Time-Dependent Reliability Modeling for Use in Major Rehabilitation of Embankment Dams and Foundation

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Navigation/Risk and Reliability

Outline

- Time-Dependent Reliability
- Hazard Functions
- Wolf Creek Major Rehabilitation Report (MRR)
  - Time-Dependent Reliability Modeling
  - Expert-Opinion Elicitation

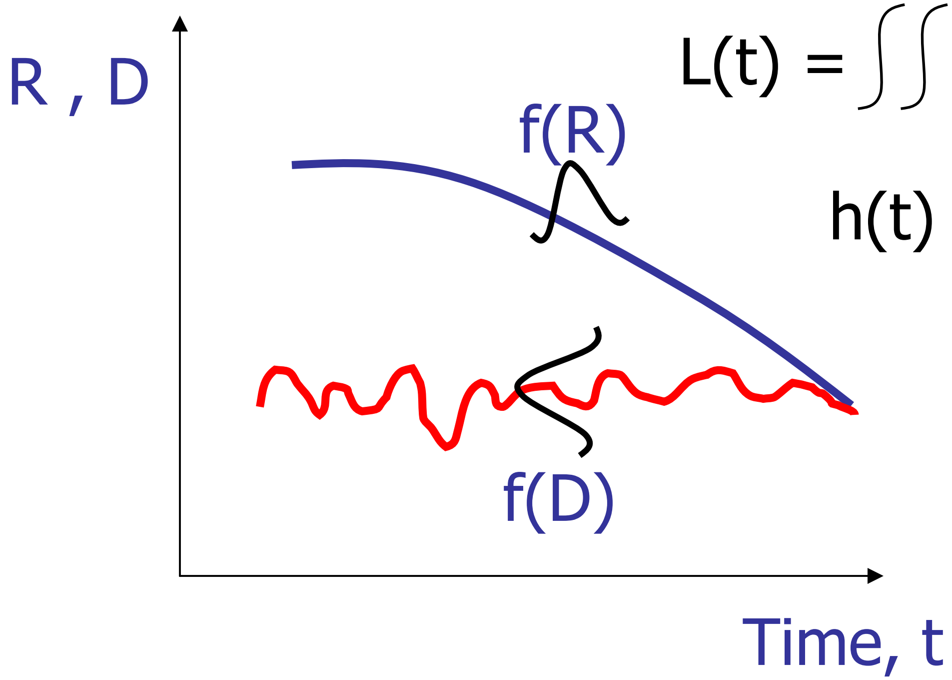
Reliability

- Probability of unsatisfactory performance (PUP)
  - Limit state defined before failure occurs
  - Problem – snapshot in time
  - Not cumulative (does not account for previous loadings)
  - Must account for degradation of structures
    - Mechanisms
      - Corrosion
      - Fatigue
      - Freeze-Thaw
      - Wear
      - Abrasion/Erosion

Time-Dependent Reliability

- Geotechnical Aspects
  - Difficult task-at-hand
    - Foundations
      - Karst
        - Used Expert-Opinion Elicitation to define PUPs
        - Snapshot
      - Alluvial
        - Used Taylor Series
        - Snapshot
    - Degradation
      - Data/Rates
      - Models

Time-Dependent Reliability



$$L(t) = \int\int f(R)*g(t)\, f(D)$$

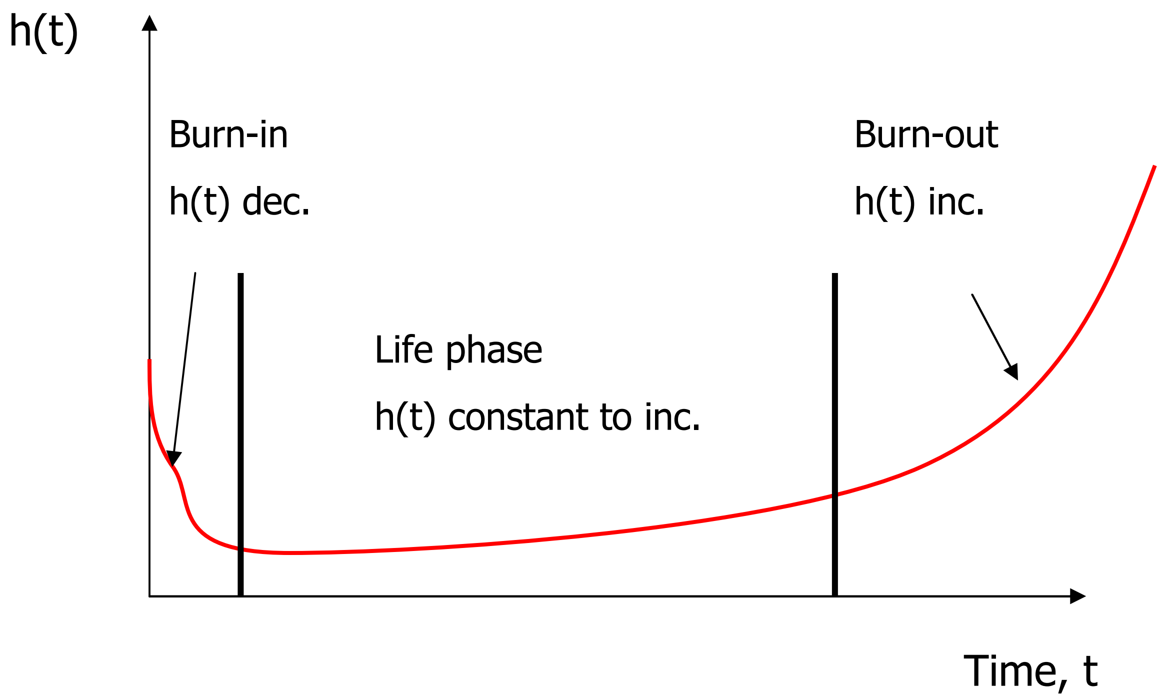
$$h(t) = -\ln d/dt\,(L(t))$$

Time-Dependent Reliability

- Hazard Function
  - Developed by actuaries in 1880's
  - Used by aerospace industry in early 1950's
  - Conditional probability
    - h(t) = PUP [t + dt, t]
      - PUP in time, t+ dt, given you have survived up to time, t
      - Based on efforts on Ohio River Mainstem Study

$$h(t) = \frac{\text{Number of unsatisfactory performances in time, t} + 1}{\text{Number of survived up to time, t}}$$

Hazard Function



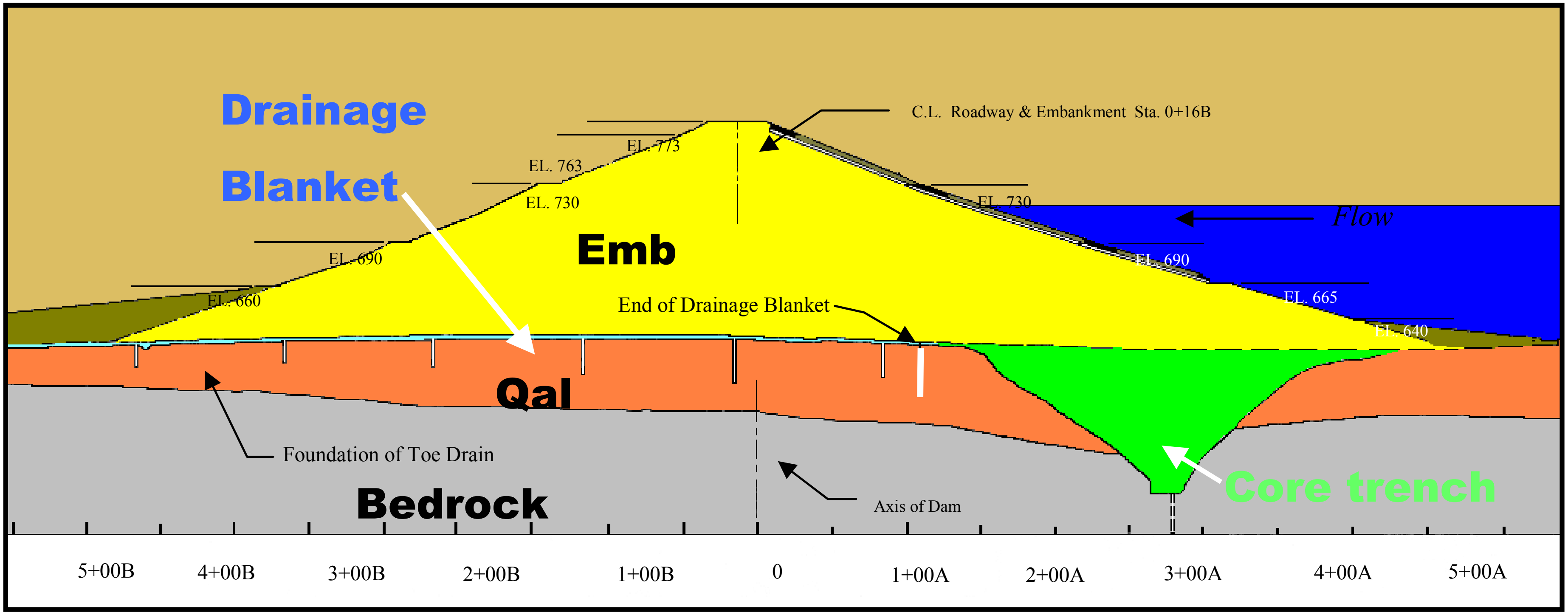
Wolf Creek Dam Project

- Concrete 240' ht 1836' length
- Earth Emb 200' ht 3900' length

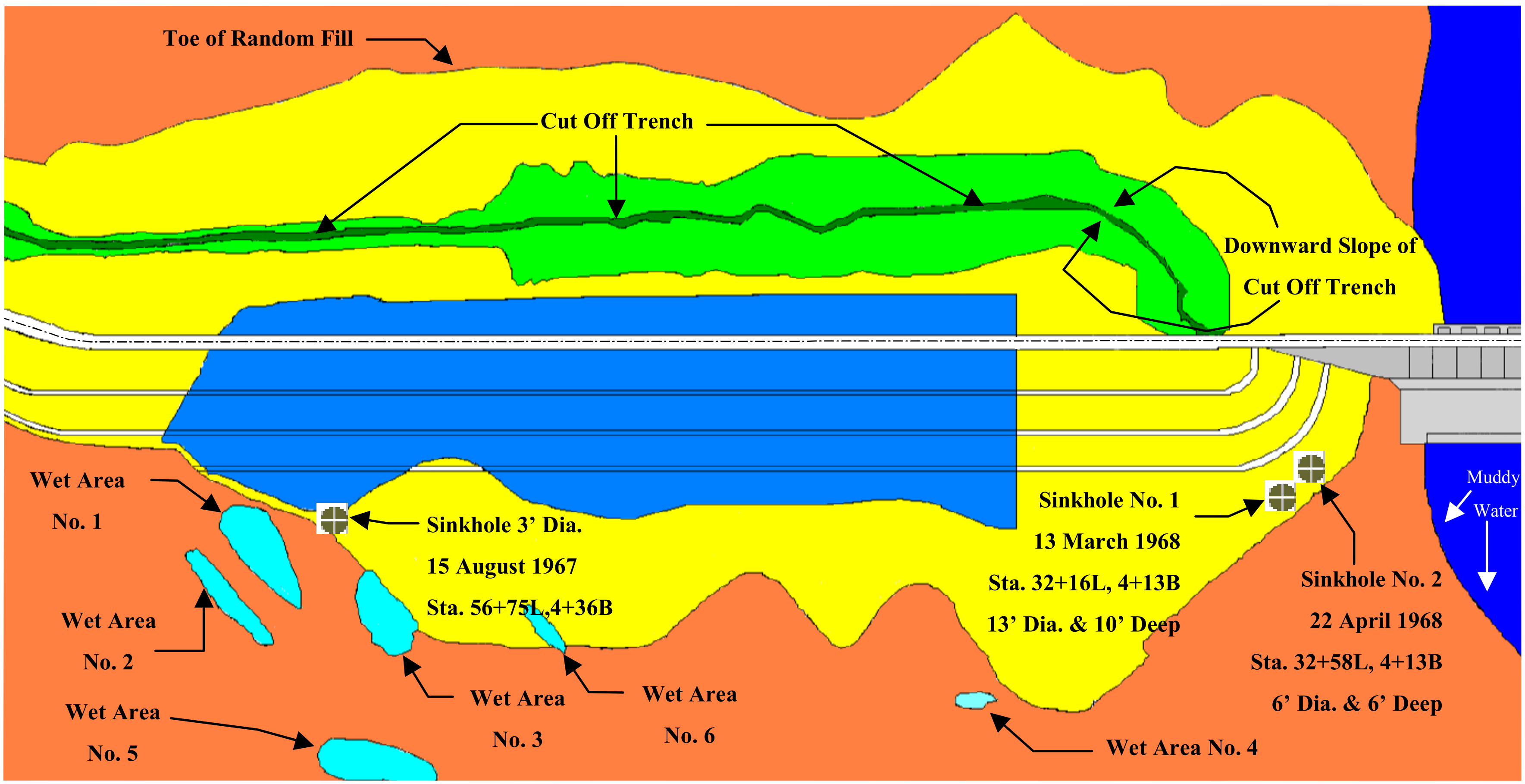
Wolf Creek Dam - History

- Designed in late 1930’s
- Construction began 1941
- Completion delayed until 1951 due to WWII
- 1967-68 Sinkholes near Switchyard + right d/s abutment wet areas D/S of embankment, muddy flows
- 1968-72 Emergency exploration / grouting
- 1975-79 Diaphragm walls construction (ICOS)

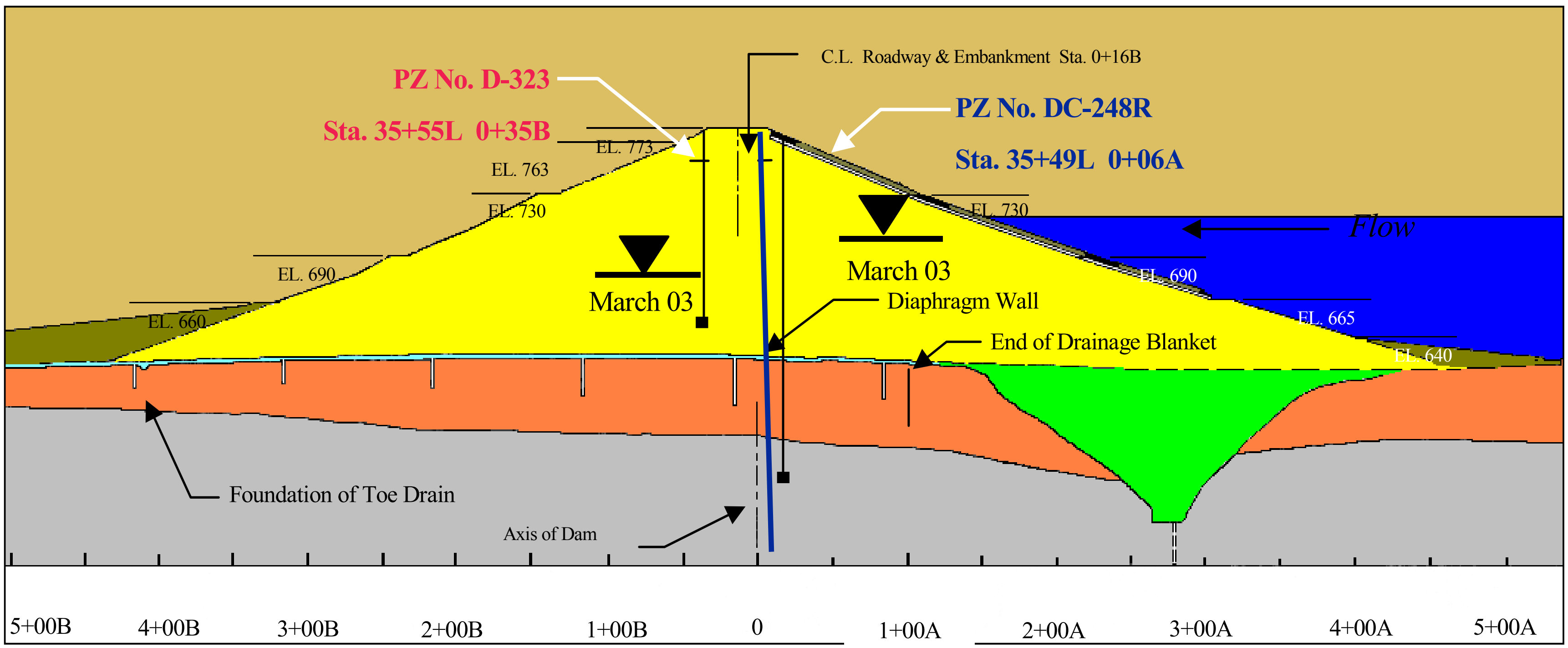
Wolf Creek Dam – Typical Section



Wolf Creek Dam – 1967/1968 Events



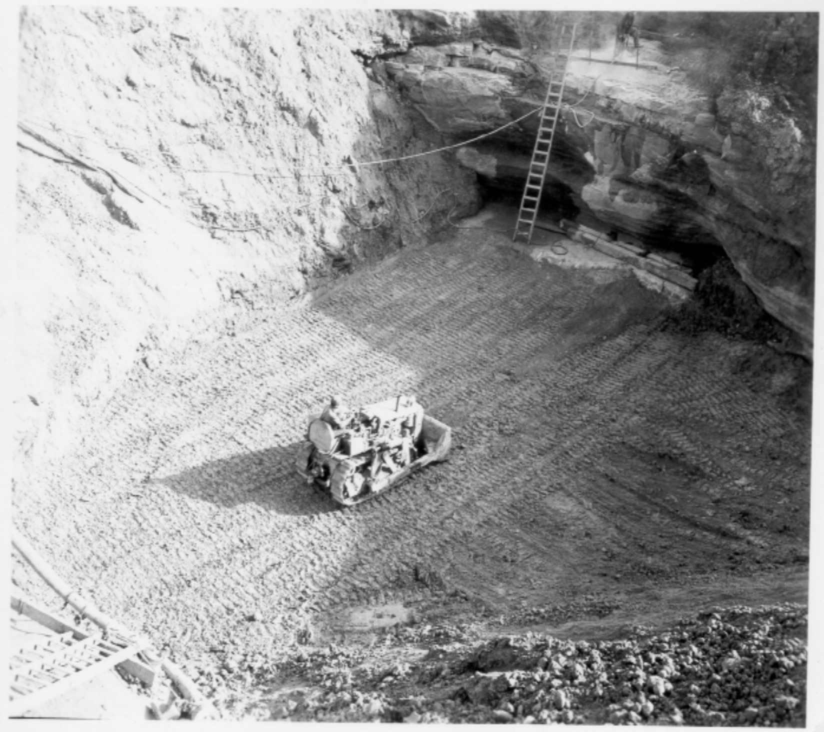
Wolf Creek Dam – Piezometers



Wolf Creek Dam – Cutoff Trench

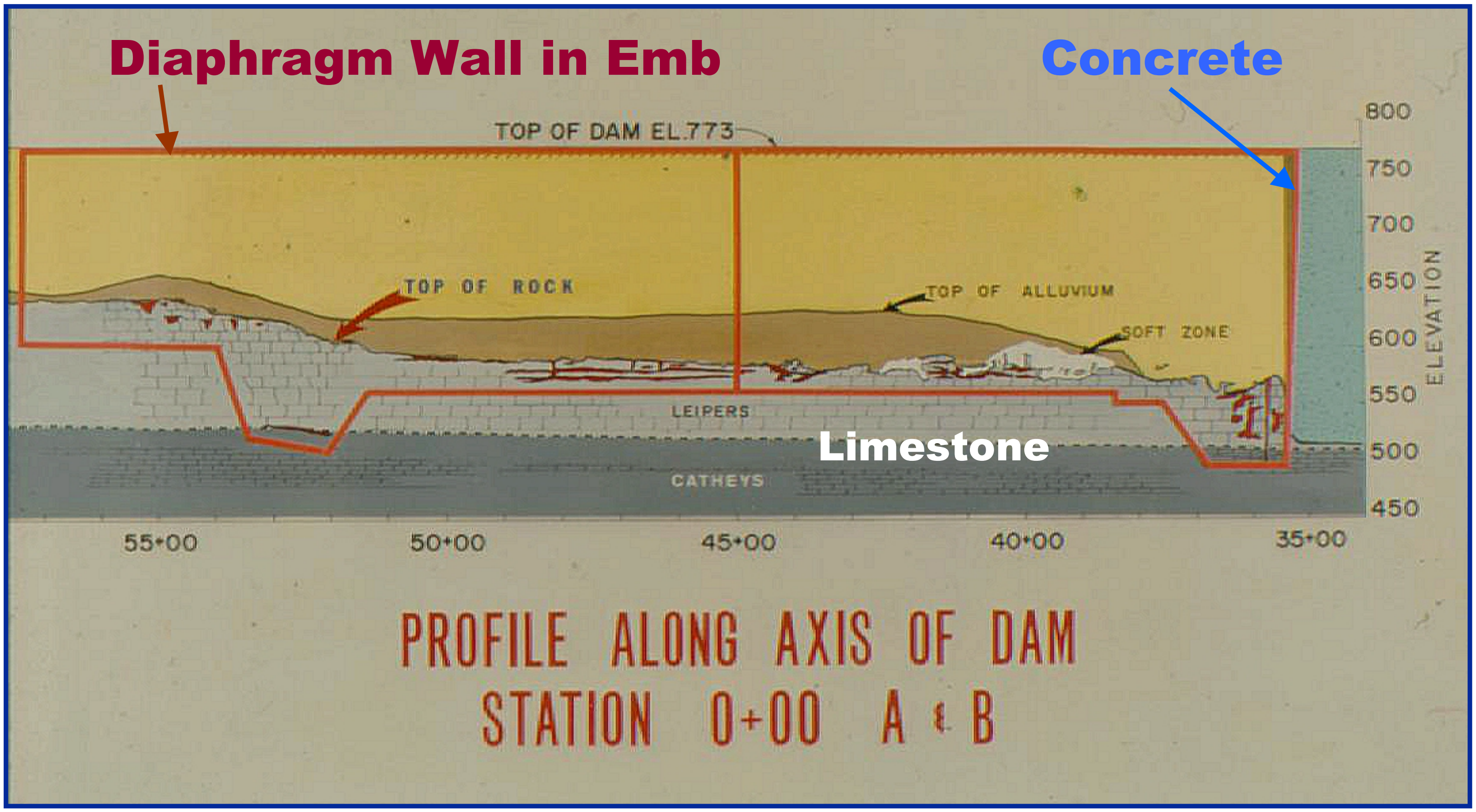
Wolf Creek Dam – Cutoff Trench

61/421 14 August 1947
Filling core trench, Mon. 37

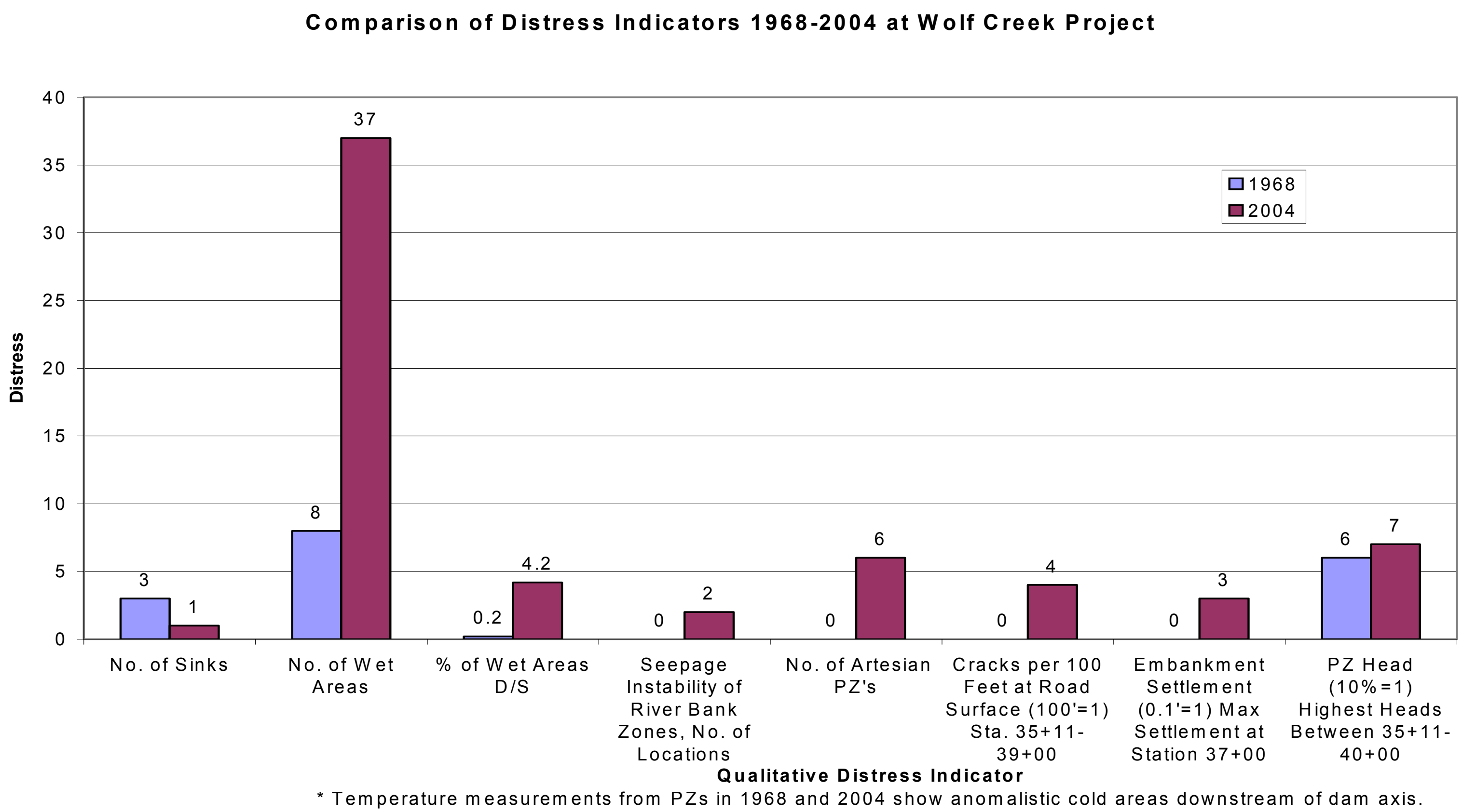


31,822 19 November 1942
View of backfilling operations in cavity at
Sta. 50+00 on cutoff trench

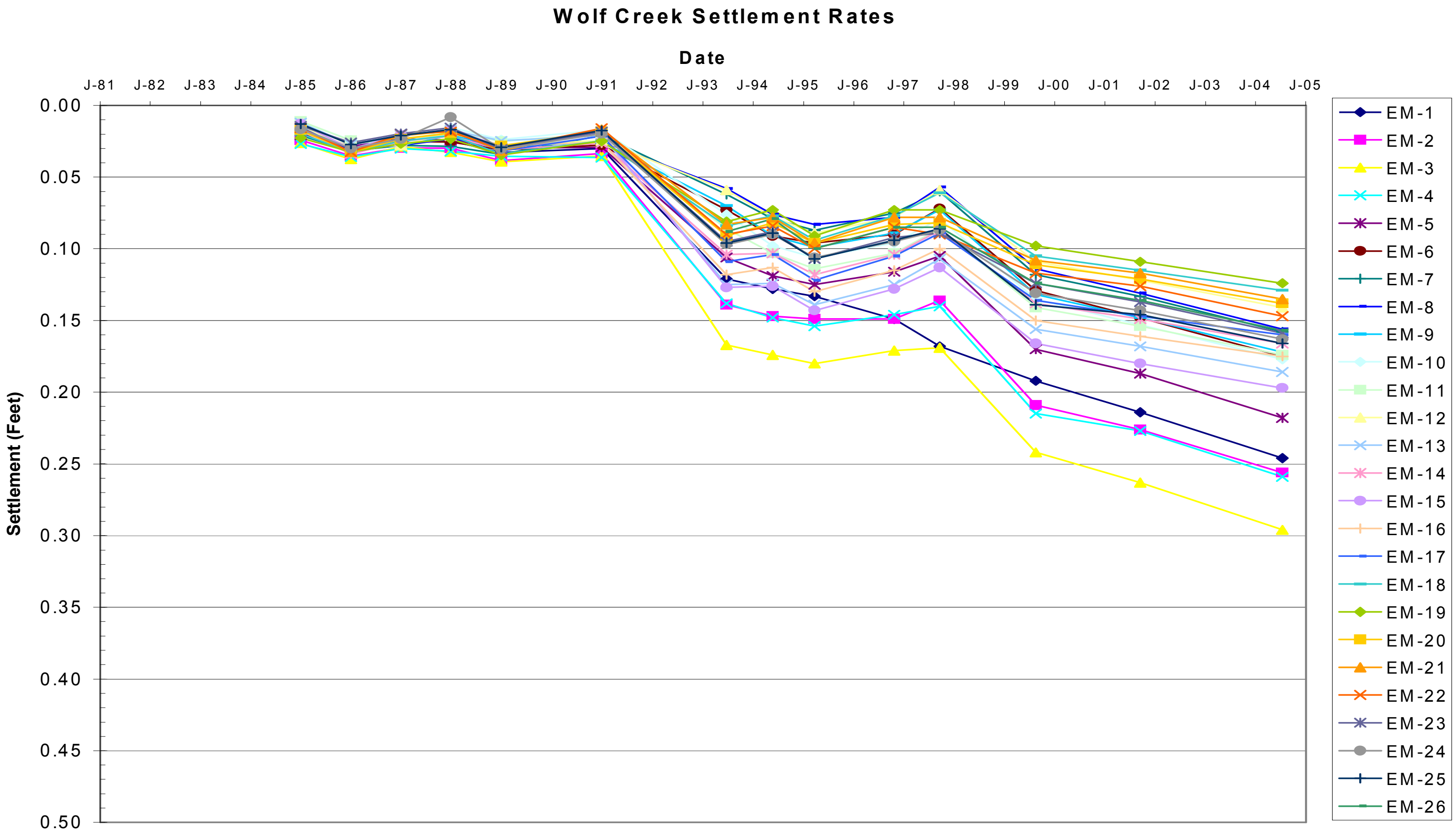
Wolf Creek Dam – Diaphragm Wall, 1975-1979



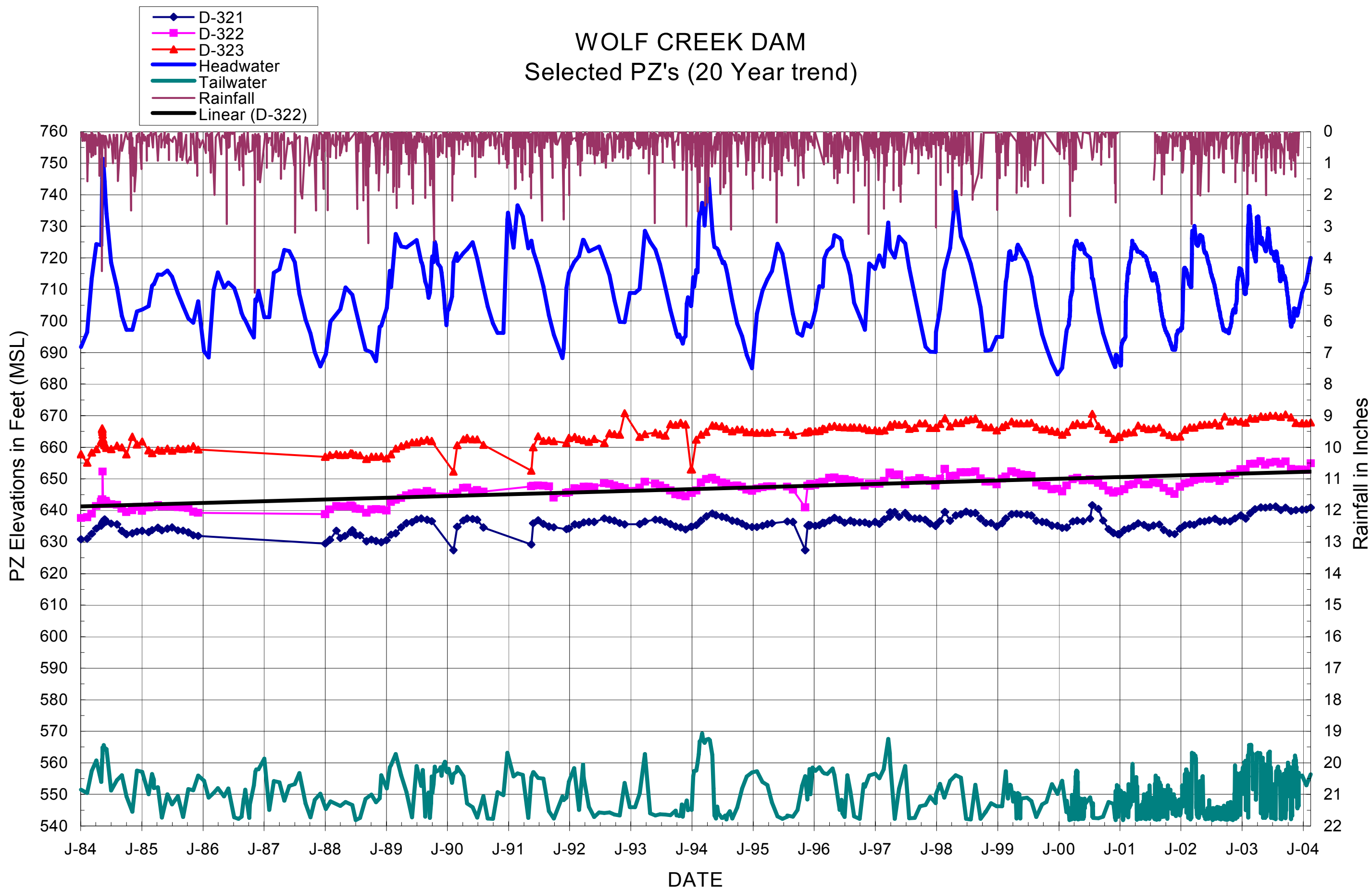
Wolf Creek Dam – Distress Indicators



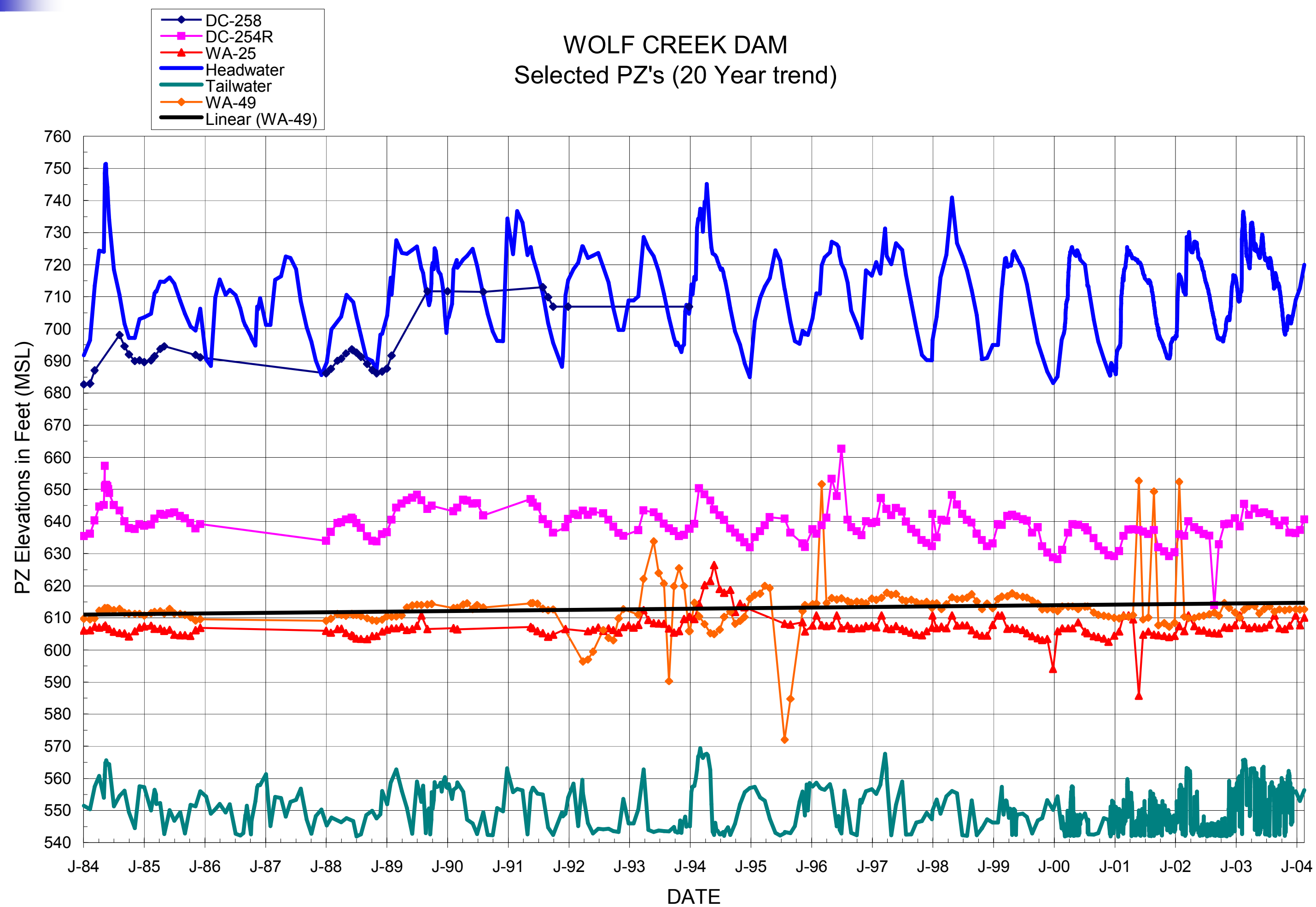
Wolf Creek Dam – Crest Settlement



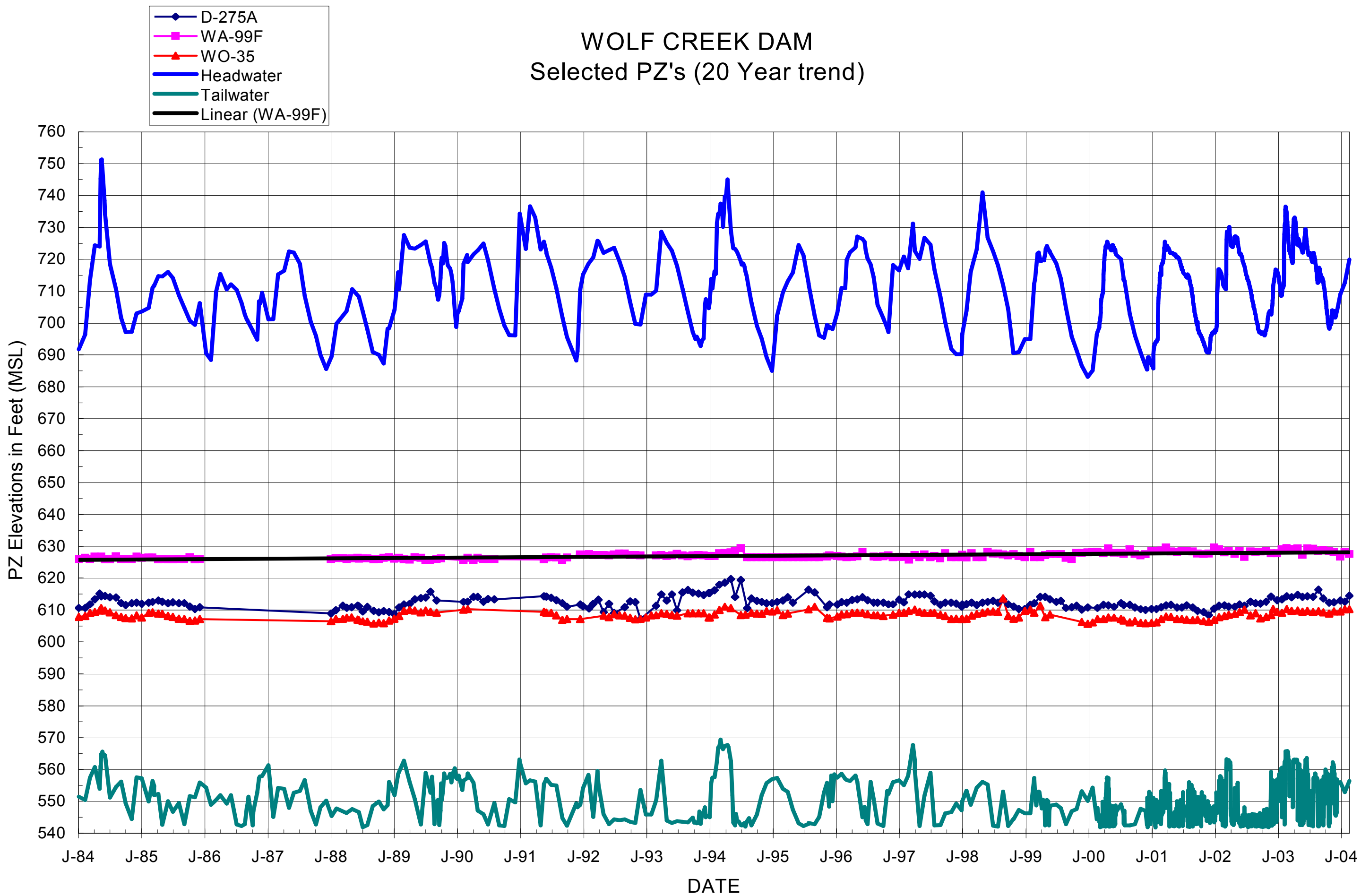
Wolf Creek Dam – Piezometric Data - Section 1



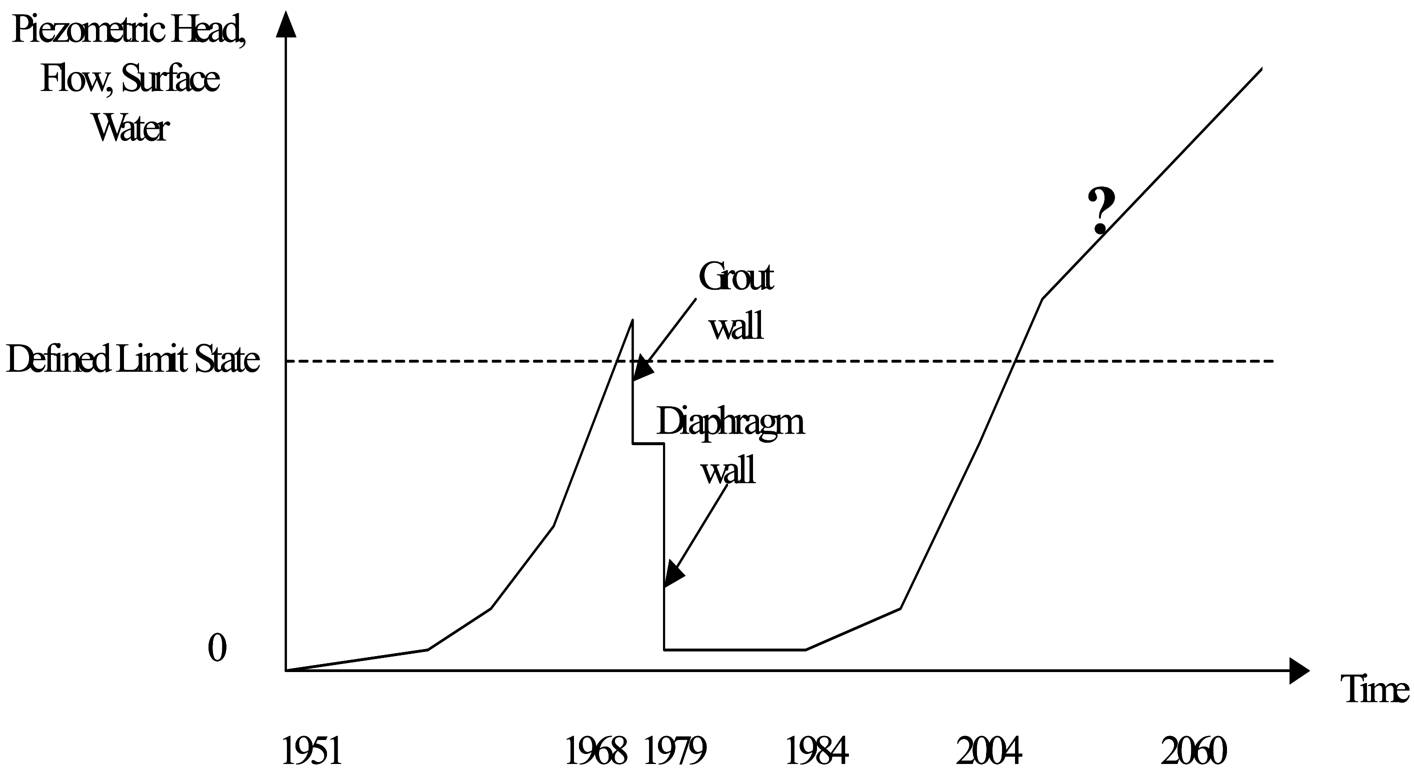
Wolf Creek Dam – Piezometric Data -Section 2



Wolf Creek Dam – Piezometric Data - Section 3



Wolf Creek Dam – Time-Dependent Reliability Concepts

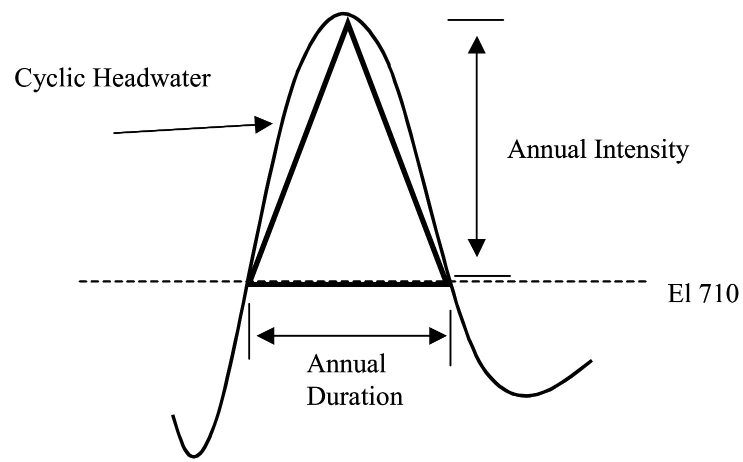


Wolf Creek Dam MRR

- Time-Dependent Reliability Model
  - Utilize permanent rise in piezometric pressures in the foundations
    - Reliable and most consistent data
    - Model three different embankment sections
    - Assume that selected limit state occurs before any decrease or fall in piezometric pressure which would indicate a more critical situation

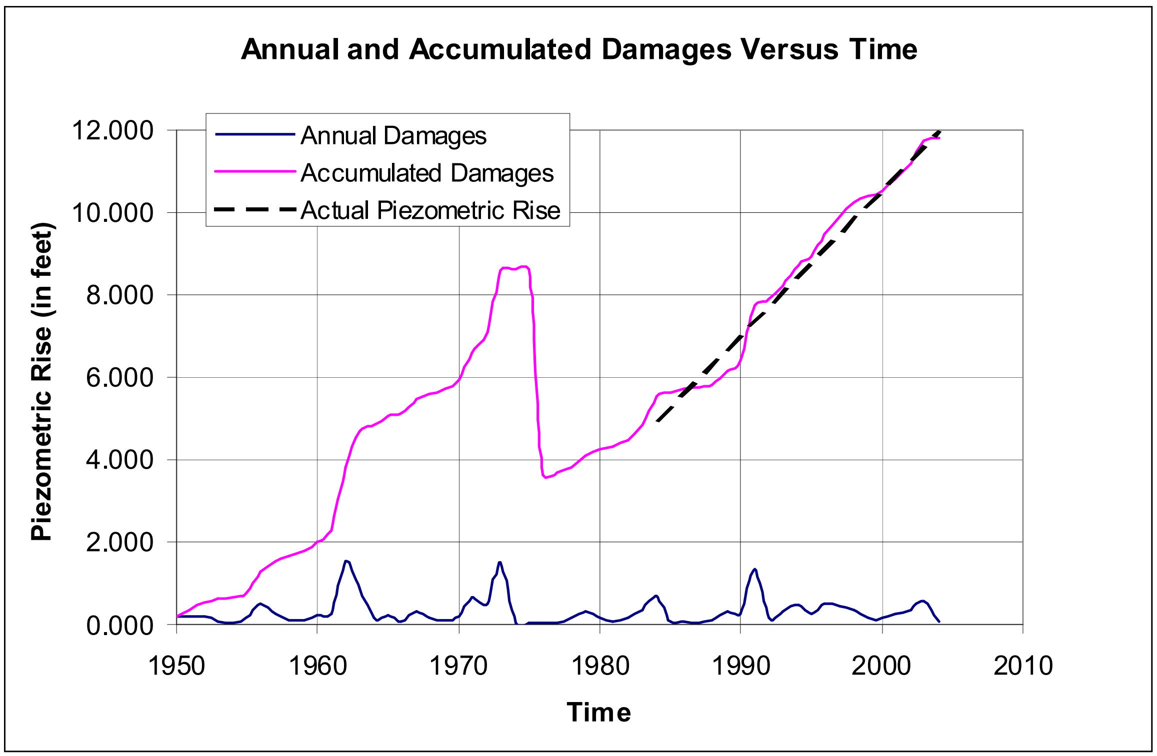
Wolf Creek Dam MRR

- Time-Dependent Reliability Model
  - Damage Accumulation Model (DAM)
    - Used in fatigue and wear rate analyses
    - Model cyclic variations of headwater above EL 710



Wolf Creek Dam MRR

- Time-Dependent Reliability Model
  - DAM Calibration



Wolf Creek Dam MRR

- Time-Dependent Reliability Model
  - Developed Monte Carlo Simulation Model
    - Accounted for entire life cycle including past remedial repairs
    - Performed 50,000 iterations for reliability calculations
  - Random Variables
    - Annual Intensity –
      - Based on historical records from 1950 to 2004
      - Truncated lognormal distribution
    - Annual Duration –
      - Based on historical records from 1950 to 2004
      - Truncated lognormal distribution

Wolf Creek Dam MRR

- Time-Dependent Reliability
  - Random Variables (cont’)
    - Spatial Variability Factor-
      - Accounts for variation in piezometric pressures in the foundation
      - Based on a wide range of piezometer data for each section
      - Incorporated as quadratic modifier to annual damage accumulation
      - Uniform distribution
        - More uncertainty in Section 3 than Sections 1 or 2 due to continued wet spots downstream and lack of diaphragm wall

Wolf Creek Dam MRR

- Time-Dependent Reliability Model
  - Limit state
    - Defined limit state for unsatisfactory performance on piezometric rise in 3 sections
    - Used Expert-Opinion Elicitation to quantify those values

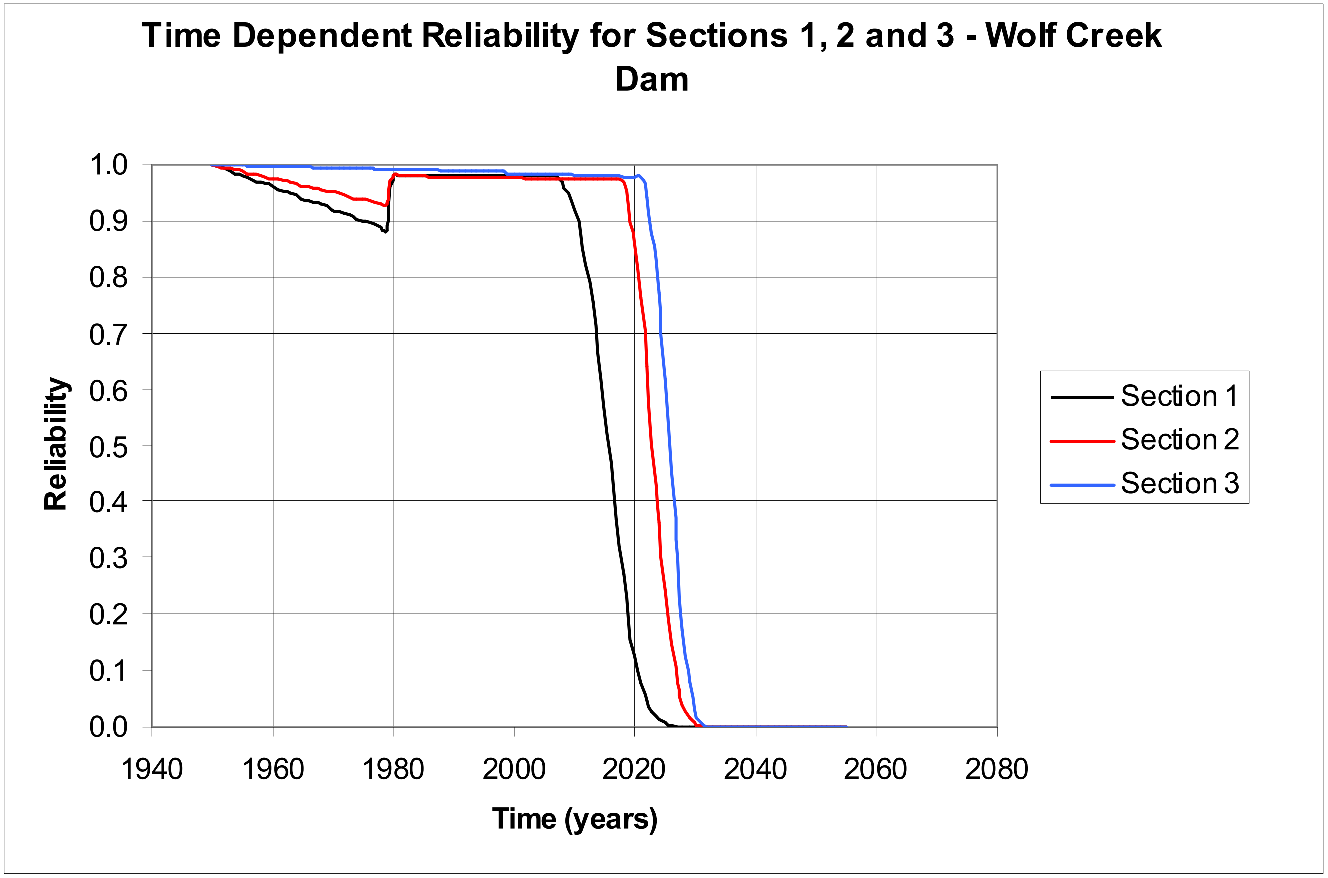
Section	Average PZ Value in 2004 (in feet)	Rise of PZ from EOE (in feet)	Unsatisfactory Performance Limit State (in feet)
1	9.3	5	14.3
2	4.1	5	9.1
3	1.2	3	4.2

Wolf Creek Dam MRR

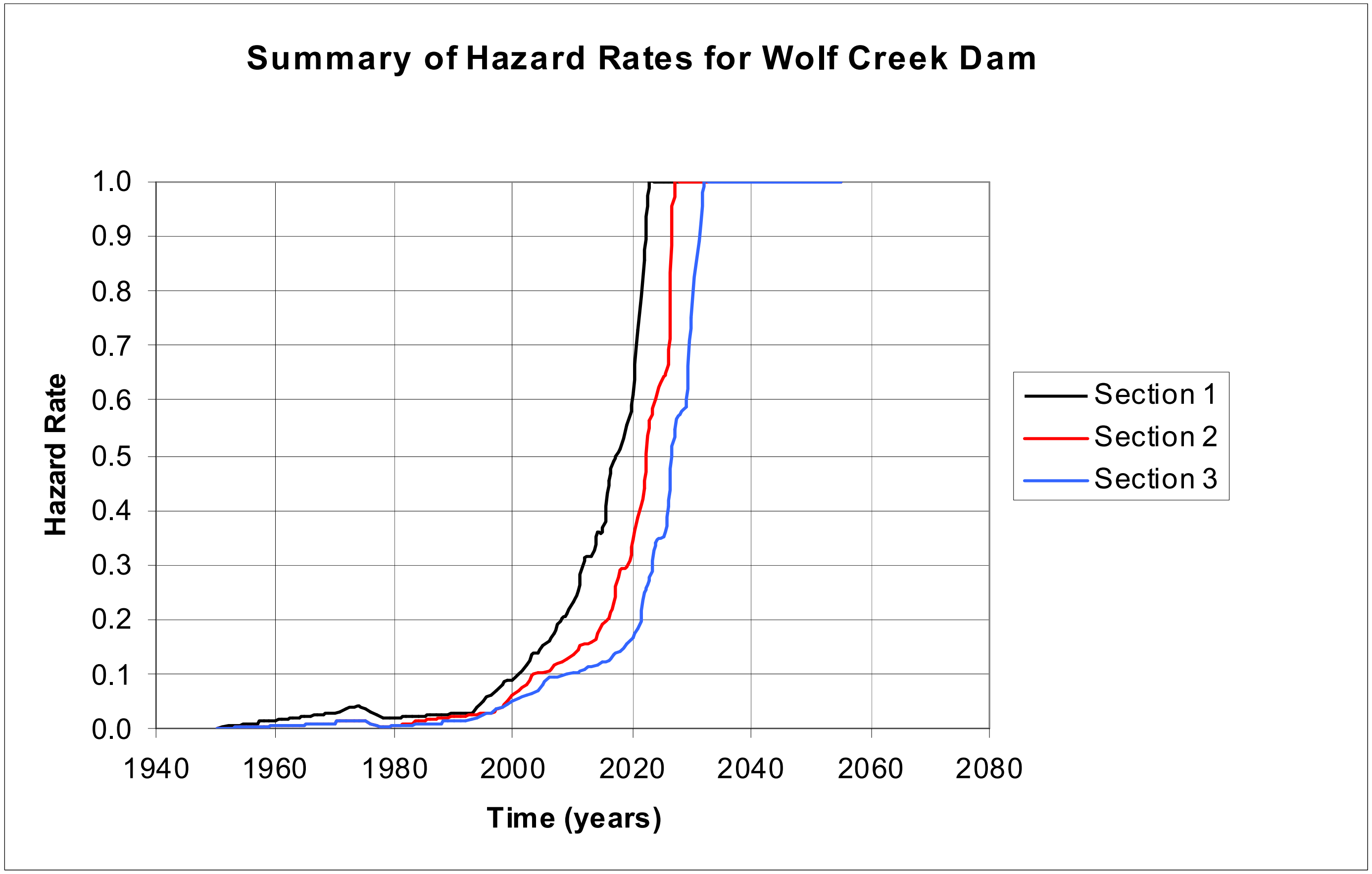
Wolf Creek Expert Elicitation

Event Name	Full Description of Issue	Expert-opinion elicitation			Summary Table	
		First Response	**Second Response**			
Unsatisfactory performance occurs in Section 1	At what future change in piezometric pressure in the foundation would you expect unsatisifactory performance in Section 1?	**Median =** 5	**Median =** 5			
				Confidence	**Minimum =**	1
	Expert #1	0.5	1	med	**25 Percentile =**	3
	Expert #2	5	5	high		
	Expert #3	10	7	med	**Median =**	5
	Expert #4	3	2	med		
	Expert #5	5	5	med	**75 Percentile =**	5
	Expert #6	5	4	high		
					90 Percentile =	6
					High =	7
	Minimum =	0.5	1			
	Median =	5	5			
	Maximum =	10	7			

Wolf Creek Dam MRR



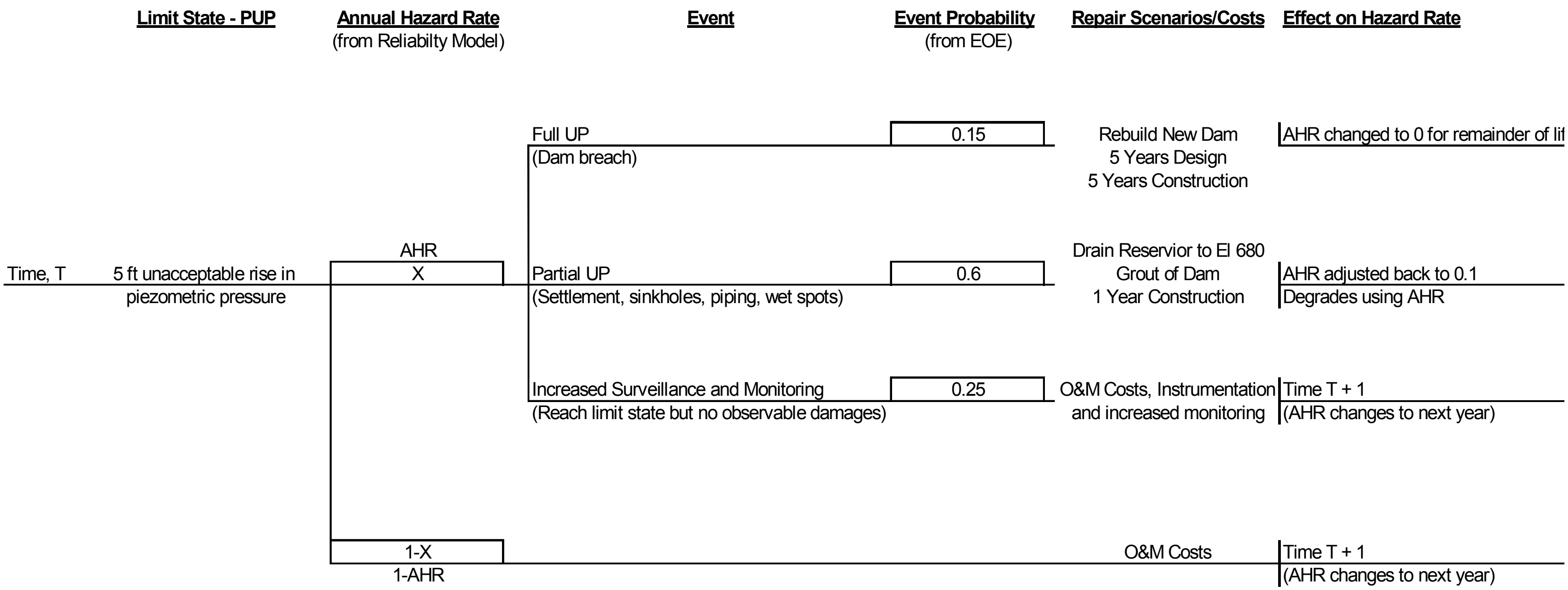
Wolf Creek Dam MRR



Wolf Creek Dam MRR

Wolf Creek Dam Event Tree

Baseline Condition - Section 1



Time-Dependent Reliability

- Conclusions
  - Time-dependent geotechnical models are difficult
    - Need to think well outside the box (deductive versus inductive thinking)
    - Incorporate and define distress indicators
      - My require some data processing
  - Understand - models are for major rehabilitation purpose to gain funding to rehab structure
    - Don’t get lost in the fine details
    - Not the true probability of failure
      - Within an order of magnitude
      - Not for dam safety