RAC
Engineers & Economists

2nd International Week on Risk Analysis
as Applied to Dam Safety and Dam Security
Theoretical-Practical Course
Universidad Politecnica de Valencia
Valencia, Spain
27 & 28 February 2008

Utah State University
IDSRM

Complete Dam Risk Analysis & Detailed Applications:

L.5 - Evaluation of Operating Restrictions for an Earthquake Hazard

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Institute for Dam Safety Risk Management - Utah State University
and RAC Engineers & Economists

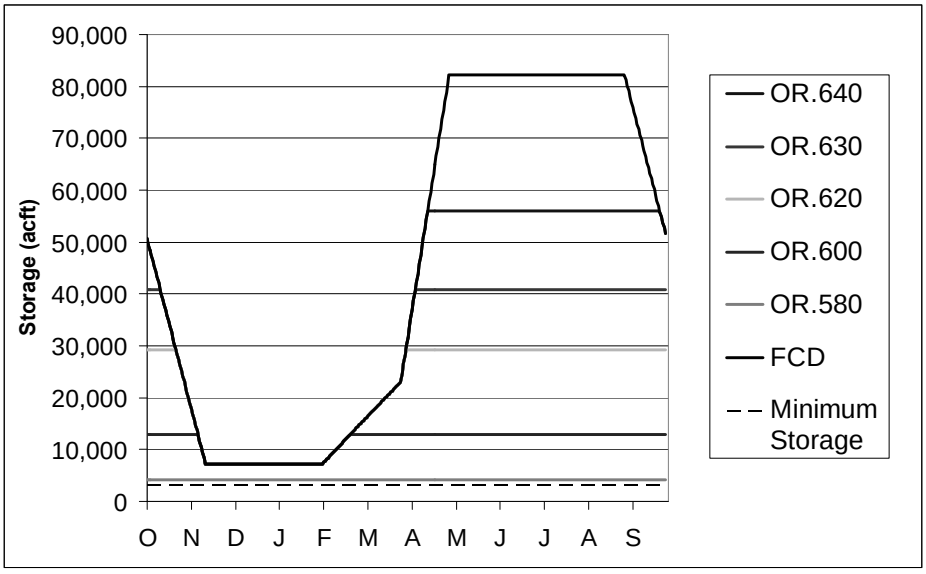
Outline

1) Overall Risk Assessment Process
2) Risk Reduction Alternatives
3) Risk Model
4) RA Results – Existing Dam and Operating Restrictions
5) Corps' Decision & Benefits

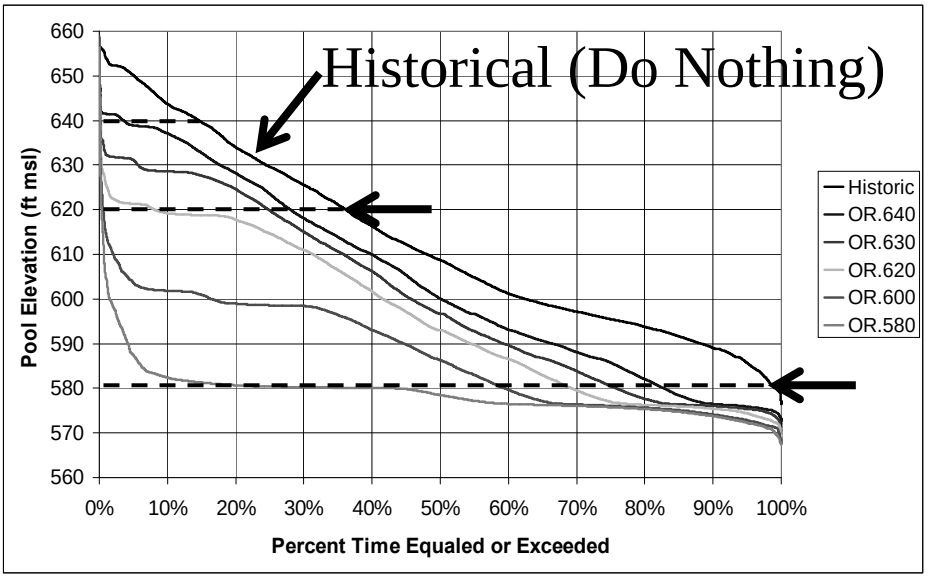
Scope of Success Dam Risk Assessment

- Initiating Events
  - Earthquake
  - Flood
  - Flood-Internal *(Piping and Instability)*
- Consequences
  - Life loss
  - Economic loss
- Conditions
  - Existing Operating Rule
  - Short Term Risk Reduction Alternatives

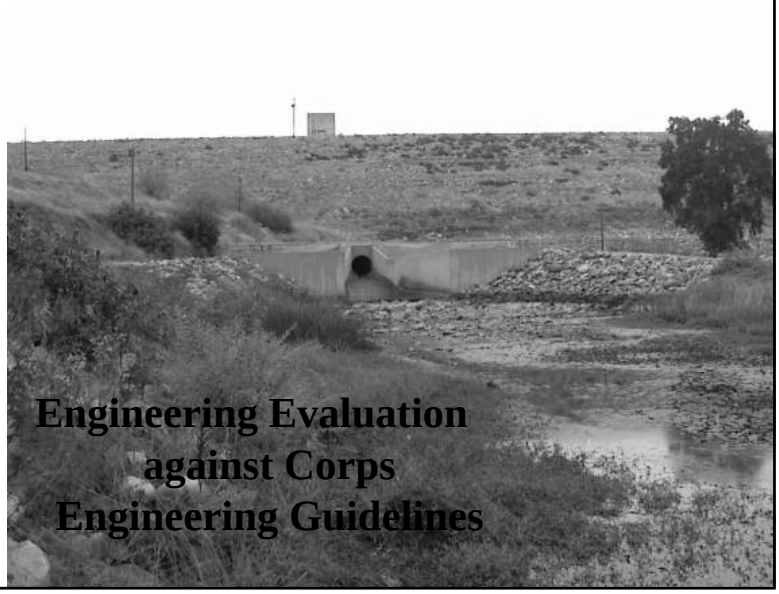
2) Short-term Potential Operating Restrictions



Stage-Duration Relationships



3) Results – Engineering Assessment of Existing Dam



Main Dam – "No Pass" Ratings
- Confirmed Deficiencies against Corp's Guidelines

1) Flood - Overall flood capacity - PMF
2) Earthquake - Embankment - Liquefaction
3) Earthquake - Embankment - Stability (includes excessive deformation)
4) Earthquake - Foundation - Liquefaction
5) Earthquake – Foundation - Stability

Main Dam – "Apparent No Pass" Ratings
- Need Additional Investigation to Confirm

1) Flood - Spillway and stilling basin system - Sill (ANP)
2) Flood - Spillway and stilling basin system - Failed Slopes
3) Flood - Embankment - Piping
4) Flood - Embankment - Wave action
5) Flood - Embankment - Abutments
6) Flood - Embankment - Foundation Piping
7) Earthquake - Appurtenances - Outlet Works Tower

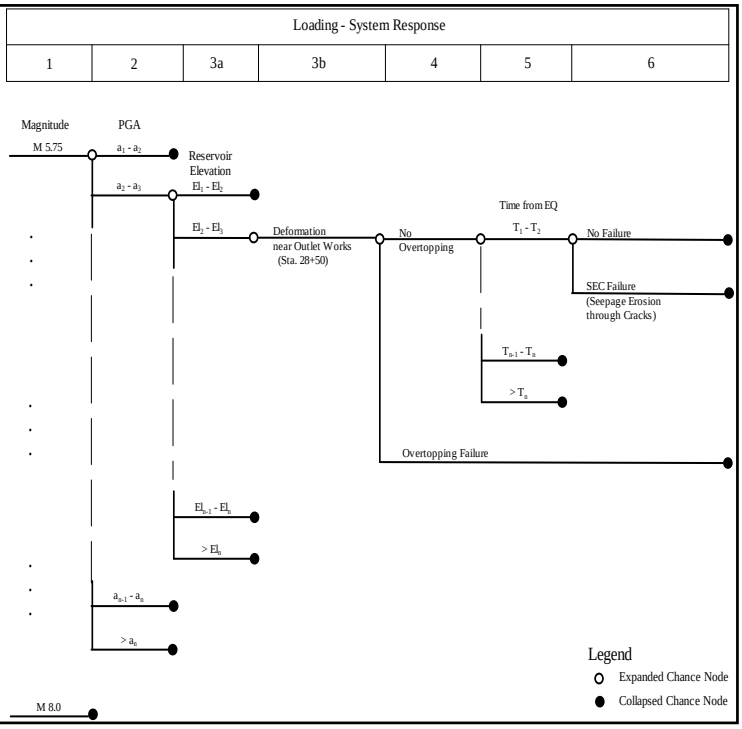
Main Dam – “Apparent Pass” Ratings - Need Additional Investigation to Confirm

1) Flood - Spillway and stilling basin system - Erodibility
2) Flood - Embankment - Stability
3) Flood - Embankment - Foundation Stability
4) Flood - Instrumentation
5) Earthquake - Appurtenances/Outlet Works - Intake Structure
6) Earthquake – Appurtenances/Outlet Works Conduit

4) Risk Assessment Model

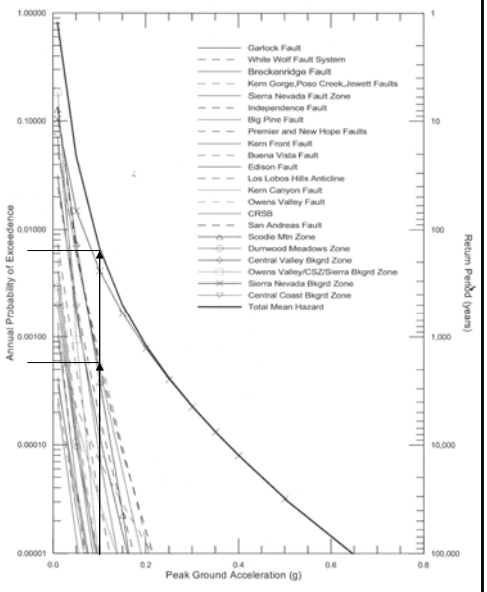
Including Supporting Engineering Analyses

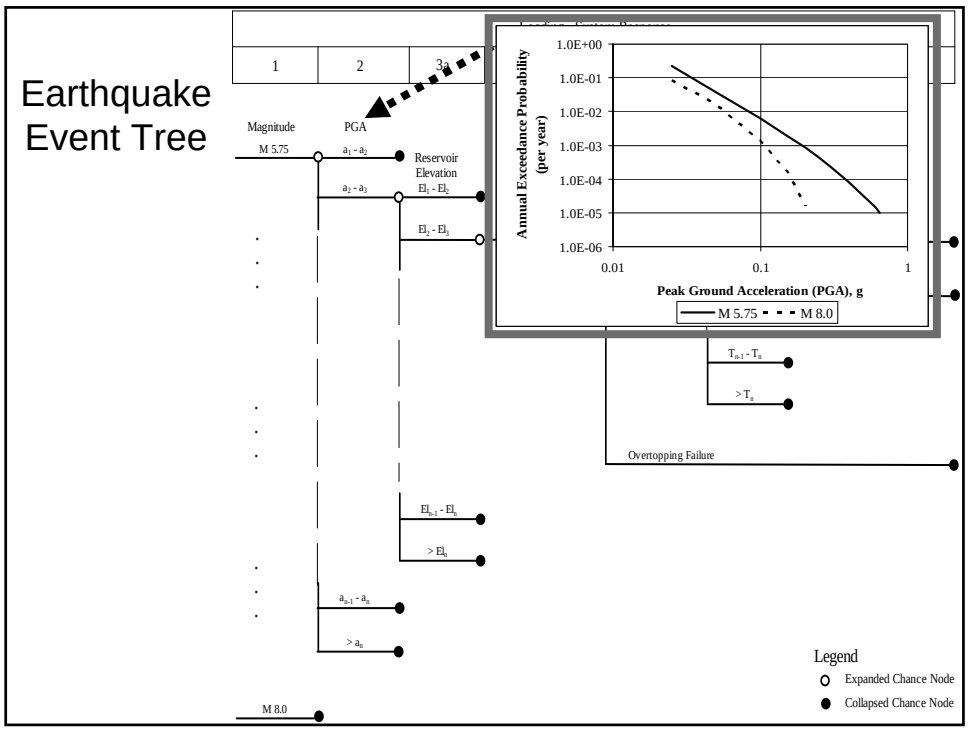
Earthquake Event Tree

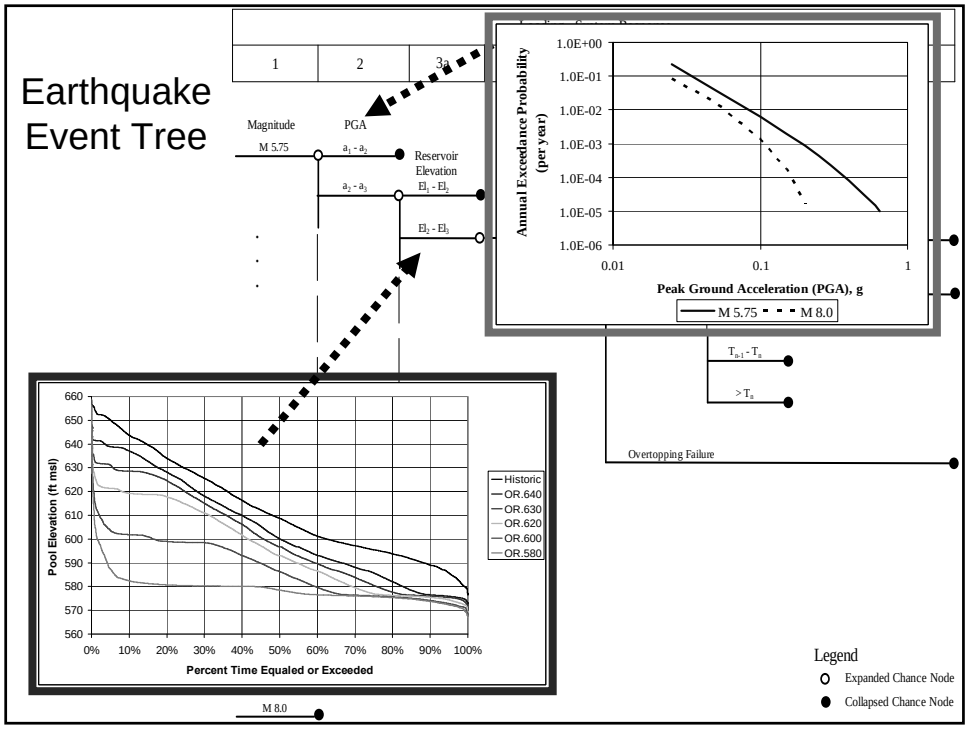


Earthquake Loading

- Consider two magnitude ranges
  - M 5.75 (background)
  - M 8.0 (White Wolf, Garlock, CRSB and San Andreas faults)

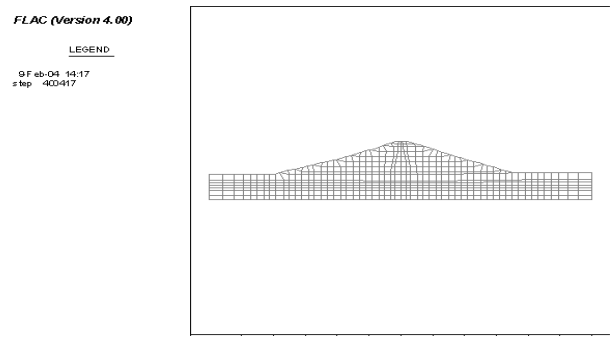


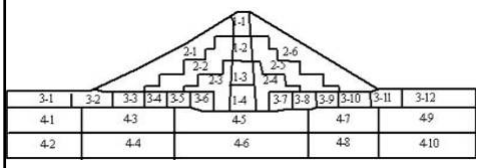

Earthquake Event Tree
1
2
3a
Magnitude
PGA
M 5.75
$a_1 - a_2$
Reservoir Elevation
$El_1 - El_2$
$a_2 - a_3$
$El_2 - El_3$
$El_{n-1} - El_n$
$> El_n$
$a_{n-1} - a_n$
$> a_n$
M 8.0
$T_{n-1} - T_n$
$> T_n$
Overtopping Failure
Annual Exceedance Probability (per year)
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
0.01
0.1
1
Peak Ground Acceleration (PGA), g
M 5.75
M 8.0
Legend
Expanded Chance Node
Collapsed Chance Node


Earthquake Event Tree
1
2
3a
Magnitude
PGA
M 5.75
$a_1 - a_2$
Reservoir Elevation
$El_1 - El_2$
$a_2 - a_3$
$El_2 - El_3$
$T_{n-1} - T_n$
$> T_n$
Overtopping Failure
Annual Exceedance Probability (per year)
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
0.01
0.1
1
Peak Ground Acceleration (PGA), g
M 5.75
M 8.0
Pool Elevation (ft msl)
660
650
640
630
620
610
600
590
580
570
560
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Time Equaled or Exceeded
Historic
OR.640
OR.630
OR.620
OR.600
OR.580
M 8.0
Legend
Expanded Chance Node
Collapsed Chance Node

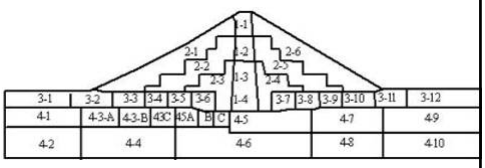
FLAC Analysis used Geomatrix Finite Element Mesh

- Calibrated FLAC Model at Station 38+50
- Liquefaction initiation
- Adjusted S_r to match Geomatrix displacement
- Applied at 28+50



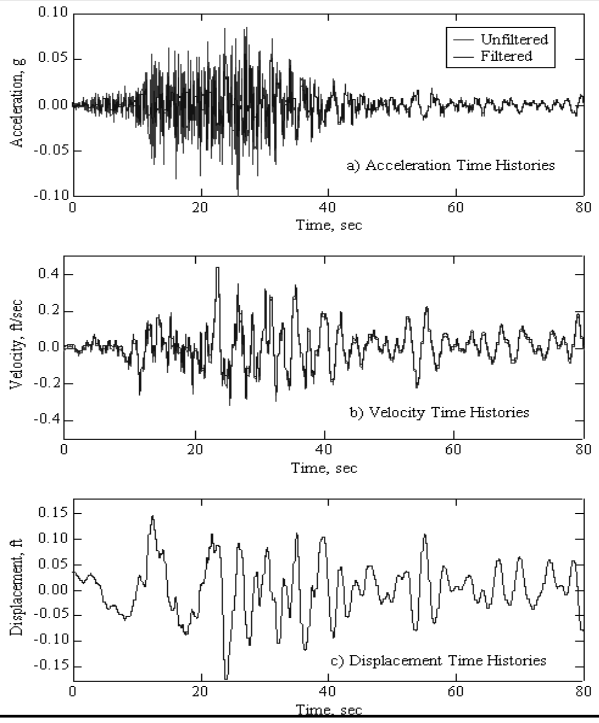


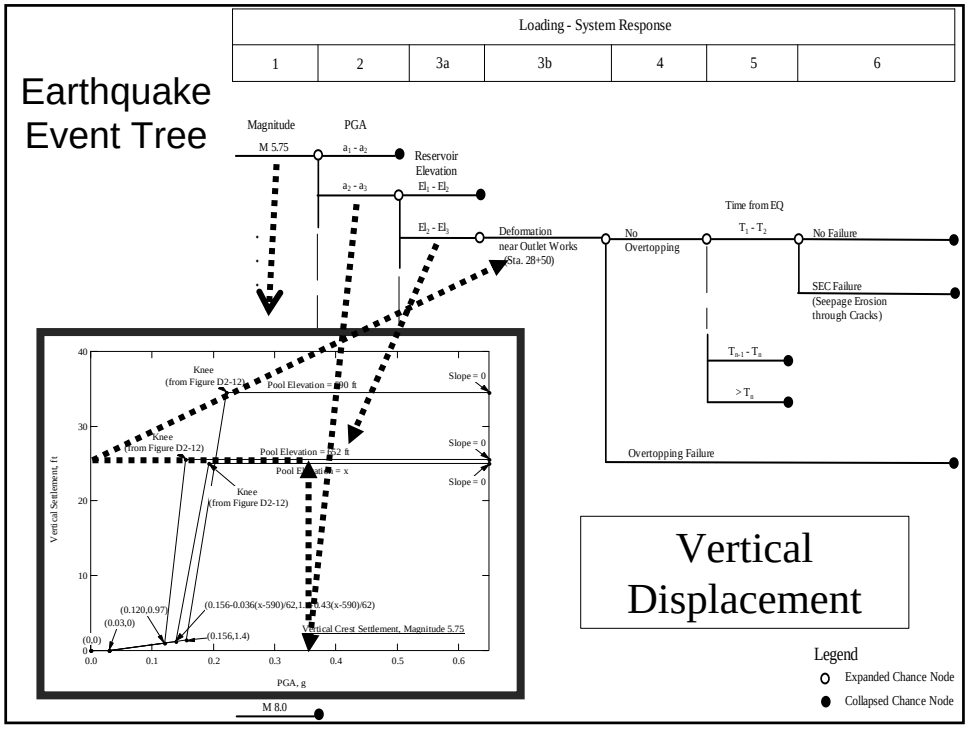
a) Soil regions at used to model Station 38+50

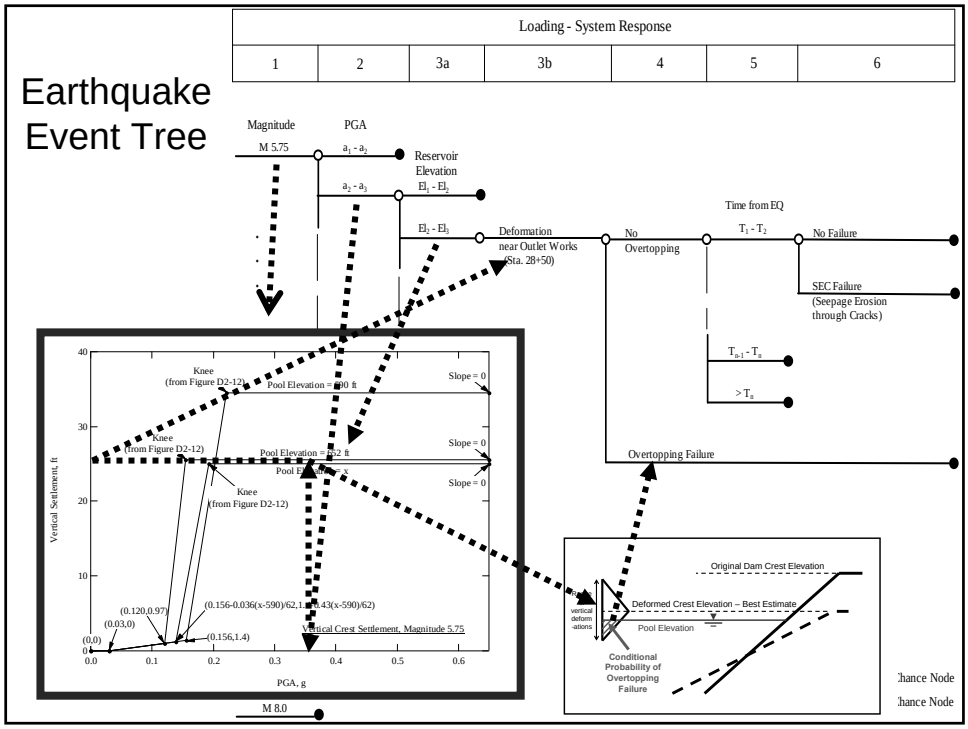


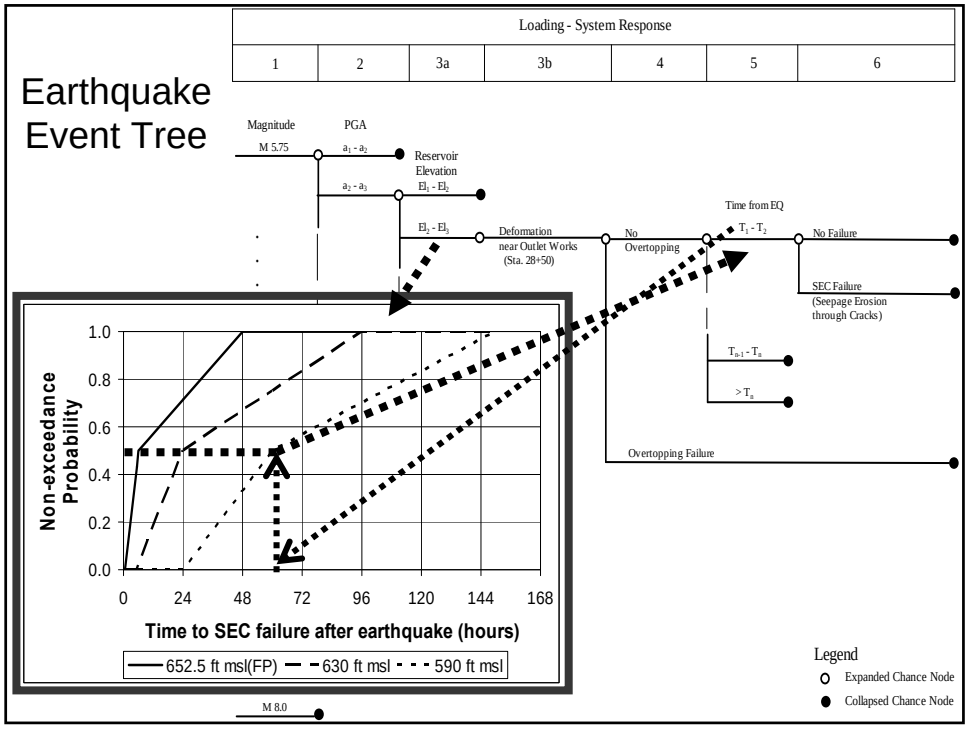
b) Soil regions at used to model Station 28+50

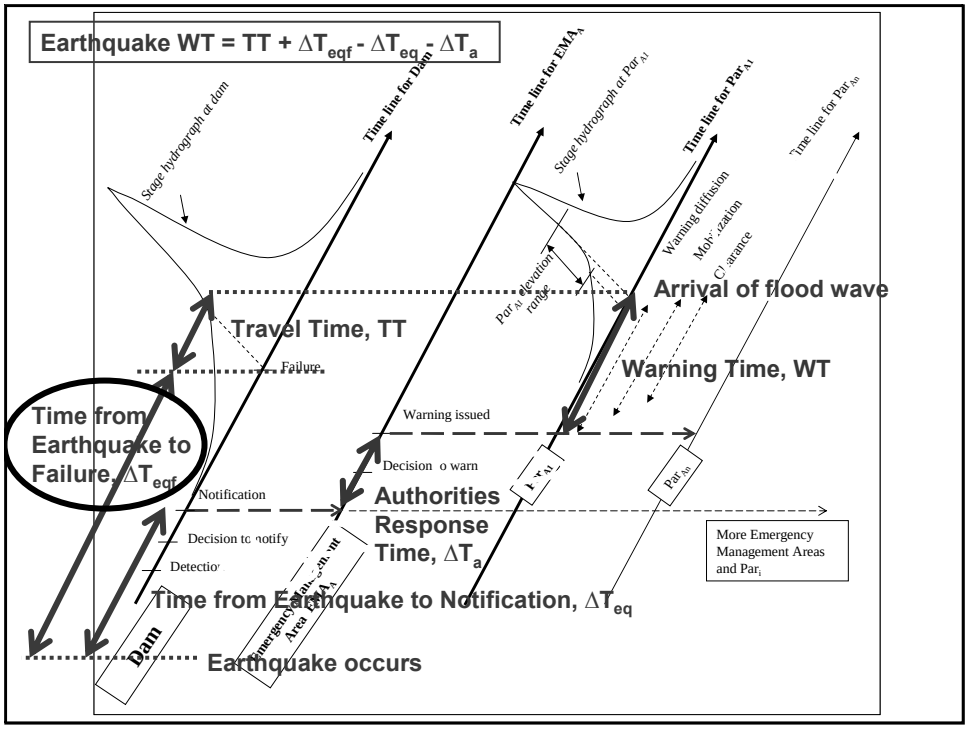
Comparison between filtered and unfiltered earthquake records used in the FLAC runs

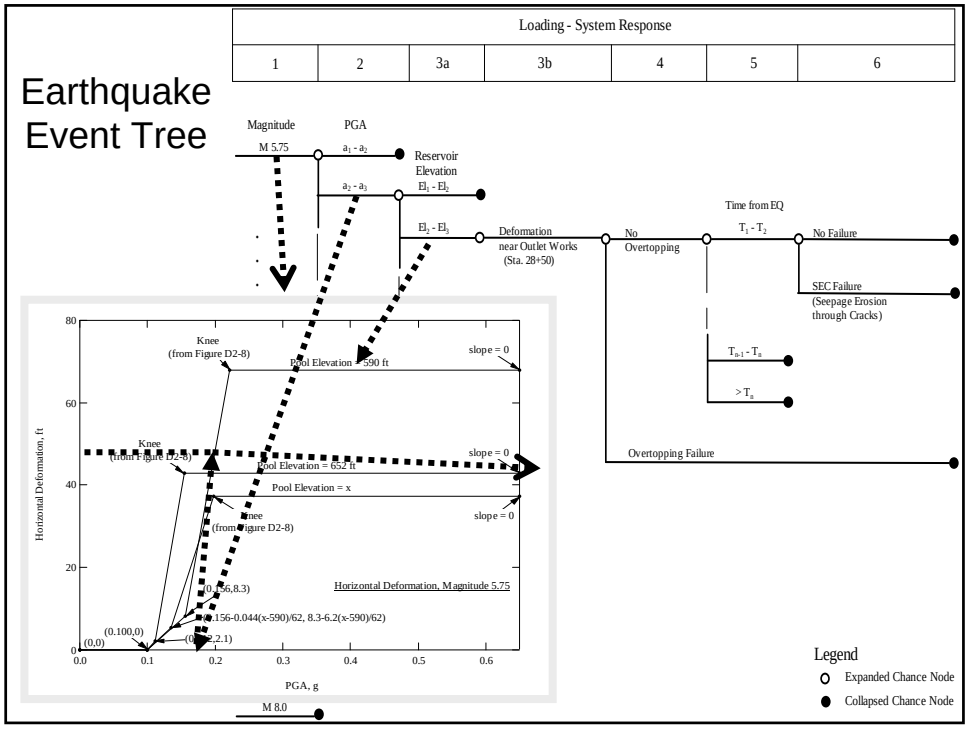


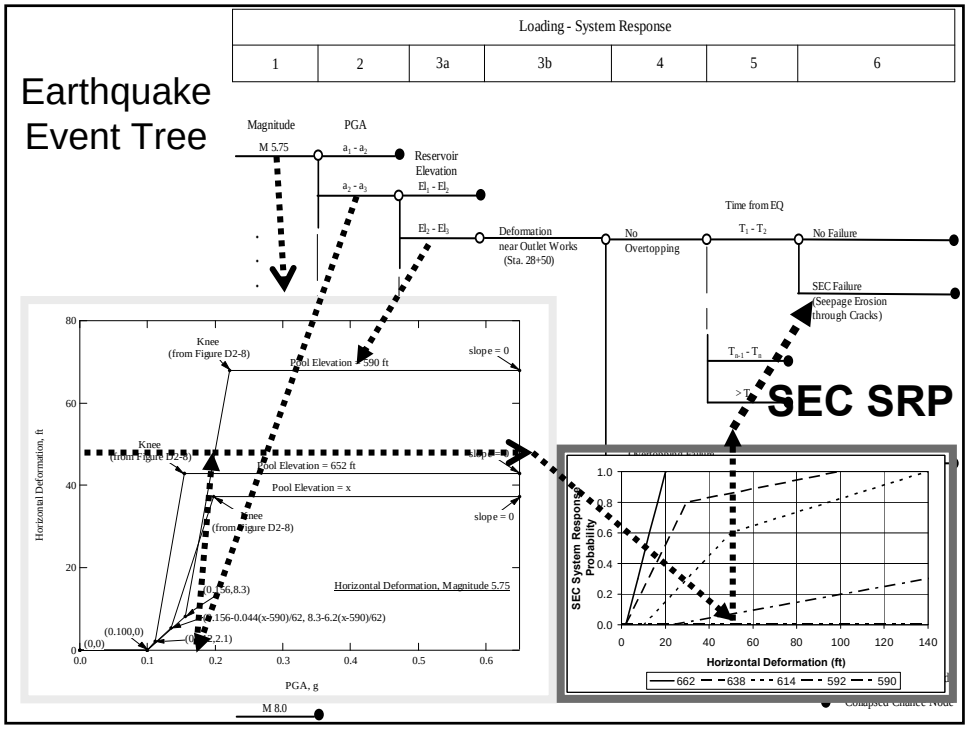

Earthquake Event Tree
Loading - System Response
1
2
3a
3b
4
5
6
Magnitude
PGA
M 5.75
$a_1 - a_2$
$a_2 - a_3$
Reservoir Elevation
$El_1 - El_2$
$El_2 - El_3$
Deformation near Outlet Works (Sta. 28+50)
Time from EQ
No Overtopping
$T_1 - T_2$
No Failure
SEC Failure (Seepage Erosion through Cracks)
$T_{n-1} - T_n$
$> T_n$
Overtopping Failure
Vertical Displacement
Legend
Expanded Chance Node
Collapsed Chance Node
Vertical Settlement, ft
PGA, g
Knee (from Figure D2-12)
Pool Elevation = 610 ft
Pool Elevation = 592 ft
Slope = 0
(0.120,0.97)
(0.03,0)
(0,0)
(0.156,1.4)
(0.156-0.036(x-590)/62,1.43(x-590)/62)
Vertical Crest Settlement, Magnitude 5.75
M 8.0


Earthquake Event Tree
Loading - System Response
1
2
3a
3b
4
5
6
Magnitude
PGA
M 5.75
$a_1 - a_2$
$a_2 - a_3$
Reservoir Elevation
$El_1 - El_2$
$El_2 - El_3$
Deformation near Outlet Works (Sta. 28+50)
Time from EQ
No Overtopping
$T_1 - T_2$
No Failure
SEC Failure (Seepage Erosion through Cracks)
$T_{n-1} - T_n$
$> T_n$
Overtopping Failure
Original Dam Crest Elevation
Deformed Crest Elevation -- Best Estimate
Pool Elevation
vertical deformations
Conditional Probability of Overtopping Failure
Vertical Settlement, ft
PGA, g
Knee (from Figure D2-12)
Pool Elevation = 610 ft
Pool Elevation = 592 ft
Slope = 0
(0.120,0.97)
(0.03,0)
(0,0)
(0.156,1.4)
(0.156-0.036(x-590)/62,1.43(x-590)/62)
Vertical Crest Settlement, Magnitude 5.75
M 8.0


Earthquake Event Tree
Loading - System Response
1
2
3a
3b
4
5
6
Magnitude
PGA
M 5.75
Reservoir Elevation
Deformation near Outlet Works (Sta. 28+50)
No Overtopping
Time from EQ
No Failure
SEC Failure (Seepage Erosion through Cracks)
Overtopping Failure
M 8.0
Non-exceedance Probability
Time to SEC failure after earthquake (hours)
652.5 ft msl(FP)
630 ft msl
590 ft msl
Legend
Expanded Chance Node
Collapsed Chance Node

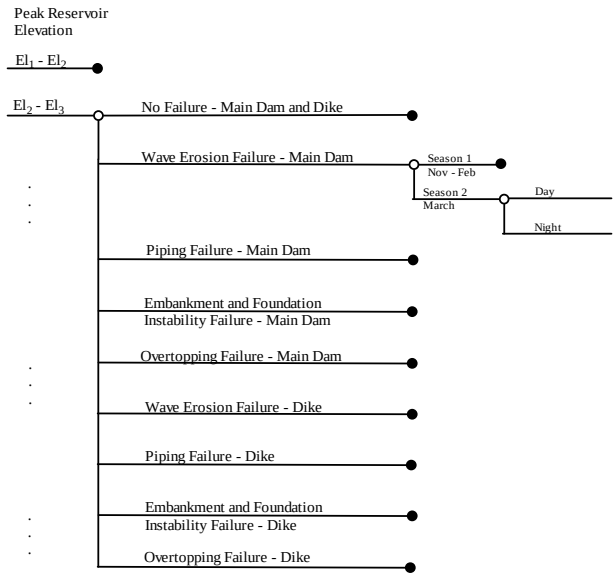

Earthquake WT = TT + ΔTeqf - ΔTeq - ΔTa
Time line for Dam
Stage hydrograph at dam
Travel Time, TT
Failure
Time from Earthquake to Failure, ΔTeqf
Notification
Decision to notify
Detection
Dam
Earthquake occurs
Time from Earthquake to Notification, ΔTeq
Authorities Response Time, ΔTa
Warning issued
Decision to warn
Warning Time, WT
Arrival of flood wave
Warning diffusion
Mobilization
Clearance
More Emergency Management Areas and Pari


Earthquake Event Tree
Loading - System Response
1
2
3a
3b
4
5
6
Magnitude
PGA
M 5.75
$a_1 - a_2$
$a_2 - a_3$
Reservoir Elevation
$El_1 - El_2$
$El_2 - El_3$
Deformation near Outlet Works (Sta. 28+50)
No Overtopping
Time from EQ
$T_1 - T_2$
No Failure
SEC Failure (Seepage Erosion through Cracks)
$T_{n-1} - T_n$
$> T_n$
Overtopping Failure
Knee (from Figure D2-8)
Pool Elevation = 590 ft
slope = 0
Pool Elevation = 652 ft
Pool Elevation = x
Horizontal Deformation, Magnitude 5.75
(0.156,8.3)
(0.100,0)
(0,0)
PGA, g
Horizontal Deformation, ft
M 8.0
Legend
Expanded Chance Node
Collapsed Chance Node

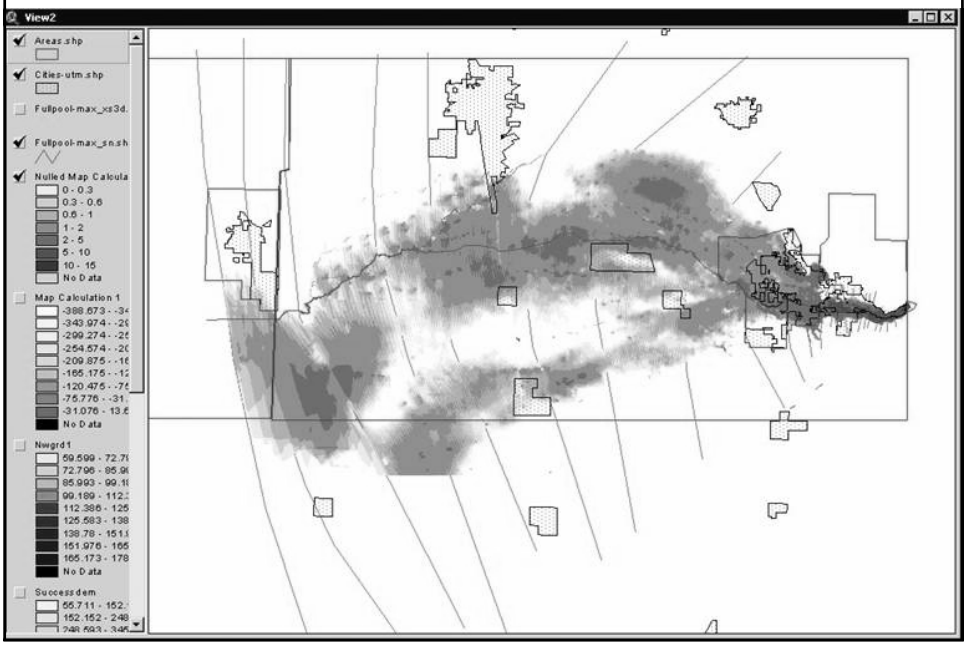

Earthquake Event Tree
Loading - System Response
1
2
3a
3b
4
5
6
Magnitude
PGA
M 5.75
Reservoir Elevation
Deformation near Outlet Works (Sta. 28+50)
No Overtopping
Time from EQ
No Failure
SEC Failure (Seepage Erosion through Cracks)
SEC SRP
Knee (from Figure D2-8)
Pool Elevation = 590 ft
Pool Elevation = 652 ft
Pool Elevation = x
slope = 0
Horizontal Deformation, Magnitude 5.75
PGA, g
Horizontal Deformation, ft
M 8.0
SEC System Response Probability
Horizontal Deformation (ft)
662
638
614
592
590

Flood and Flood-Internal Event Tree

Level of Branching	Loading - System Response		Consequences	
	1	2	A	B



Dam Breach Inundation: Earthquake – Full Pool



Cost of Operating Restrictions

1) Agricultural losses associated with reductions in irrigation water
2) Increased flood damages in an historic terminal lake, Tulare Lake agricultural area.
3) Net recreational losses, allowing for shifts to other lakes in the region
   - $2.1 m for OR.630 and OR.640
   - $2.8 m for OR.580, OR.600 and OR.620

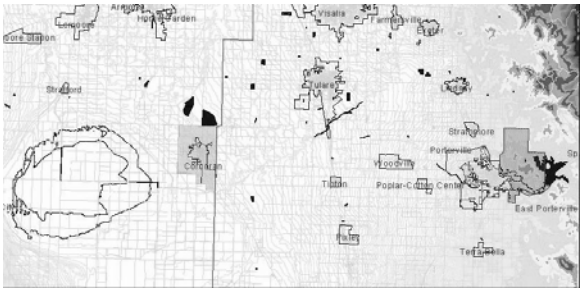


Table 1. Estimated Economic Losses to Downstream Agricultural Interests

Potential Operating Restriction	Representative Water Year					Average Annual Economic Losses ($/year)
	Very Dry	Dry	Below Average	Average	Wet	
	1976	1964	1985	1996	1980	
OR 640	$0	$0	$0	$940,660	$1,065,050	$401,142
OR 630	$0	$0	$635,810	$2,014,530	$2,152,920	$960,652
OR 620	$0	$0	$1,420,440	$2,836,050	$2,952,250	$1,441,748
OR 600	$878,220	$1,038,240	$2,590,700	$3,940,300	$3,797,220	$2,448,936

Table 2. Estimated Additional Flood Damages to Agricultural Lands in Tulare Lakebed

Potential Operating Restriction	Representative Water Year					Average Annual Additional Flood Damages ($/year)
	Very Dry	Dry	Below Average	Average	Wet	
	1976	1964	1985	1996	1980	
OR 640	$0	$0	$0	$0	$3,100,000	$620,000
OR 630	$0	$0	$0	$0	$3,100,000	$620,000
OR 620	$0	$0	$0	$0	$3,200,000	$640,000
OR 600	$0	$0	$0	$0	$7,500,000	$1,500,000

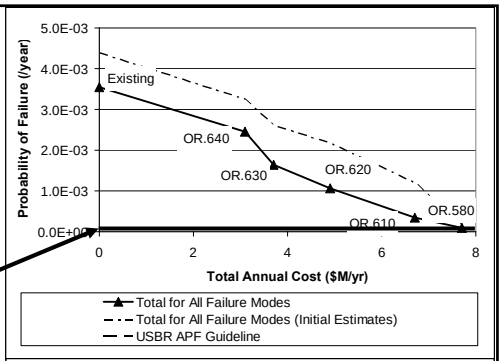
5) Risk Assessment Results – Existing Dam & Operating Restrictions

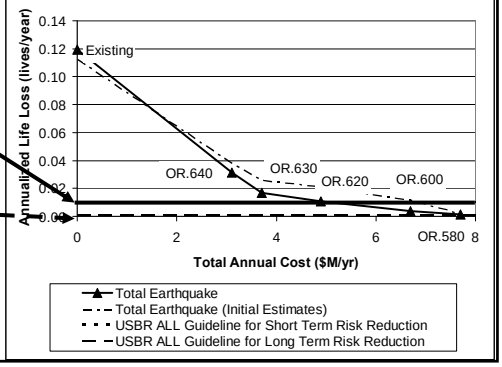
Risk Evaluation Guidelines

1) USBR Public Protection Guidelines
2) Corps Draft DSAP Tolerable Risk Guidelines
3) Australian National Committee on Large Dams (ANCOLD)
4) UK Health & Safety Executive (UK HSE)

Comparison with Reclamation Public Protection Guidelines

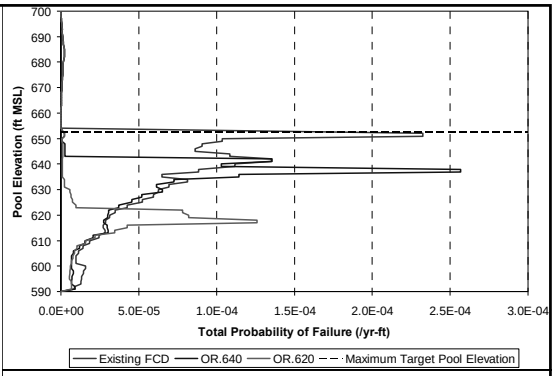
- APF – Annual Probability of Failure < 1 in 10,000/year
- ALL – Annualized Life Loss
  - > 0.01 lives/year – Short-term risk reduction
  - > 0.001 lives/year – Long-term risk reduction



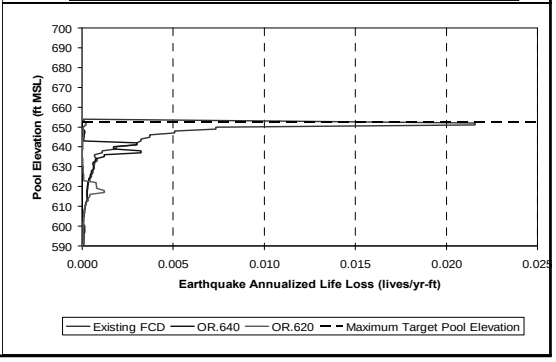


Annualized Risk as a Function of Pool Elevation

- Total Probability of Failure (/year-foot)

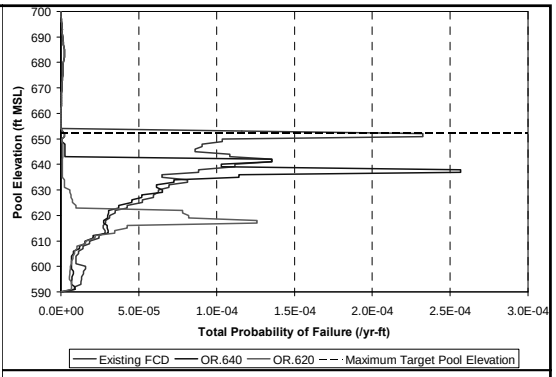


- Annualized Life Loss (lives/year-foot)

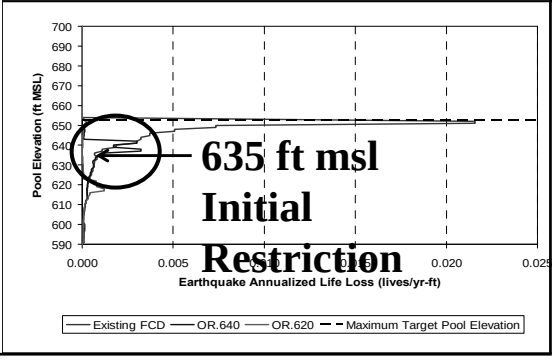


Annualized Risk as a Function of Pool Elevation

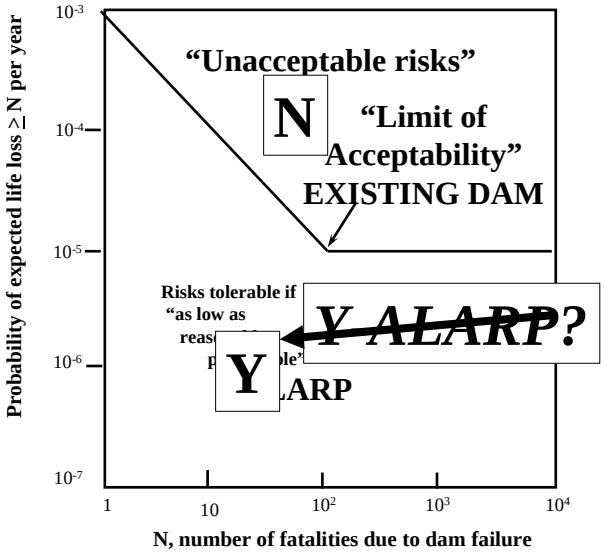
- Total Probability of Failure (/year-foot)



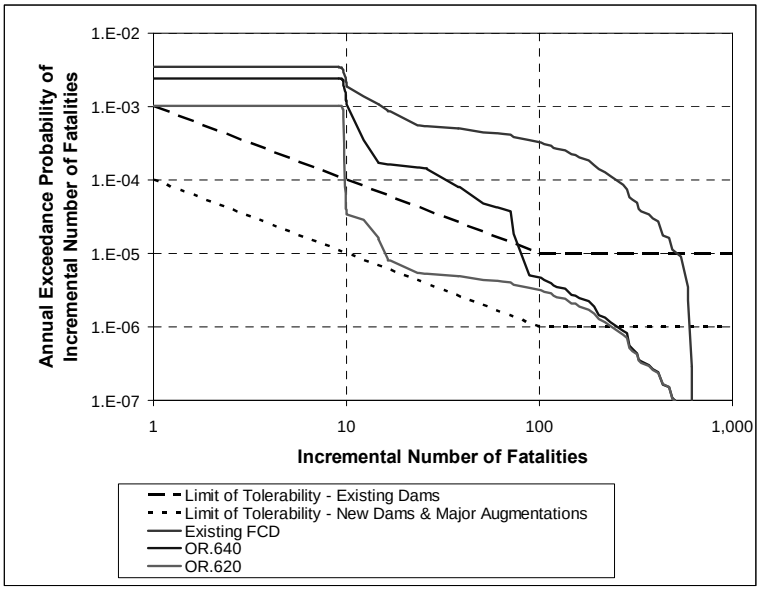
- Annualized Life Loss (lives/year-foot)

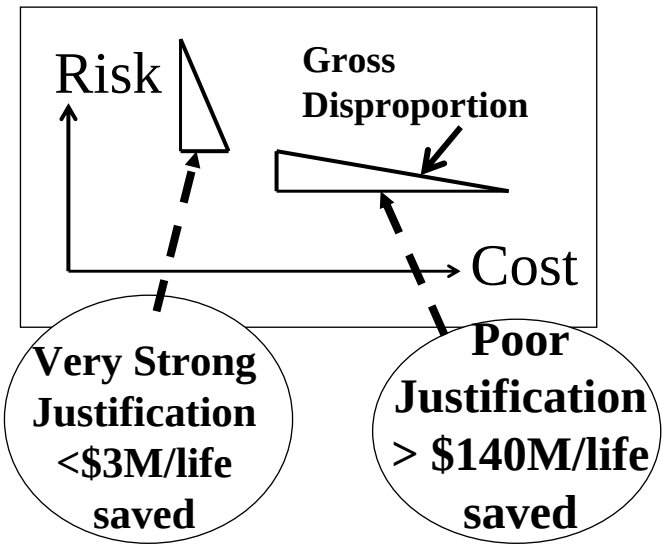


ANCOLD (2003)
Societal Risk Guidelines



Australian National Committee on Large Dams (ANCOLD)





ALARP – Gross Disproportion

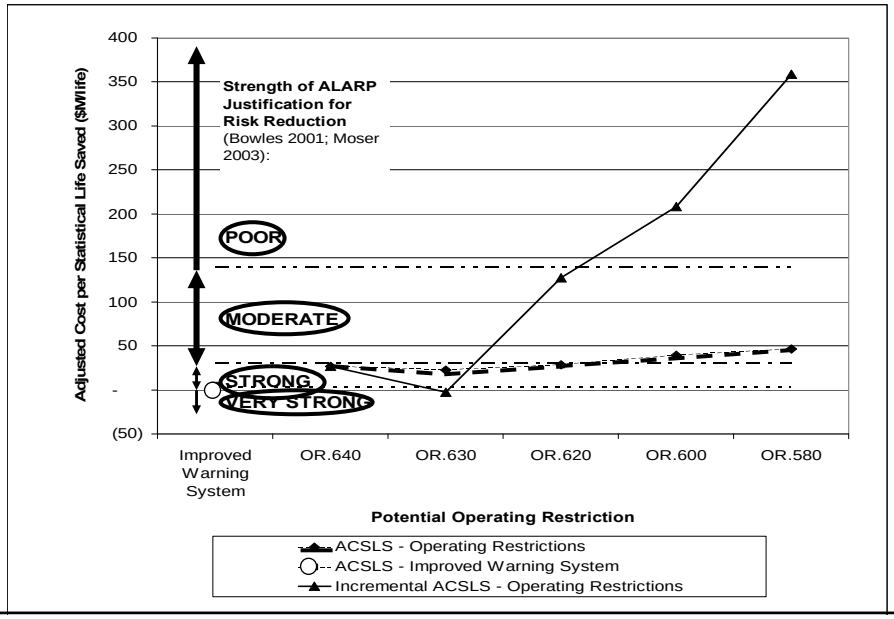
As Low As Reasonably Practicable

ALARP Strength of Justification Ratings (Example)

To inform and not to prescribe the ALARP test outcome

Based on U.S. Federal government practice (USDOT has refused > $3M - OMB max. used: $140M)

Total and Incremental Adjusted Cost per Statistical Life Saved and ALARP Justification Ratings



6) Corps of Engineers' Decision & Benefits of RA

Decision Makers

- District Dam Safety Committee
  - from project inception
  - decisions on project scoping
  - evaluation of preliminary results
  - discussions on decision options
- Showed the great interest in effects of uncertainty in the risk estimates on the justification for each decision option
- Decision matrix summarized each decision option:
  - estimated risk reduction
  - residual risks
  - risk evaluation outcomes
  - economic impacts

Final Decision Matrix

(1)	(2)	(3.1)	(3.2)	(3.3)	(4.1)	(4.2)	(5.1)	(5.2)	(5.4)	(5.5)	(5.6)
		RESIDUAL EARTHQUAKE RISK AS PERCENT OF EXISTING RISK			EVALUATION AGAINST TOLERABLE RISK GUIDELINES		COST OF OPTION ($M/year)				
DECISION OPTION	CHARACTERIZATION OF DECISION OPTION	Probability of Failure	Annualized Life Loss	Risk Cost	USBR Tier 1 & Draft Corps Level I	USBR Tier 2 & Draft Corps Level II	Impact on Agricultural Water Users	Flood Damages in Tulare Lakebed	Impact on Recreation	Cost to Community & Corps	Total
		(/year)	Life Loss x Probability (lives/year)	Dam Failure Damages x Probability ($/year)	Annualized Life Loss for Earthquake < 0.01 & 0.001lives/year	Total Probability of Failure < 1 in 10,000/year					
Do Nothing (100% Existing Capacity)	**1) Disregards Strong Justification for Short Term Measures by USBR Public Protection Guidelines and other Tolerable Risk Guidelines. 2) Poor defensibility. 3) Likely would not be well received by public.**	100% (1 in 285/year)	100% (0.119lives/year)	100% ($2.3M/year)	Strong Justification to reduce Long & SHORT Term Risks	Strong Justification to reduce LONG Term risks					
Improved Warning & Evacuation System (Indicative) (100% Existing Capacity)	1) Most cost effective option for reducing potential life loss. 2) Needs more detailed evaluation than the indicative evaluation performed. 3) Requires cooperation of community emergency mangers and public information.	100% (1 in 285/year)	65% (0.077lives/year)	100% ($2.5M/year)	Strong Justification to reduce Long & SHORT Term Risks	Strong Justification to reduce LONG Term risks				$0.2M	$0.2M
OR.640 (68% Existing Capacity)	**1) Significant reduction in likelihood of most rapidly developing Seepage-Erosion through Cracks and unexpected Overtopping Failure Modes, which have no warning or short warning times in areas close to dam. 2) Achieves most of the potential life loss risk reduction available from Operating Restrictions in range of 75 - 600 lives.**	69% (1 in 413/year)	26% (0.031lives/year)	67% ($1.54M/year)	Strong Justification to reduce Long & SHORT Term Risks	Strong Justification to reduce LONG Term risks	$0.4M ($0 - $3.0M)	$0.6M ($0 - $3.1M)	$2.1M		$3.1M
OR.630 (50% Existing Capacity)	**1) Reduces Likelihood of moderately rapidly developing Seepage-Erosion through Cracks Failures. 2) Achieves most of the potential life loss risk reduction available from Operating Restrictions in range of 10 - 75 lives.**	46% (1 in 623/year)	14% (0.017lives/year)	41% ($0.95M/year)	Strong Justification to reduce Long & SHORT Term Risks	Strong Justification to reduce LONG Term risks	$1.0M ($0 - $2.2M)	$0.6M ($0 - $3.1M)	$2.1M		$3.7M
OR.620 (35% Existing Capacity)	**1) Further reduction in life loss mainly in range of less than 10 lives.**	29% (1 in 979/year)	9% (0.011lives/year)	22% ($0.51M/year)	Strong Justification to reduce Long & SHORT Term Risks	Strong Justification to reduce LONG Term risks	$1.4M ($0 - $3.0M)	$0.6M ($0 - $3.2M)	$2.8M		$4.9M
OR.600 (16% Existing Capacity)	**1) Highest operating restriction that appears to meet the USBR Tier 1 Guideline for short term risk. 2) Does not consider cost as a factor in protecting the public. 3) Cost borne by community and agricultural interests.**	9% (1 in 3,256/year)	3% (0.004lives/year)	5% ($0.12M/year)	Strong Justification to reduce LONG Term Risks	Strong Justification to reduce LONG Term risks	$2.4M ($0.9M - $3.8M)	$1.5M ($0 - $7.5M)	$2.8M		$6.7M
OR.580 (5% Existing Capacity)	**1) Only Option that appears to meet USBR Tier 2 Guideline. 2) Does not consider cost as a factor in protecting the public. 3) Cost borne by community and agricultural interests.**	1% (1 in 19,221/year)	1% (0.001lives/year)	1% ($0.03M/year)	Strong Justification to reduce LONG Term Risks	**Appears to meet this guideline, subject to satisfying ALARP considerations**	$3.1M ($1.1M - $4.8M)	$1.9M ($0 - $9.4M)	$2.8M		$7.7M

The Corps' Decision

- Corps' objective:

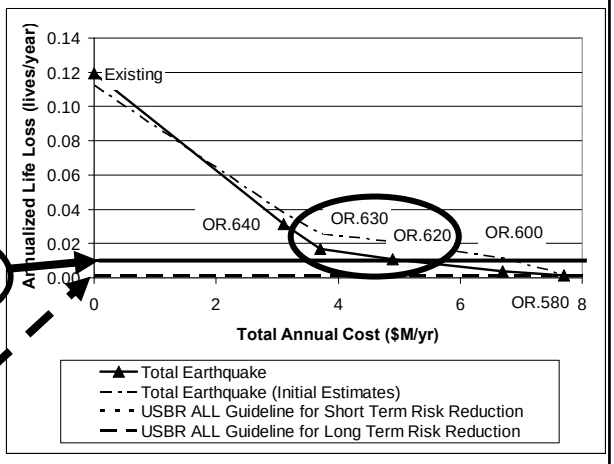
  to do all that was reasonably practicable to reduce the residual risk to the public

  - meet USBR ALL guideline of 0.01 lives/yr for justification of short-term risk reduction

1) March 2004 – OR.635
   - before spring fill
   - Draft report
   - low inflows – 635 ft msl not reached
2) December 2004 - OR.620
   - Final report incorporating ITR changes
   - Moderate economic impacts of OR.620 - mainly wet years
     - average annual agricultural loss $1.4 m/yr ($0 in dry years - $2.9 m in wet years)
     - average annual flood damages $0.6 m ($0 in dry years - $3.2 m in wet years)
     - average annual recreational loss $2.8 m

Justification of OR.620 instead of OR.630

- Reclamation ALL Public Protection Guideline – Annualized Life Loss
  - > 0.01 lives/year – Short-term risk reduction
  - > 0.001 lives/year – Long-term risk reduction



The Corp's Decision

Justification of OR.620 instead of OR.630:

1) low confidence that ALL < 0.01 lives/yr for OR.630
2) poor defensibility for OR.630
   - considering established USBR practice of implementing short-term measures when ALL > 0.01 lives/yr
   - reinforced by not meeting other international tolerable risk guidelines
3) small additional economic impacts over OR.630
   - average annual agricultural loss +$0.5 m/yr ($0 in dry years to +$0.8 m in wet years)
   - no significant increase in annual flood damages
   - annual recreational loss of +$ 0.7 m

Who was involved in the RA?

- Project Water Users
  - Will bear cost of operating restrictions
    - reduced water supply
    - reduced flood control
    - reduced recreation benefits
  - Agricultural water users involved throughout RA
    - estimated their economic impacts from Potential Operating Restrictions
- Downstream Communities
  - Bear the risk of an Earthquake-induced dam failure
  - Bear some of the economic impact of Potential Operating Restrictions
  - Importance of community consultation
- Corps Engineering Team
  - Difficulty in setting aside conservative "design" or "factor of safety" perspective for characterizing seismic "performance"
  - ITR Panel played a key role in pointing out this conservative bias in the Initial Risk Assessment, which lead to the revisions of several key inputs

Benefits of Success Dam RA

- Rational and defensible basis for decision on Potential Operating Restrictions
- New insights and understanding:
  - Potential Earthquake failure modes
  - Relative likelihood of sudden vs. delayed failure modes
  - Relationship between pool elevation and dam failure risk (large scale life loss and major economic damages)
- Tolerable risk evaluation:
  - Comparison with the USBR's established practice for justifying short-term risk reduction measures
  - Other tolerable risk guidelines, including ALARP considerations, provided additional justification for decision
  - Most tolerable risk guidelines will remain unmet until a structural fix is completed

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