Session 4 Economic Impacts of a Karst Foundation Wolf Creek Dam,

US Army Corps of Engineers,
Nashville District
Outline of Topics

- Project Description.
- General Background.
- Reliability Studies.
- Interim Risk Reduction Measures.
- Operating Restrictions.
- Economic Impacts.
Project Features
EMBANKMENT PLAN AND SECTION

- Cut Off Trench
- Drainage Blanket
- Toe of Random Fill
• Treatment techniques were inadequate for this geology
• Most of the alluvium left in place
• Except for cut-off trench, no embankment foundation treatment
• Cutoff trench design and construction inadequate
Overhangs and loose rocks will only be removed where they cross the line of the trench, since the earthfill in the sides of the trench will have the function only of stability and not of an absolutely uniform tight contact with the trench walls. Tamping will supplement the regular rolling of the fill as required under the overhangs and irregular salients.
Solution Features

Cave
1968 Sinkhole

Switchyard

Sinkhole
1960’s and 70’s Remedial Features

- Diaphragm Wall
- Earth Emb
Post Wall Performance – Wet Areas
March 2004

Existing Diaphragm Wall
Risk is defined as the probability of unsatisfactory performance times the consequences of the unsatisfactory performance.

For Wolf Creek, based on a breach of the dam the estimated consequences are up to 350 lives lost and over $3 billion in damages.

How do we establish the probability of unsatisfactory performance?

It is especially difficult to predict the behavior in Karst.
Excerpts from a presentation by

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September 2002
Most problems of interest involve or could be represented by an event tree.

Given some water level:

- Sand Boil: $p = 0.5$
- Carries material: $p = 0.3$
  - Close to levee: $p = 0.6$ (0.09)
  - Not close: $p = 0.4$ (0.06)
- Doesn’t: $p = 0.7$ (0.35)
Probabilities for the Event Tree - How????

A) $f$ (Uncertainty in parameter values) Reliability Index Methods ($\beta$)
- Monte Carlo method
- FOSM methods
  - point estimate
  - Taylor’s Series
    - Mean Value
    - Hasofer-Lind

B) Frequency Basis
- Exponential, Weibull, or other lifetime distribution

C) Judgmental Values
- Expert elicitation
A) **Pr(f) = Function of Parameter Uncertainty**

- Identify performance function and limit state, typically \( \ln(FS) = 0 \)
- Identify random variables, \( X_i \)
- Characterize random variables, \( -E[X], \sigma_X, \rho \)
- Determine \( E[FS], \sigma_{FS} \)
- Determine Reliability Index, \( \beta \)
- Assume Distribution and calculate \( Pr(f) = f(\beta) \)
Pros and Cons of $b, \Pr(U)$

**Advantages**
- "Plug and Chug"
- fairly easy to understand with some training
- provides some insight about the problem

**Disadvantages**
- Still need better practical tools for complex problems
- Non-unique, can be seriously in error
- No inherent time component
- only accounts for uncertainties related to parameter values and models
B) Frequency-based Probabilities

- Represent probability of event per time period
- Poisson / exponential model well-recognized in floods and earthquakes
- Weibull model permits increasing or decreasing event rates as $f(t)$, well developed in mechanical & electrical applications
- Some application in material deterioration
- Requires historical data to fit
Pros and Cons of Frequency Models

**Advantages**
- Can be checked against reality and history
- Can obtain confidence limits on the number of events
- Is compatible with economic analysis

**Disadvantages**
- Need historical data
- Uncertainty in extending into future
- Need “homogeneous” or replicate data sets
- Ignores site-specific variations in structural condition
C) Judgmental Probabilities

- Mathematically equivalent to previous two, can be handled in same way
- Can be obtained by **Expert Elicitation**
  - a systematic method of quantifying individual judgments and developing some consensus, in the absence of means to quantify frequency data or parameter uncertainty
Pros and Cons of Judgmental Probabilities

**Advantages**
- Gives you a number when nothing else will
- May be better reality check than parameter uncertainty approach
- Permits consideration of site-specific information
- Some experience in application to dams

**Disadvantages**
- Distrusted by some (including some within Federal Agencies)
- Some consider values “less accurate” than calculated ones
- Non-unique values
- Who is an expert?
1. Analysis from Major Rehabilitation Report (MRR)
   - Based on analysis of stress indicators
   - Limit State defined as condition that would require operational restrictions. Limit State threshold selected by expert elicitation.
   - Damage accumulation based on projection of instrumentation data coupled with historical pool stages using a Monte Carlo simulation.
   - Reviewed by an independent panel of experts
   - Stress indicators show gradual change from 1984 to present
   - Considered risk to be high
   - Analysis based on engineering judgment
2. Screening Portfolio Risk Assessment

- In-house Corps expertise
- Reviewed MRR and other data
- Purpose to determine ranking in severity of Corps dams
- Placed Wolf Creek in the “Urgent and Compelling” category
3. Independent Peer Review Panel

- Independent Consultants
- Purpose to validate the SPRA process and review projects in the “Urgent and Compelling” category
- Recommended immediate operating restrictions at Wolf Creek
- Considered risk to be high
- Analysis based on engineering judgment
All three studies conclude the project is deficient.

Immediate measures should be taken to reduce the risk.

Some of them can be implemented without serious negative impact.
Risk Reduction Actions
Interim Risk Mitigation Measures

- Dam Safety Program
- Monitoring 24/7
- Increased instrumentation
- Enhanced and aggressive EAP process
- Public Meetings
- Independent Expert Panel
- Stockpiling material
Risk Reduction Actions

- Trigger Events that Would Require Emergency Drawdown
  - Significant abnormal instrumentation readings
  - Sinkholes or settlement in the dam
  - Muddy flows
  - Slide in the dam slope

- Modified Lake Level Operation
Operating Restrictions
Lower the Lake = Lower the Risk

- This decision comes with a cost.
- The benefits derived from the project diminish as the lake is lowered.
- How do you make the decision which balances lowered risk with lost benefits.
Project Benefits And Lake Level Target Zone

- Flood Control
  - Average annual flood damages prevented = $34 million
- Hydropower
  - $77 million / year
- Recreation
  - 5 million visitors per year
  - $159 million impact on local economy
- Water Supply
- Water Quality
- Navigation
4. RAC Engineers and Economists Study (Operating Restrictions) Utah State U. Initiated before Peer Group.

- Used risk assessment methodology to determine effect on risk of various operating restrictions
- Preliminary ‘bounding analysis’ showed unacceptable level of risk
- Uses process similar to ‘expert elicitation’ to quantify engineering judgment
Wolf Creek Dam
Section
Damage Progression

1. Pipe begins in rock and expands to alluvium
2. Secondary element in wall fails
3. Pipe expands through alluvium
4. Breach and failure
5. Rapid tailwater fluctuations during power generation

RAC First Failure Scenario
The Event Tree

1968 Emergency grouting program
1979 Diaphragm Walls Complete

1967 & 68 Muddy flow and sink hole

The Event Tree:
1. Pipe begins in rock and expands to alluvium
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Grout Curtain
Cutoff Trench
Alluvium
Catheys Formation
Liepers Formation
Piezometers
Annualized Probability of Failure

![Graph showing annualized probability of failure.](image)

- **20% Confidence of not being exceeded**
- **50%**
- **80%**

Limit for Individual Risk & USBR Public Protection Guideline:

- **80%**
What Does This Mean?

- None of the operating restrictions meet the criteria for tolerable risk except those that require structural modification of the project.
- These restrictions result in a loss of annual benefits totaling $200 million.
- There are severe environmental consequences to these restrictions.
- Unforeseen consequences?
Where Are We Now

- Decision based on previous risk studies + impacts that result and health and safety concerns for upstream residents. (Water Intakes). Corporate decision not solely District jurisdiction.
- Operate the pool at 680 – flat.
- Incremental approach. If distress indicators improve and grouting proceeds, evaluate new operating level. If not, consider more severe restrictions.
How accurately can \( Pr(f) \) be calculated?

Not very accurately (my opinion) --
Many ill-defined links in process:
- variations in deterministic and probabilistic models
- different methods of characterizing soil parameters
- \( \phi - c \) strength envelopes are difficult
- slope is a system of slip surfaces
- distributions of permeability and permeability ratio
- difficult to quantify spatial correlation in practice
- difficult to account for length of embankments
- difficult to account for independence vs correlation of multiple monoliths, multiple footings, etc.
First Emergency Grouting $15 million
Composite Cut Off Wall $ 90 million
Current Emergency Grouting $50 million
Future Cut Off Wall $250 million ±
Impact Costs

- Lost hydropower generation = $70 million
- Cost of extending launching ramps = $165K
- Cost of extending water intakes = $several million
- Lost revenue from recreation = $65 million
- Fish hatchery modifications $750K +
- Others
Questions

\[ E[FS] = FS \left( E[X_i] \right) \]

\[ \text{Var}[FS] = \sum \left( \frac{\partial FS}{\partial X_i} \right) \sigma^2_{x_i} \]

\[ \Delta FS = \sum \left( \frac{FS(X_{i-}) - FS(X_{i+})}{2} \right)^2 \]