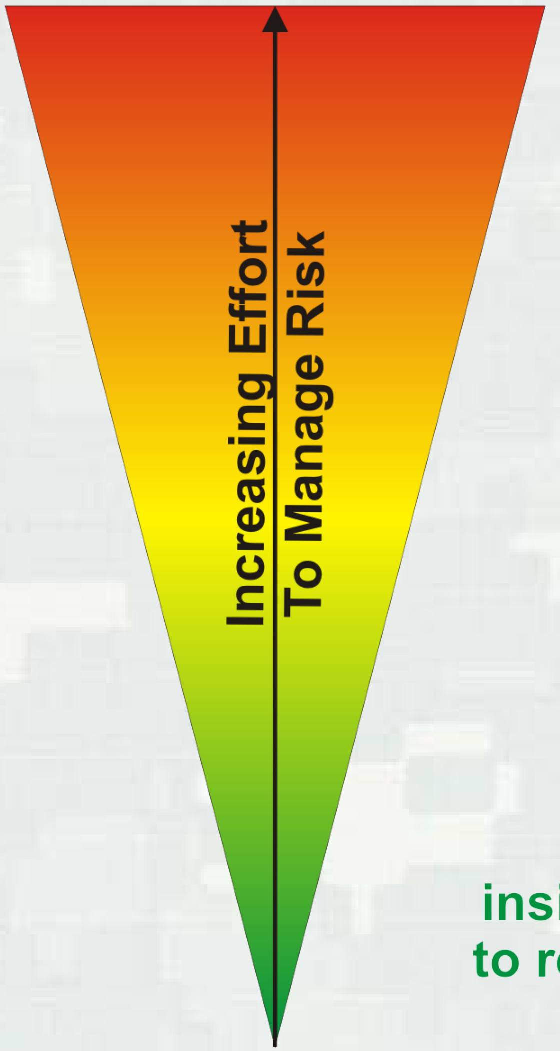
Dams

- Tall
- Narrow
- Much Information
- Built by the Corps
- Owned by the Corps
- Long Performance History

Levees

- Short
- Long
- No Information
- Built by Farmer Paul
- Owned by Someone
- No Performance History

Tolerable Risk Framework



Unacceptable Region

Risks cannot be justified except in extraordinary circumstances

Tolerable/ Intolerable Region

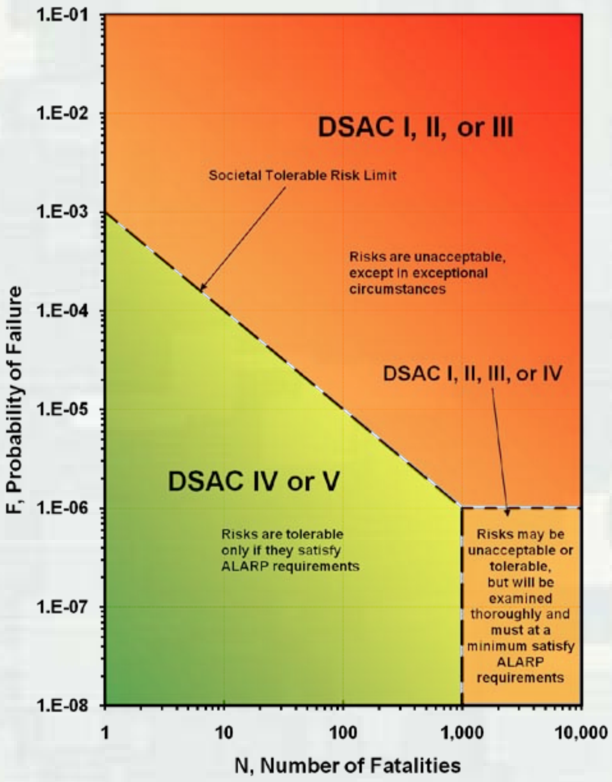
People and society are prepared to accept risk in order to secure benefits

Broadly Acceptable Region

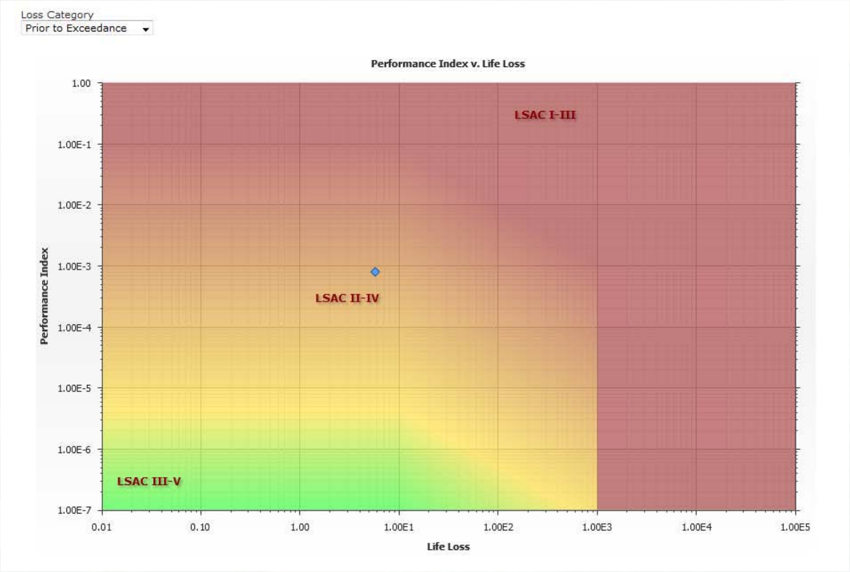
Risk regarded as insignificant, further effort to reduce risk not required unless easily achieved

Decisions Drive Process

Dams



Levees



Dam Safety Action Class

Table 2.1 USACE Dam Safety Action Classification Table*		
Dam Safety Action Class	**Characteristics of this class**	**Actions for dams in this class**
I **URGENT AND COMPELLING** (Unsafe)	**CRITICALLY NEAR FAILURE** Progression toward failure is confirmed to be taking place under normal operations. Almost certain to fail under normal operations from immediately to within a few years without intervention. **OR EXTREMELY HIGH RISK** Combination of life or economic consequences with probability of failure is extremely high.	Take immediate action to avoid failure. Validate classification through an external peer review. Implement interim risk reduction measures, including operational restrictions, and ensure that emergency action plan is current and functionally tested for initiating event. Conduct heightened monitoring and evaluation. Expedite investigations to support justification for remediation using all resources and funding necessary. Initiate intensive management and situation reports.
II **URGENT** (Unsafe or Potentially Unsafe)	**FAILURE INITIATION FORESEEN** For confirmed (unsafe) and unconfirmed (potentially unsafe) dam safety issues, failure could begin during normal operations or be initiated as the consequence of an event. The likelihood of failure from one of these occurrences, prior to remediation, is too high to assure public safety. **OR VERY HIGH RISK** The combination of life or economic consequences with probability of failure is very high.	Implement interim risk reduction measures, including operational restrictions as justified, and ensure that emergency action plan is current, and functionally tested for initiating event. Conduct heightened monitoring and evaluation. Expedite confirmation of classification. Give very high priority for investigations to support justification for remediation.
III **HIGH PRIORITY** (Conditionally Unsafe)	**SIGNIFICANTLY INADEQUATE OR MODERATE TO HIGH RISK** For confirmed and unconfirmed dam safety issues, the combination of life or economic consequences with probability of failure is moderate to high.	Implement interim risk reduction measures, including operational restrictions as justified, and ensure that emergency action plan is current and functionally tested for initiating event. Conduct heightened monitoring and evaluation. Prioritize for investigations to support justification for remediation considering consequences and other factors.
IV **PRIORITY** (Marginally Safe)	**INADEQUATE WITH LOW RISK** For confirmed and unconfirmed dam safety issues, the combination of life or economic consequences with probability of failure is low and may not meet all essential USACE guidelines.	Conduct elevated monitoring and evaluation. Give normal priority to investigations to validate classification, but no plan for risk reduction measures at this time.
V **NORMAL** (Safe)	**ADEQUATELY SAFE** Dam is considered safe, meeting all essential USACE guidelines with no unconfirmed dam safety issues. **AND RESIDUAL RISK IS CONSIDERED TOLERABLE.**	Continue routine dam safety activities, normal operation, and maintenance.

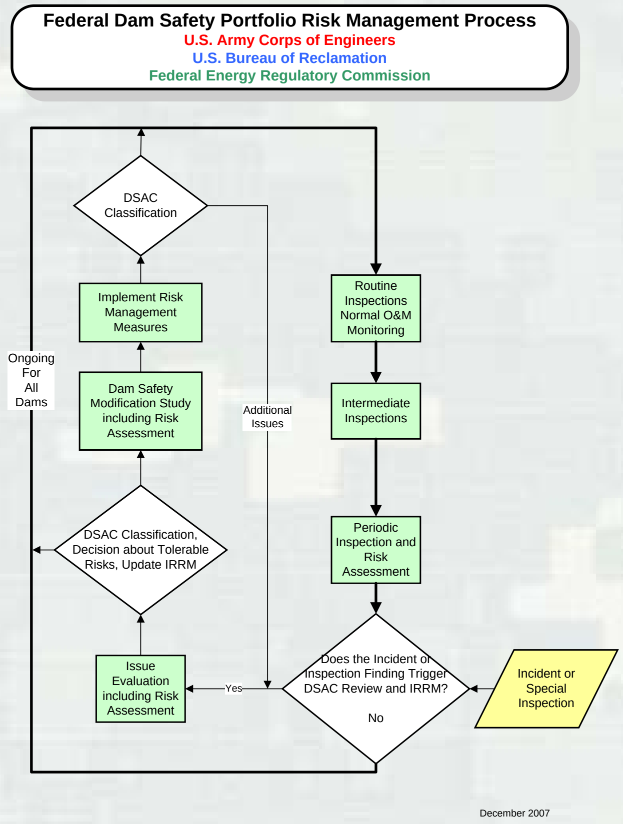
* At any time for specific events a dam, from any action class, can become an emergency requiring activation of the emergency plan

Levee Safety Action Class

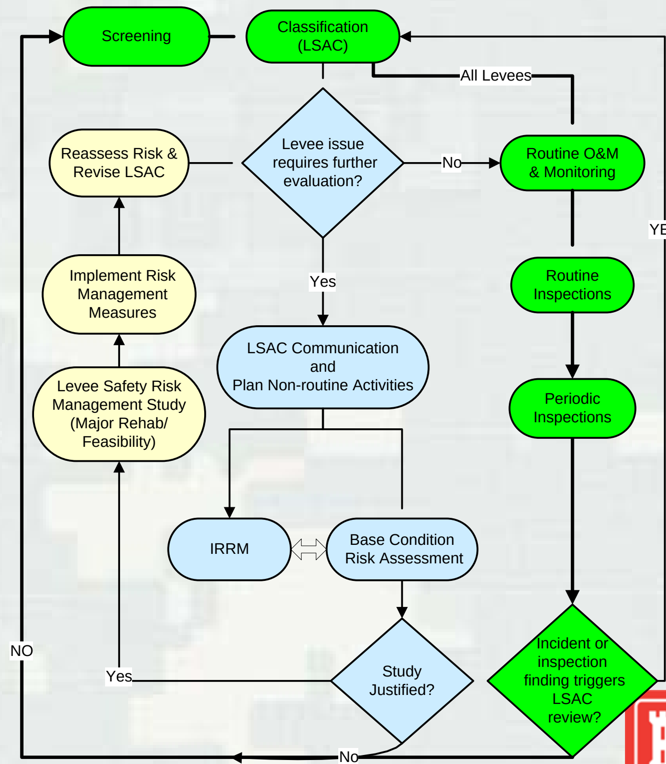
Levee Safety Action Classification			
Class	Urgency	Characteristics	Actions
I	Urgent and Compelling (Unsafe)	Likelihood of inundation with associated consequences characterizing each class.	Actions recommended for each class and level of urgency.
II	Urgent (Unsafe or Potentially Unsafe)		
III	High Priority (Potentially Unsafe)		
IV	Priority (Marginally Safe)		
V	Normal (Adequately Safe)		

Dams vs. Levees

Dams



Levees



General Philosophy

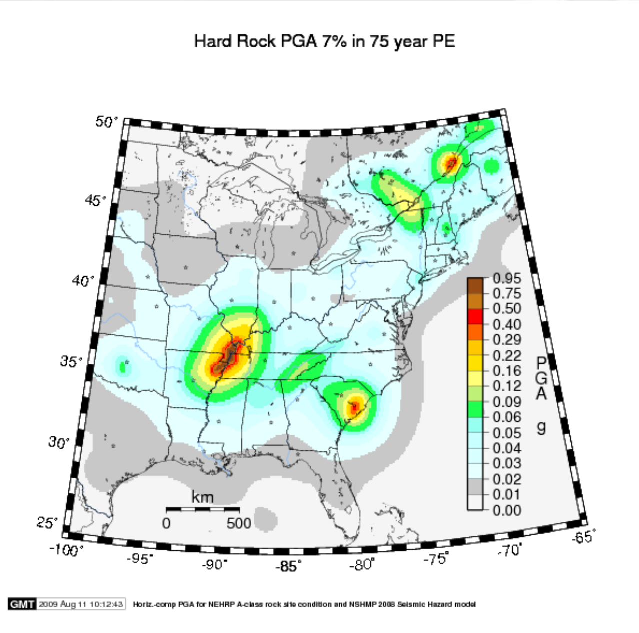
- Screening – rapid pass through the portfolio
- Periodic Assessment – recurring examination of risks
- Issue Evaluation – trying to decide if risks are actually issues
- Modification – trying to decide the best method to address identified risks

Dam Screening

- Focus of screening is to make consistent risk evaluations
- Secondary focus of screening is to make accurate risk evaluations
- Less than 4 hours per dam, 7 raters
- Answer:
  - Adequate, Probably Adequate, Probably Inadequate, Inadequate
  - OBE, MCE

Levee Screening

- Focus of screening is to make consistent risk evaluations
- Secondary focus of screening is to make accurate risk evaluations
- Less than 20 hours per levee
- 1 rater
- Answer:
  - ►Integrated seismic probability
  - ►Qualitative Answers



Screening Objectives

- Conservatively determine the likelihood of seismic failure relative to the portfolio of all dams
- Important conclusions:
  - Is it obviously ok?
  - Is it obviously a problem?
  - Does it require more study? If so, in what way?

Screening Conclusions

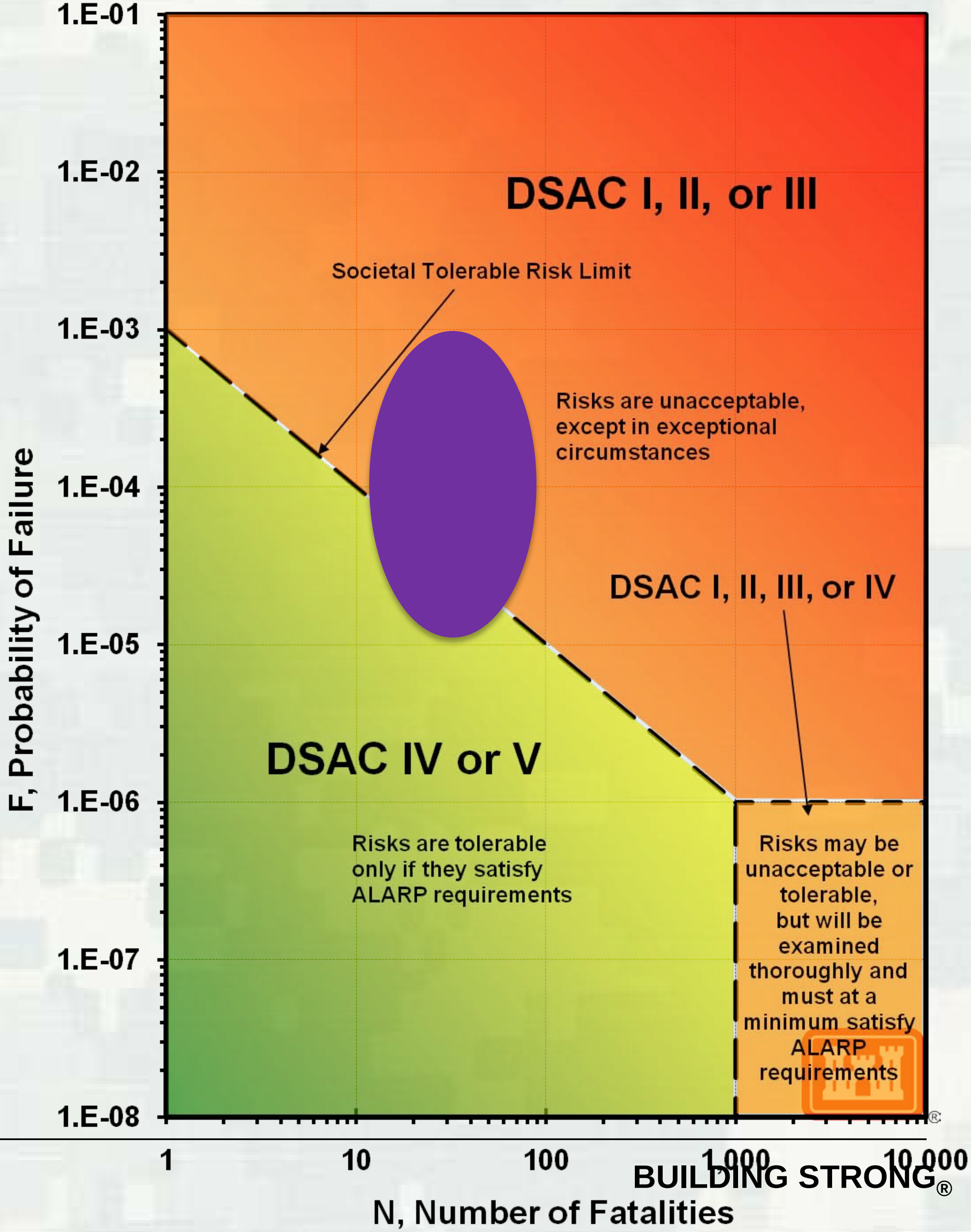
Dams

Engineering Rating Summary					
Feature Flood Control Dam	Normal Water Level	50% Exceedence Duration Normal Water Level with OBE	50% Exceedence Duration Normal Water Level with MDE	Unusual (300yr)	Extreme - (PMF)
Concrete Gravity Section					
External Stability	PI	A	PA	PI	PI
Internal Stability	PI	A	PA	PI	PI
Foundation Stability	PA	A	PA	PA	PA
Foundation - Seepage & Piping	PI	A	A	PI	PI
........................Void	NA	NA	NA	NA	NA
Abutment Foundation Stability (Dam Structure)	PA	A	PA	PA	PA
Spillway and/or Stilling Basin System					
Structural Stability	PI	A	PA	PI	PI
Structural Capacity	PI	A	PA	PI	PI
Walls - Overtopping	A	A	A	A	A
Gates - Structural, Electrical and Mechanical	A	A	A	A	A
Gate Piers - Structural Capacity	A	A	A	A	A
Erodibility	A	A	A	A	A
........................Void	NA	NA	NA	NA	NA
Sill	A	A	A	A	A
Outlet Works and Conduits					
Embankment Piping at Conduit	NA	NA	NA	NA	NA
Gates - Structural, Electrical and Mechanical	PA	A	PA	PA	PA
Intake Tower Stability	NA	NA	NA	NA	NA
Intake/Tunnel/Conduit Structural Failure	NA	NA	NA	NA	NA
Tunnel/Conduit Joint Failure	NA	NA	NA	NA	NA
Embankment					
Embankment Seepage & Piping	NA	NA	NA	NA	NA
Erosion: Toe, Surface & Crest	A	A	A	A	A
Abutments Seepage & Piping	NA	NA	NA	NA	NA
Abutments Stability and/or Liquefaction	NA	NA	NA	NA	NA
Foundation Seepage & Piping	NA	NA	NA	NA	NA
Embankment Stability and/or Liquefaction	NA	NA	NA	NA	NA
Foundation Stability and/or Liquefaction	NA	NA	NA	NA	NA
Reservoir Rim					
Stability - Landslide	A	A	PA	A	A
Loss of Storage Capacity - Silt	A	A	A	A	A
Erosion	A	A	A	A	A
Mines	NA	NA	NA	NA	NA

Levees

Performance Type	Performance Index	Life Safety Index	Economic Index
Capacity Exceedance	88.18%	83.13%	88.18%
Embankment and Foundation Seepage and Piping	4.36%	6.28%	4.36%
Embankment Stability	.02%	.03%	.02%
Embankment Erosion	.11%	.17%	.11%
Closure Systems	.3%	.28%	.3%
Floodwall Stability	2.81%	4.05%	2.81%
Floodwall Underseepage and Piping	4.21%	6.06%	4.21%

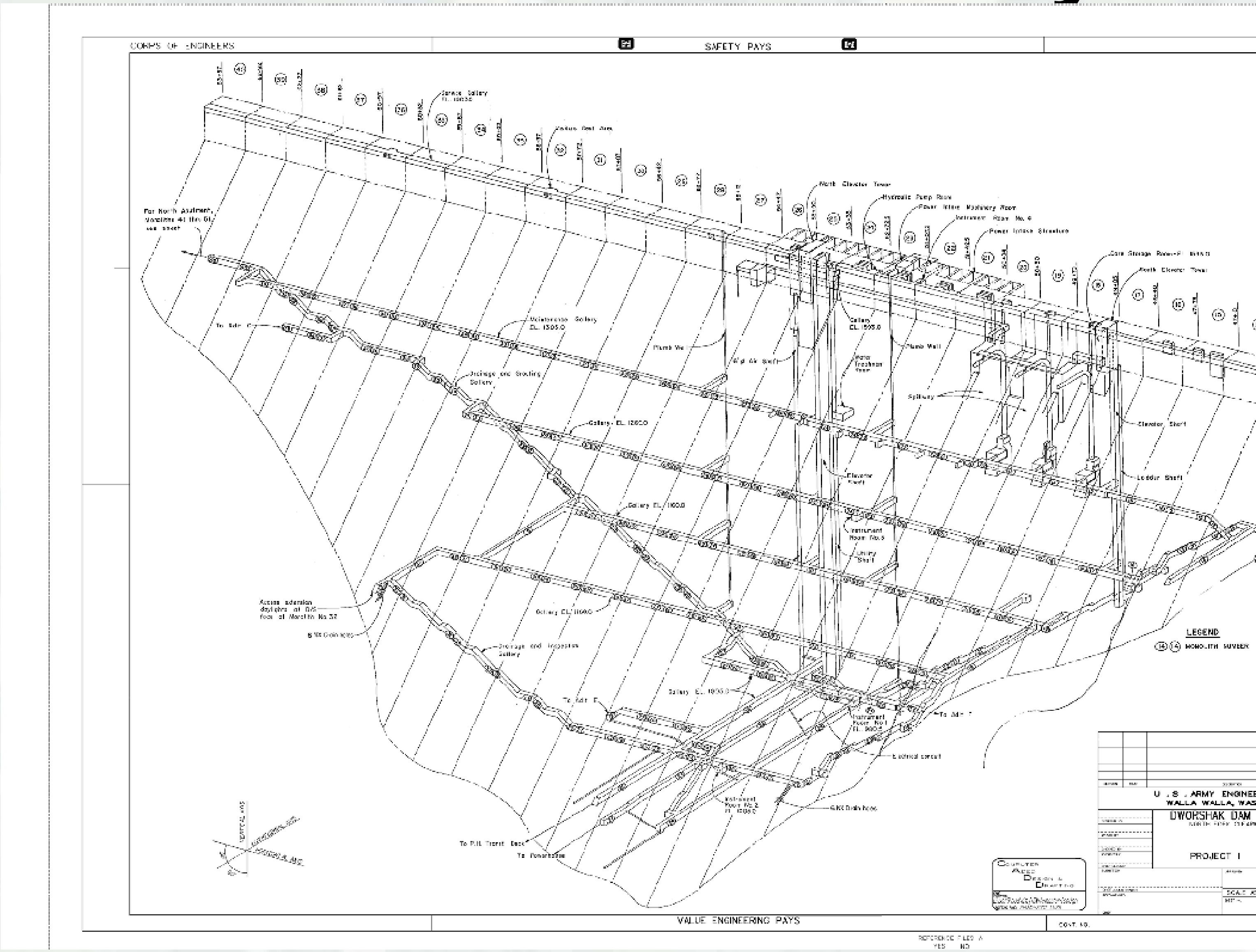
Societal Tolerable Risk Chart



Periodic Assessments

- Shift focus to failure modes
- Increase accuracy using event tree models
- Increase accuracy with small loss in consistency
- Completed by one person
- Peer reviewed by another person
- Agency Technical Review
- Senior Oversight Group

Seismic Stability



Seismic Failure Modes

- PFM 7 Failure of spillway gates due to EQ
- PFM 32 Instability of monolith section with longitudinal (vertical) cracking
- PFM 33 Instability of monolith uncracked sections

Seismic Loading

External Stability of the Concrete Dam (PFM#33) – Uncracked Section

- Assumptions remain the same as in hydrologic loading for analysis parameters.
  - Phi 79.6 degrees and cohesion 212 psi (mean value)
- M19 and M23 analyzed.
- Horizontal acceleration assumed to be 2/3 PGA.
- Vertical acceleration assumed to be 0.1 to 0.25 of PGA (uniformly distributed)
  - Values and range decided upon after consultation with Dr. Bob Ebeling of ERDC
- PGA obtained from USGS ground motion calculator.

PFM#33- Risk Analysis Results Sliding at Base

- Seismic analysis done for PGAs ranging from 0.025g to 0.55g
- Non-zero probabilities of exceeding limit states were not reached until a PGA of 0.45g and a pool elevation of 1603.32 (M19) or PGA reached 0.55g with lower reservoir levels.
- Tables reflect *conditional* probability of limit state (FS<1 for sliding along base) being exceeded given combination of seismic load and coincident pool.
- Limit state analysis controlled by shear failure of toe as opposed to sliding along dam/foundation interface

Monolith 19

Pool (NAVD88)	Static	PGA 0.45	PGA 0.55
1553.32	0.00	0.00	0.00
1573.32	0.00	0.00	0.12
1583.32	0.00	0.00	0.39
1593.32	0.00	0.00	0.80
1603.32	0.00	0.07	1.00
1606.32	0.00	0.17	1.00
1609.32	0.00	0.28	1.00
1612.32	0.00	0.38	1.00
1614.32	0.00	0.45	1.00
1616.32	0.00	0.54	1.00
1624.4	0.00		

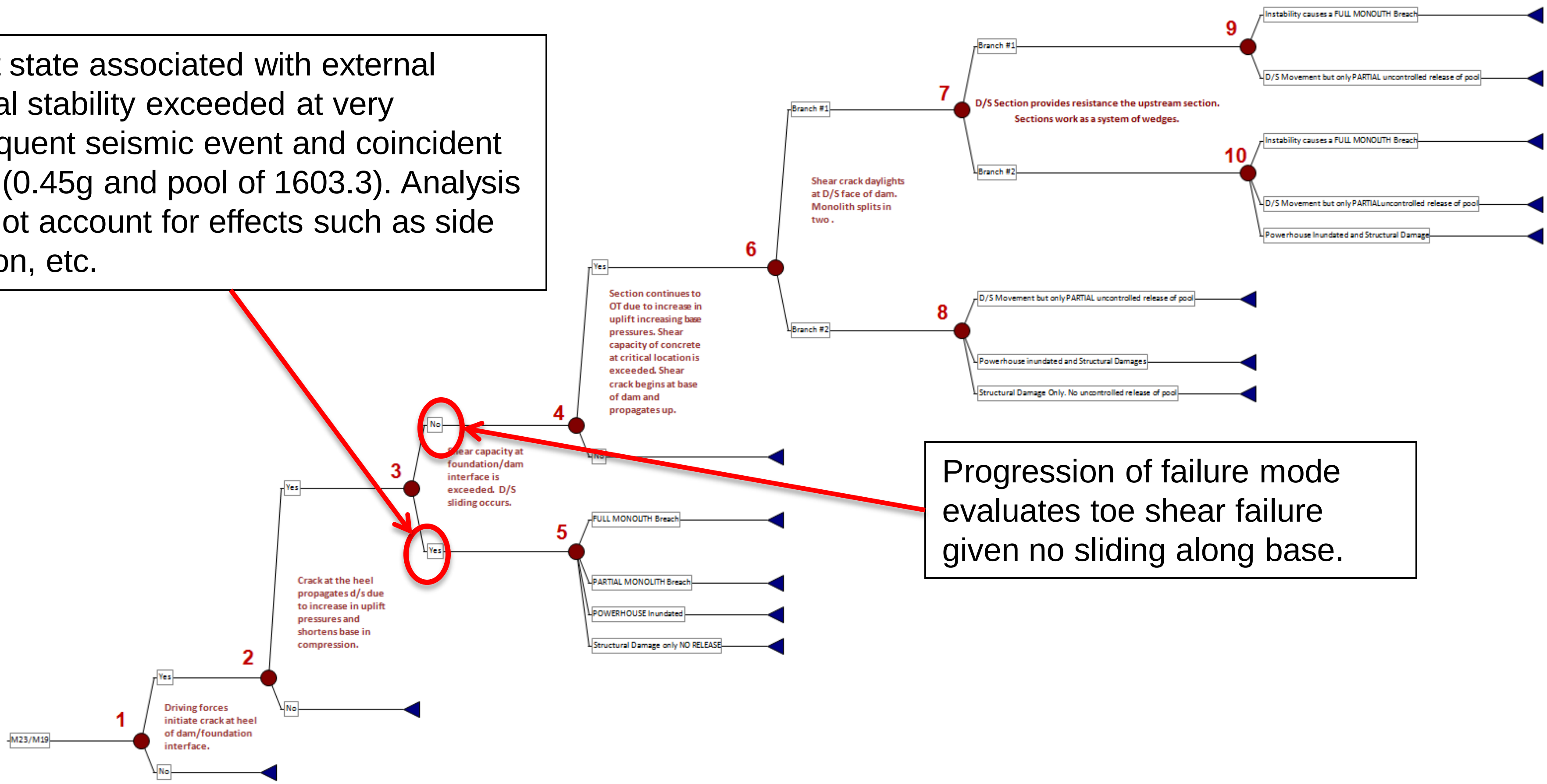
Monolith 23

Pool (NAVD88)	SRP	PGA 0.45	PGA 0.55
1553.32	0.00	0.00	0.12
1573.32	0.00	0.00	0.16
1583.32	0.00	0.00	0.21
1593.32	0.00	0.00	0.35
1603.32	0.00	0.00	0.39
1606.32	0.00	4.38E-11	0.43
1609.32	0.00	2.48E-07	0.47
1612.32	0.00	1.22E-06	0.51
1614.32	0.00	3.65E-05	0.56
1616.32	0.00	1.91E-04	0.59
1624.4	0.00		

Seismic Loading

PFM #33 - M19 and M23 Event Tree

Limit state associated with external global stability exceeded at very infrequent seismic event and coincident pool (0.45g and pool of 1603.3). Analysis did not account for effects such as side friction, etc.

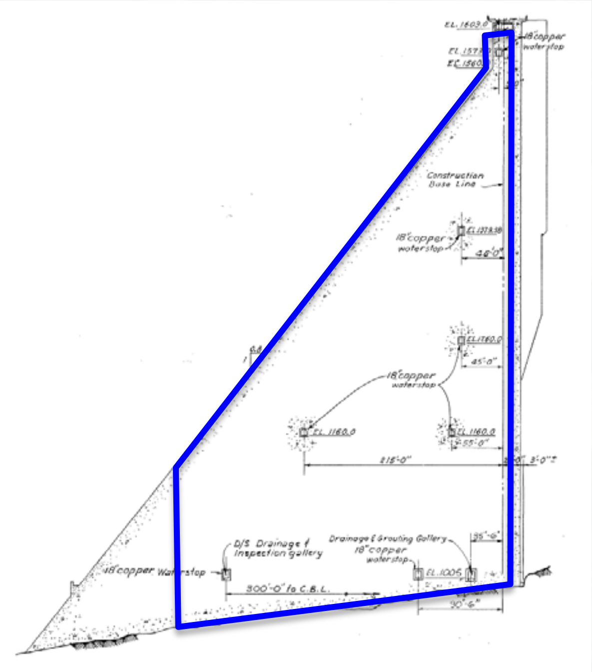


Progression of failure mode evaluates toe shear failure given no sliding along base.

Seismic Loading

PFM #33 – Toe Shear Failure of Non-cracked Section

- Analysis variables were carried over from external stability analysis including drain efficiency.
- Full value of PGA assumed to calculate shear demand.
- Base pressures calculated on a per foot basis.
- Base pressures compared to the concrete shear capacity at a “critical” location and a factor of safety was calculated.
- Two analysis ran with shear capacities of **500** psi (from unconfined testing) and **1000** psi.
- Shear capacity of 1000 psi reasonable assumption based on final concrete testing report dated December 1967.



Remaining u/s portion no longer stable

Seismic Loading

Internal Stability Uncracked Section Risk Analysis Results

Shear Capacity = 500 psi

Pool (NAVD88)	Static	0.125g	0.175g	0.225g	0.275g
1553.32	1.86	1.34	1.2	1.08	0.94
1593.32	1.58	1.17	1.03	0.88	
1603.32	1.52	1.12	0.98		
1609.32	1.48	1.09			
1612.32	1.47	1.08			
1616.32	1.44	1.05			

Values reflect FS calculations for mean values associated with shear capacity at critical location

Requires combination of infrequent seismic event coupled with coincident high reservoir

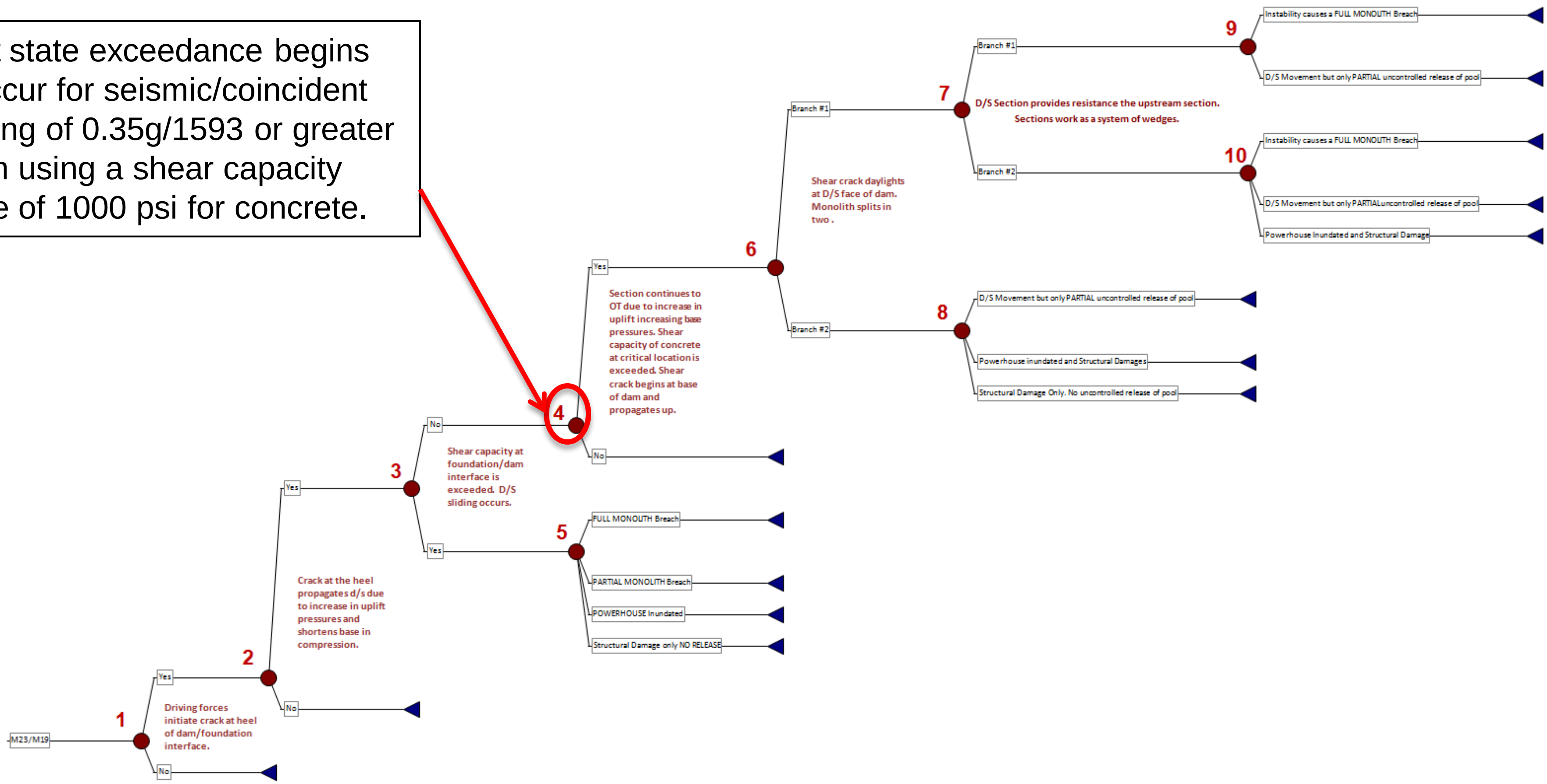
Shear Capacity = 1000 psi

Pool (NAVD88)	Static	0.125g	0.175g	0.225g	0.275g	0.35g	0.43g
1553.32	3.72	2.69	2.4	2.15	1.88	1.45	0.98
1593.32	3.16	2.35	2.06	1.76	1.43	0.99	
1603.32	3.04	2.24	1.96	1.65	1.32		
1609.32	2.97	2.18	1.89	1.57	1.24		
1612.32	2.93	2.16	1.85	1.53	1.2		
1616.32	2.89	2.11	1.82	1.48	1.15		

Seismic Loading

PFM #33 - M19 and M23 Event Tree

Limit state exceedance begins to occur for seismic/coincident loading of 0.35g/1593 or greater when using a shear capacity value of 1000 psi for concrete.



Seismic Loading

External Stability Sensitivity Analysis – Sliding at Base

- As in static case shear failure of the toe will only occur if foundation shear strength high enough to resist a sliding failure.
- Sensitivity analysis done on foundation phi due to insufficient test data.
  - 40 degrees
    - This value was set as a lower bound for the analysis where failure may occur due to a sliding failure and not a shear failure of the toe.
  - 55 degrees (more reasonable value for foundation at site)
    - Based on online research for properties of Granite Gneiss. Used to characterize sensitivity of cross section.
  - Most likely value of 212 psi used for cohesion

Seismic Loading

Sensitivity Analysis Results

M19

Pool (NGVD29)	Pool (NAVD88)	Static (Phi = 40)	Static (Phi = 55)	0.125	0.125	0.225	0.225	0.35	0.35	0.45	0.45	0.55	0.55
1550	1553.32	3.22E-07	4.01E-13	6.01E-06	4.66E-11	0.000	1.37E-09	0.003	4.03E-08	0.18	0.00	0.99	0.38
1570	1573.32	8.76E-07	1.97E-12	1.60E-05	2.17E-10	0.000	2.26E-09	0.027	1.65E-07	0.79	0.00	0.97	0.81
1580	1583.32	1.45E-06	4.56E-12	2.77E-05	4.59E-10	0.001	2.83E-09	0.083	4.33E-07	0.98	0.01	1.00	0.95
1590	1593.32	2.50E-06	9.48E-12	4.48E-05	5.18E-10	0.001	4.02E-09	0.261	2.40E-06	1.00	0.06	1.00	1.00
1600	1603.32	3.96E-06	2.13E-11	8.17E-05	5.35E-10	0.003	4.96E-09	0.644	1.97E-05	0.97	0.63	1.00	1.00
1603	1606.32	4.57E-06	2.51E-11	9.77E-05	5.66E-10	0.004	5.44E-09	0.770	4.02E-05	0.97	0.72	1.00	1.00
1606	1609.32	5.22E-06	3.35E-11	1.21E-04	4.95E-10	0.006	5.51E-09	0.874	9.87E-05	0.98	0.80	1.00	1.00
1609	1612.32	6.09E-06	4.23E-11	1.49E-04	5.90E-10	0.008	7.10E-09	0.946	2.10E-04	0.99	0.88	1.00	1.00
1611	1614.32	6.71E-06	5.13E-11	1.75E-04	5.39E-10	0.010	1.02E-08	0.972	4.64E-04	1.00	0.93	1.00	1.00
1613	1616.32	7.37E-06	5.61E-11	2.04E-04	5.10E-10	0.013	9.63E-09	0.988	8.39E-04	1.00	0.97	1.00	1.00
1621.08	1624.4	0.00											

M23

Pool (NGVD29)	Pool (NAVD88)	Static (Phi = 40)	Static (Phi = 55)	0.125	0.125	0.225	0.225	0.35	0.35	0.45	0.45	0.55	0.55
1550	1553.32	6.92E-08	0.00	4.58E-06	0.00	8.14E-05	1.06E-10	0.005	2.88E-08	0.163	6.38E-06	0.95	0.01
1570	1573.32	1.94E-07	0.00	1.18E-05	0.00	2.66E-04	7.61E-10	0.022	1.15E-07	0.527	1.10E-04	1.00	0.13
1580	1583.32	3.47E-07	0.00	1.90E-05	0.00	4.58E-04	1.09E-09	0.047	3.49E-07	0.768	6.10E-04	1.00	0.43
1590	1593.32	5.84E-07	0.00	3.04E-05	0.00	8.71E-04	1.52E-09	0.104	1.15E-06	0.933	2.86E-03	1.00	0.65
1600	1603.32	9.75E-07	0.00	5.22E-05	0.00	1.74E-03	2.99E-09	0.218	4.11E-06	0.991	1.73E-02	1.00	0.79
1603	1606.32	1.74E-06	0.00	9.83E-05	0.00	4.04E-03	4.68E-08	0.375	1.54E-04	0.993	0.147	1.00	0.90
1606	1609.32	2.18E-06	0.00	1.25E-04	0.00	5.33E-03	5.28E-08	0.442	2.62E-04	0.991	0.237	1.00	0.93
1609	1612.32	2.35E-06	0.00	1.49E-04	0.00	6.21E-03	9.51E-08	0.513	3.99E-04	0.990	0.330	1.00	0.96
1611	1614.32	2.61E-06	0.00	1.86E-04	0.00	7.55E-03	9.91E-08	0.562	5.23E-04	0.985	0.387	1.00	0.98
1613	1616.32	2.87E-06	0.00	1.93E-04	0.00	8.55E-03	1.66E-07	0.610	7.62E-04	0.984	0.444	1.00	0.99
1621.08	1624.4	0.00E+00											

Seismic Loading

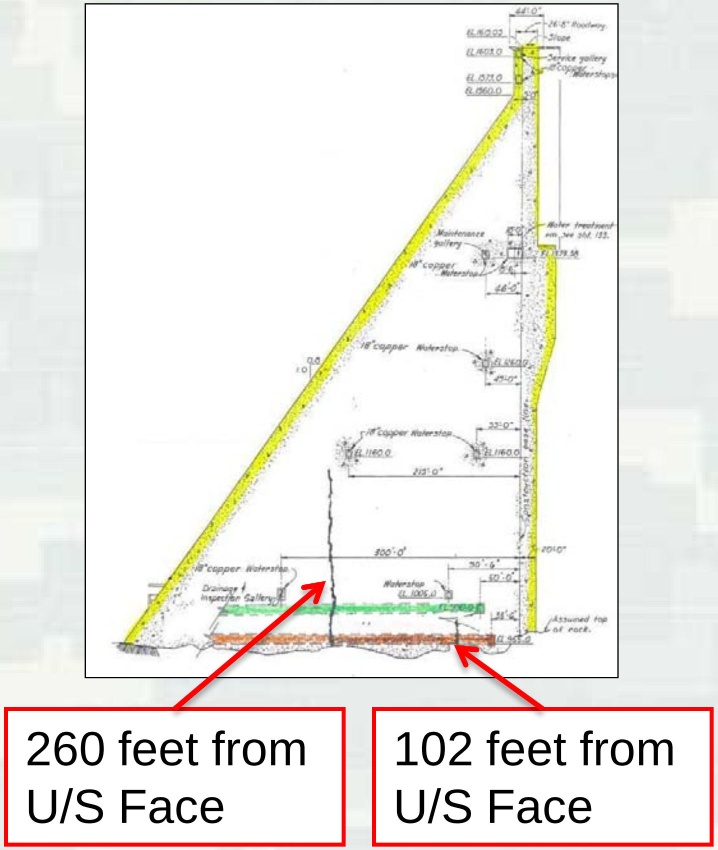
Conclusions Stability Analysis of Uncracked Section

- External stability under seismic loads done with some conservatism
  - Slightly lower ranges set on drain efficiency distribution
  - No 3D effects taken into account; no consideration of side friction
  - M19 only worst case scenario for uplift included in analysis
  - Drains no longer effective once crack at the heel progresses beyond the line of drains.
- Internal stability of cracked section is the controlling failure mechanism associated with the monoliths. Monolith M24 has the most extensive vertical cracking.
- IES Team and NWW District team both believe that the risk of the concrete dam will be controlled by the internal stability of M24 and not of the uncracked section.

Seismic Loading

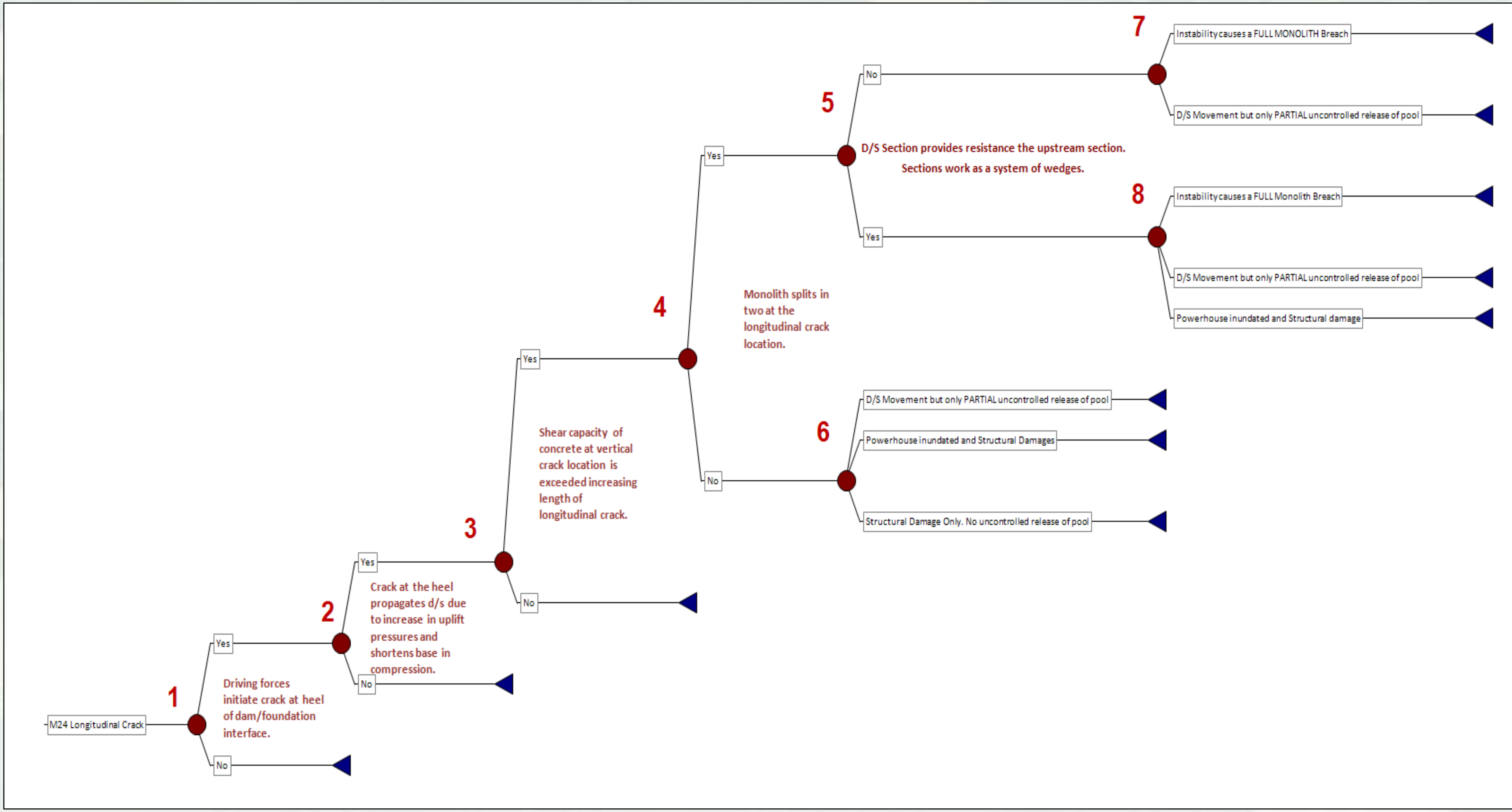
Internal Stability of the Concrete Dam (PFM#32) – Cracked Section

- Monoliths with existing longitudinal cracking are the “weakest link”.
- M24 is the worst by a considerable margin.
- Cracks are believed to extend from foundation/concrete interface vertically into dam.
- Both cracks in M24 believed to be related to thermal stress from original construction
- Expert Opinion Elicitation used to evaluate this failure mode due to limited analysis capabilities.



Seismic Loading

PFM#32 – Event Tree Cracked Section



Seismic Loading

PFM#32 – Event Tree

- Node 1: Driving forces initiate crack at heel of dam/foundation interface.
- Node 2: Crack at heel propagates d/s due to increase in uplift forces and shortens base in compression.
- Node3: Shear capacity of the concrete at critical location is exceeded. Shear crack begins at base of dam and propagates up.
- Node 4: Shear crack daylight at d/s face of dam splitting monolith in two.
  - If the crack arrests before daylighting redistribution of forces still occurs due to the increase in crack length. Failure due to sliding could occur
  - Node 6: Failure scenarios if monoliths remains intact :
    - D/S Movement but only PARTIAL uncontrolled release of pool
    - Powerhouse inundated and Structural Damages
    - Structural Damages only. No Uncontrolled release of pool.

Seismic Loading

PFM#32 – Event Tree

- Node 5: D/S Section provides resistance to u/s section. Sections work as system of wedges.
- Node 7: D/S section does not provide resistance to U/S section. Each wedge acting independently. Failure scenarios evaluated:
  - Instability causes FULL monolith failure
  - D/S movement but only PARTIAL uncontrolled release of pool
- Node 8: D/S section does provide resistance to U/S section. Wedges acting as a system. Breach severities evaluated:
  - Instability causes FULL monolith failure
  - D/S movement but only PARTIAL uncontrolled release of pool
  - Powerhouse inundation and structural damage

Seismic Loading
PFM#32

- Seismic acceleration included in elicitation: 0.17g, 0.25g and 0.35g
  - These values were chosen based on data available from external stability analysis done by the IES team and previously FEA done by NWW.
- Pool elevations included 1503.32 and 1603.32
  - Based on previous analysis results, probabilities of a shear failure were more sensitive to changes in seismic loading and not pool loading.
  - Team agreed that two pool elevations would capture hydrologic loading range.
- Nodes 1 and 2 were assumed to be "virtually certain" to occur based on the loading included in the elicitation.
- Nodes 3-10 and 4 failure scenarios were evaluated in the EOE.

Seismic Loading
PFM#32 – Failure Scenarios

1. Full Monolith Breach
   - Significant d/s movement occurs.
   - Breach dimensions equal to the width and height of the monolith.
   - D/S slide would rupture waterstops, increase uplift pressures.
   - Section would not become stable after small deformations.

2. Partial Monolith Breach
   - Section would become stable after relatively small deformations.
   - Significant portion of dam still retains pool but waterstops would be ruptured flooding galleries and causing some uncontrolled release of pool.

Seismic Loading

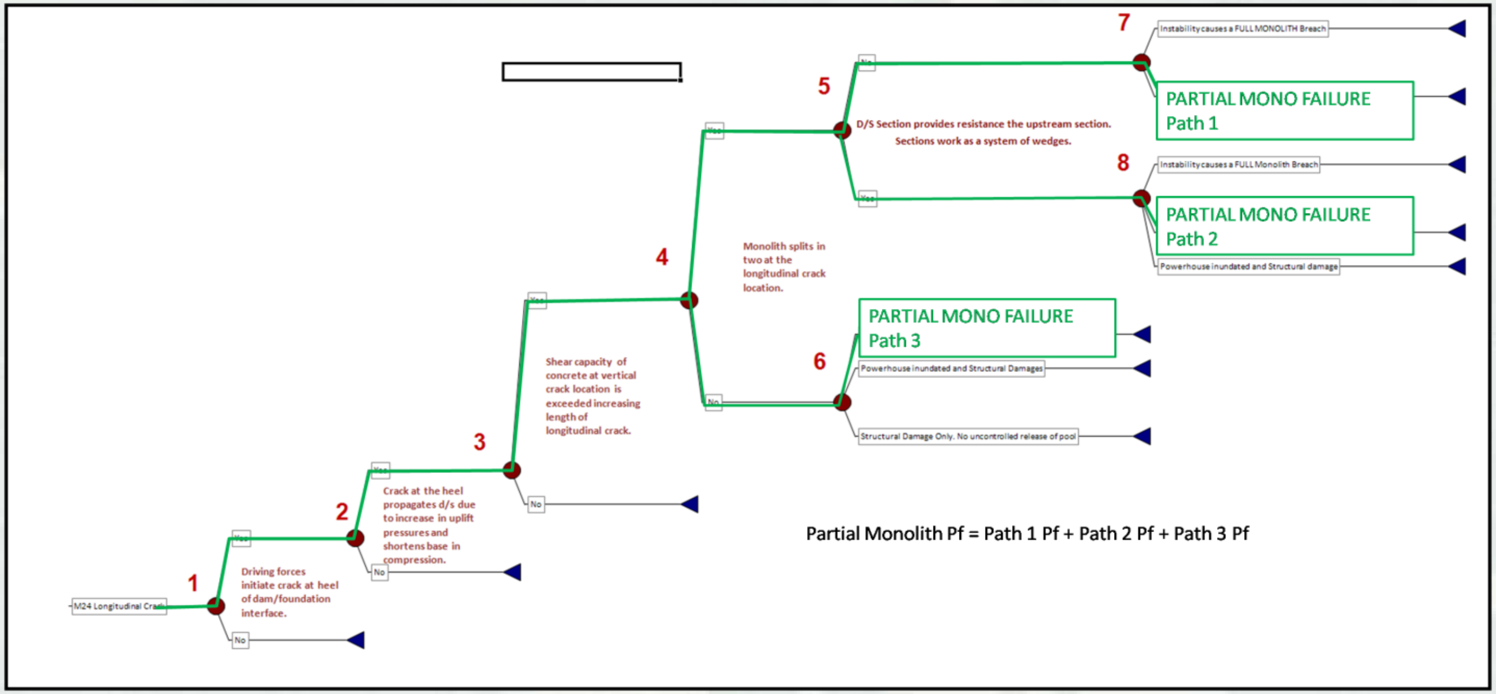
PFM#32 – Failure Scenarios

3. Powerhouse Failure
   - D/S release of pool limited to powerhouse only.
   - Powerhouse inundated due to increased flow through ruptures waterstops and existing cracking.
   - Loss of Life due to 24-hr personnel at powerhouse.

4. Structural Damage Only with No Uncontrolled Release of Pool
   - Minimal damage to structure with no uncontrolled release of pool d/s or to powerhouse.
   - Economic damages only.
   - Considered a "Non-Failure" scenario possible even if limit state exceedance occurs.

Seismic Loading

PFM#32 – Final System Response Probabilities



Once probabilities were elicited they were combined based on the Breach severity and failure path.

Seismic Loading

PFM#32 – Final System Response Probabilities

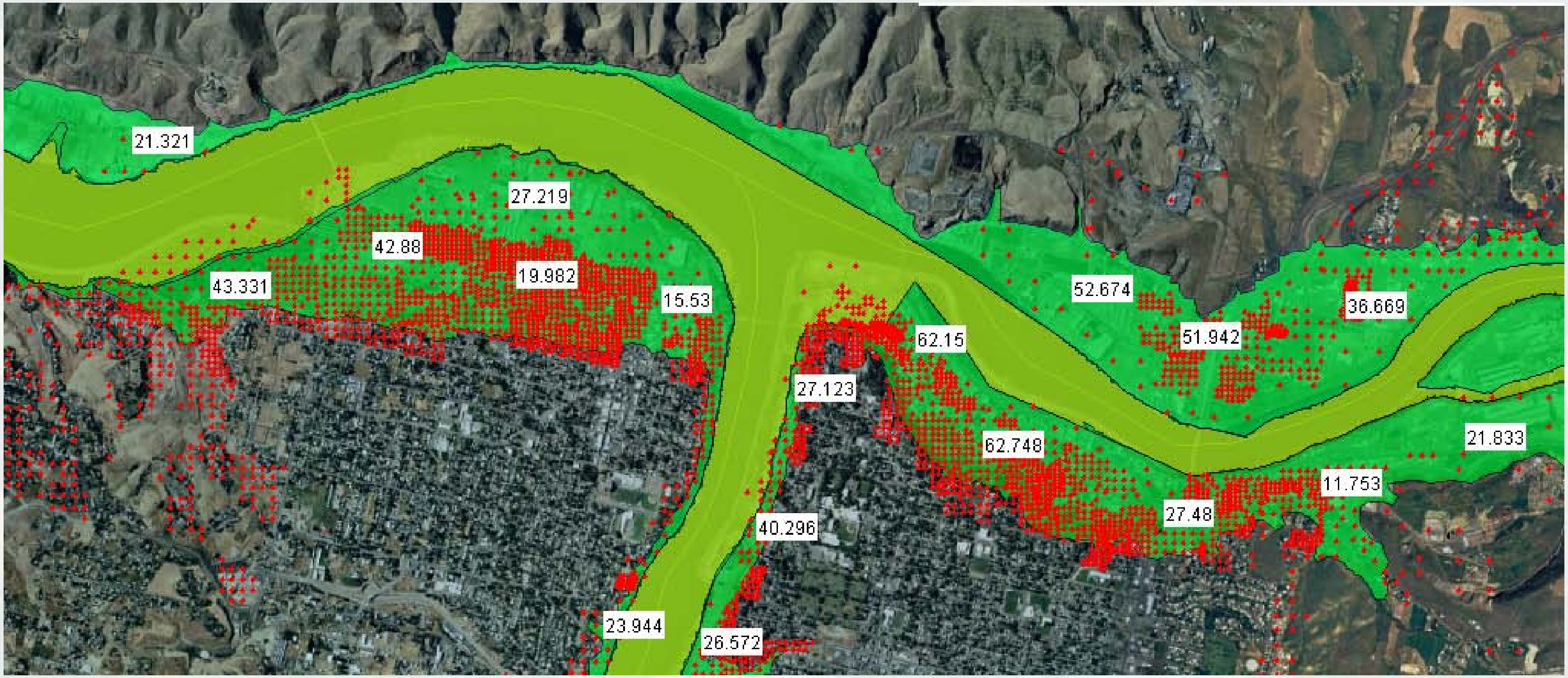
Total Probability for Full Breach				
PGA	1503.32	1553.32	1603.32	1607.3
0.15	0	0	0	0
0.17	1.34E-03	1.86E-03	2.41E-03	2.41E-03
0.25	1.23E-02	1.72E-02	2.21E-02	2.21E-02
0.35	3.79E-02	5.31E-02	6.83E-02	6.83E-02

Total Probability for Partial Breach				
PGA	1503.32	1553.32	1603.32	1607.3
0.15	0	0	0	0
0.17	1.11E-02	1.40E-02	1.70E-02	1.70E-02
0.25	8.32E-02	1.10E-01	1.37E-01	1.37E-01
0.35	2.19E-01	3.03E-01	3.87E-01	3.87E-01

Total Probability for Powerhouse Inundation				
PGA	1503.32	1553.32	1603.32	1607.3
0.15	0	0	0	0
0.17	3.86E-02	3.77E-02	3.69E-02	3.69E-02
0.25	2.62E-01	2.40E-01	2.19E-01	2.19E-01
0.35	6.21E-01	5.26E-01	4.31E-01	4.31E-01

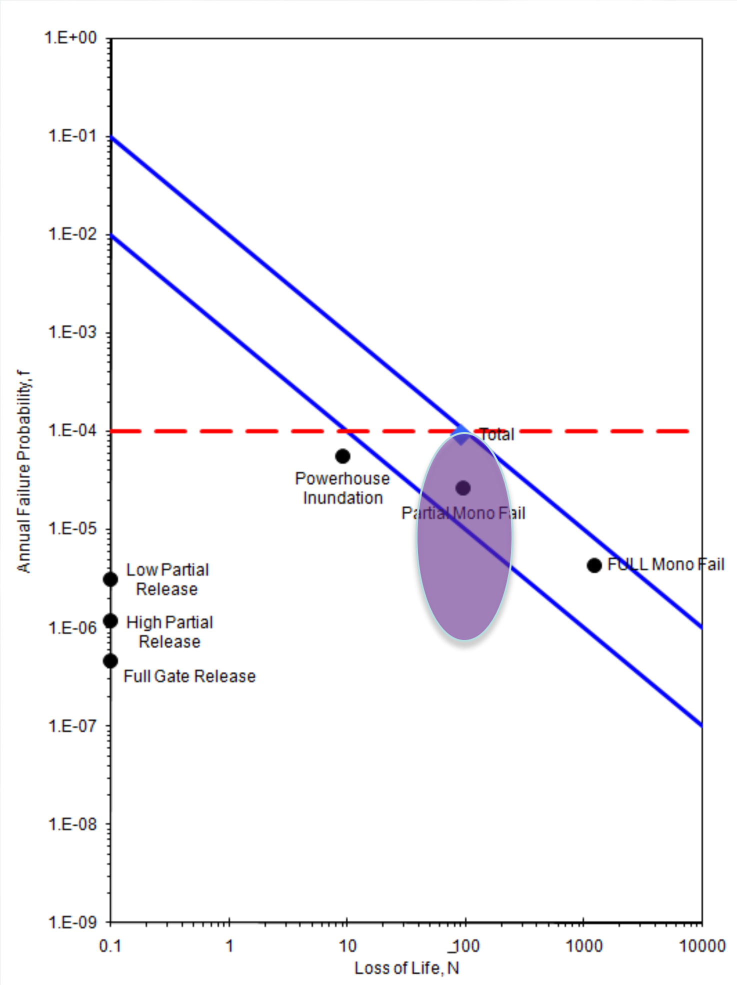
- Two most dominant failure scenarios are the Partial Monolith Breach and Powerhouse Inundation.
- Attributed to difficulty in predicting amount of movement of monolith.

Consequences



Risk Estimate

Tolerable Risk Guidelines f-N Chart



Conclusion

- Start with the basics
- Try to be consistent
- Slowly increase level of effort and detail
- Continually manage effort and decisions
- Only do as much as you have to in order to support the decision to be made