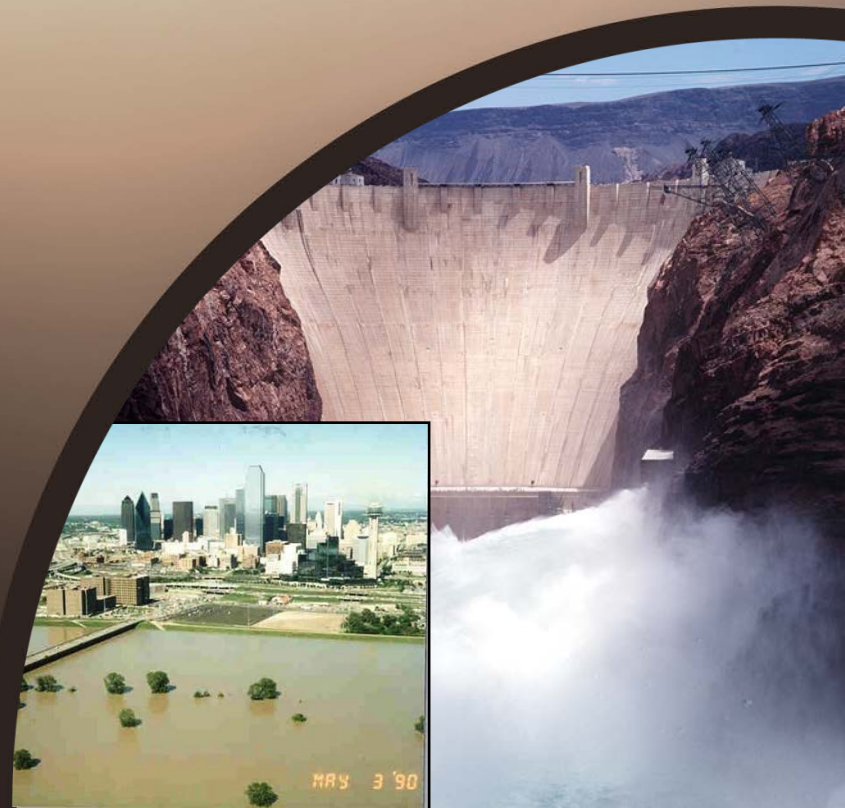
Best Practices in Dam and Levee Safety Risk Analysis

Introduction

26 February 2015



US Army Corps of Engineers
BUILDING STRONG®

Definitions

- Risk – probability of adverse consequences x consequences
  - P(load) x P(failure) $_{\text{given the load}}$ x Consequences $_{\text{given failure}}$
- Risk Analysis – A quantitative calculation or qualitative evaluation of risk
- Risk Assessment – The process of deciding whether risk reduction actions are needed

Dam Safety Risk Analysis is New?

"The possibility of failure must not be lost sight of. To sum up in a concrete manner, it is my judgment that the chances of failure with the water at varying elevations will be substantially as follows:

	ELEVATION	CHANCES
	3795	1 in 5000
	3800	1 in 2000
LIKELIHOOD	3805	1 in 500
	3810	1 in 100
	3815	1 in 10

In case of failure, while there might be no loss of life, yet the loss in time, in property, in money and in prestige would many times over exceed the cost of even an entirely new structure."

CONSEQUENCES

Thaddeus Merriman, New York, February 21, 1912

Why Risk Analysis?

- Following the failure of Teton Dam in 1976, Reclamation was asked to begin developing risk analysis methodology for dams (risk is mentioned in dam safety legislation)
- USACE recognized need to implement risk analysis following failure of levees in New Orleans during Hurricane Katrina
- Need to improve and balance risk reduction benefits with limited budget (e.g. upgrading a few dams to pass the PMF vs. using available budget to reduce risk at many dams)
- More transparency and justification for dam and levee safety decisions was desired

Guiding Principles

- Risk analysis procedures, although quantitative, do not provide precise numerical results. Thus, the nature of the risk evaluation needs to be advisory, not prescriptive, such that site specific considerations, good logic, and all relevant external factors could be applied in decision making, rather than reliance on a 'cookbook' numeric criteria approach.

- The numbers, while important, are less important than understanding and clearly documenting what the major risk contributors are and why.

Building Blocks

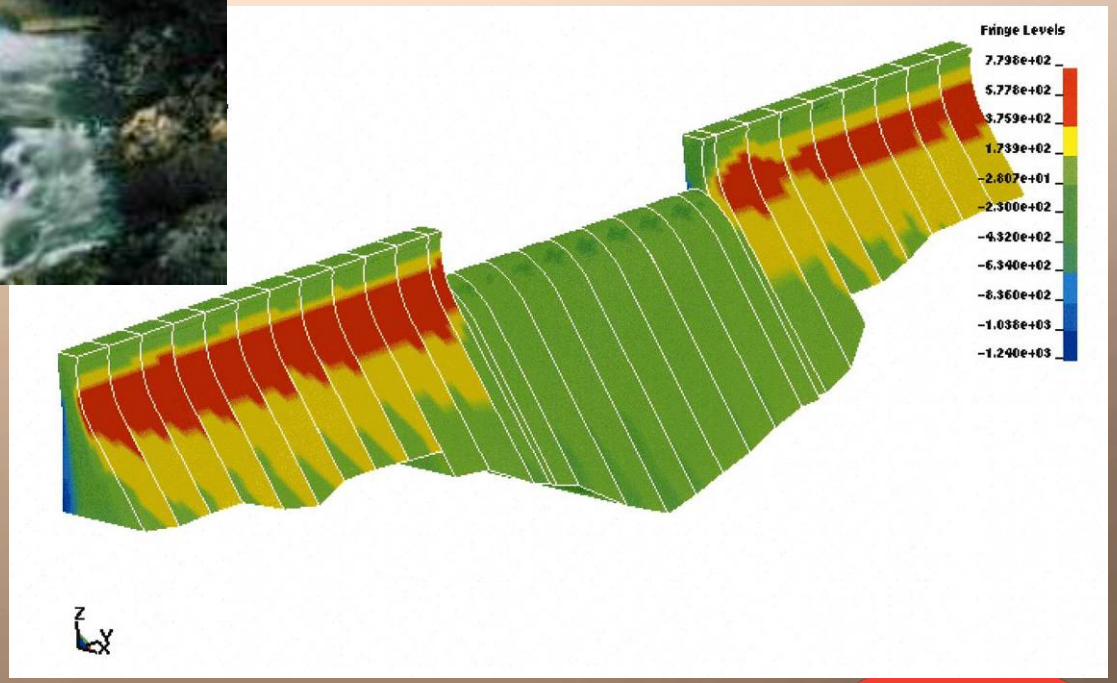
- Seismic and Hydrologic Hazard Assessments
- Failure Mode Analysis and Screening
- Event Trees and System Response Curves
- Probabilistic Analysis and Models
- Subjective Probability and Expert Elicitation
- Consequence Evaluation

- This course will focus on these, their application to a few more significant specific potential failure modes, and how to convey the results.
- The manual covers application to several potential failure modes that will not be presented in the course.

Example to Illustrate Process

MCE Analysis

Red – tensile stresses exceed strength

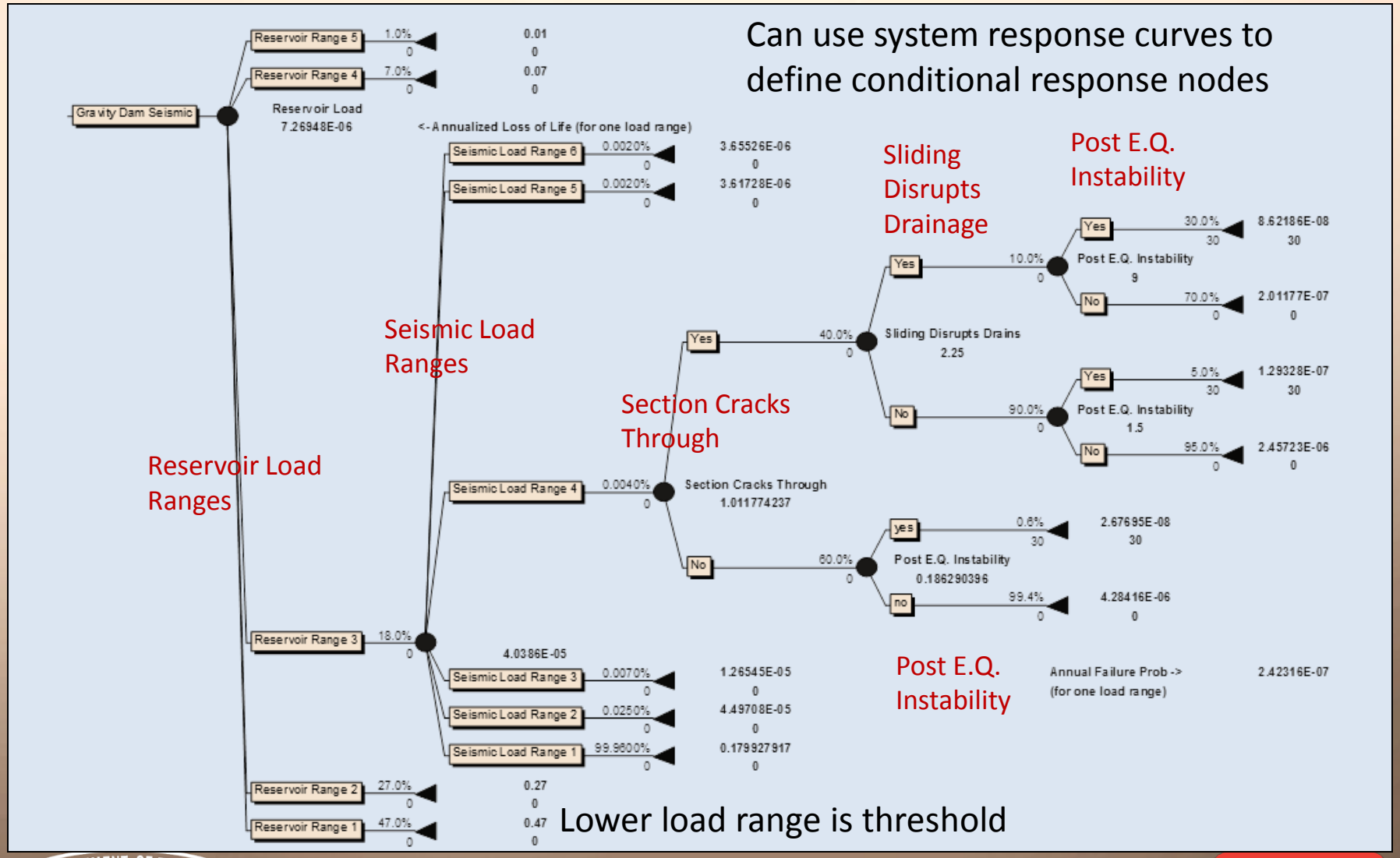


Failure Mode Description

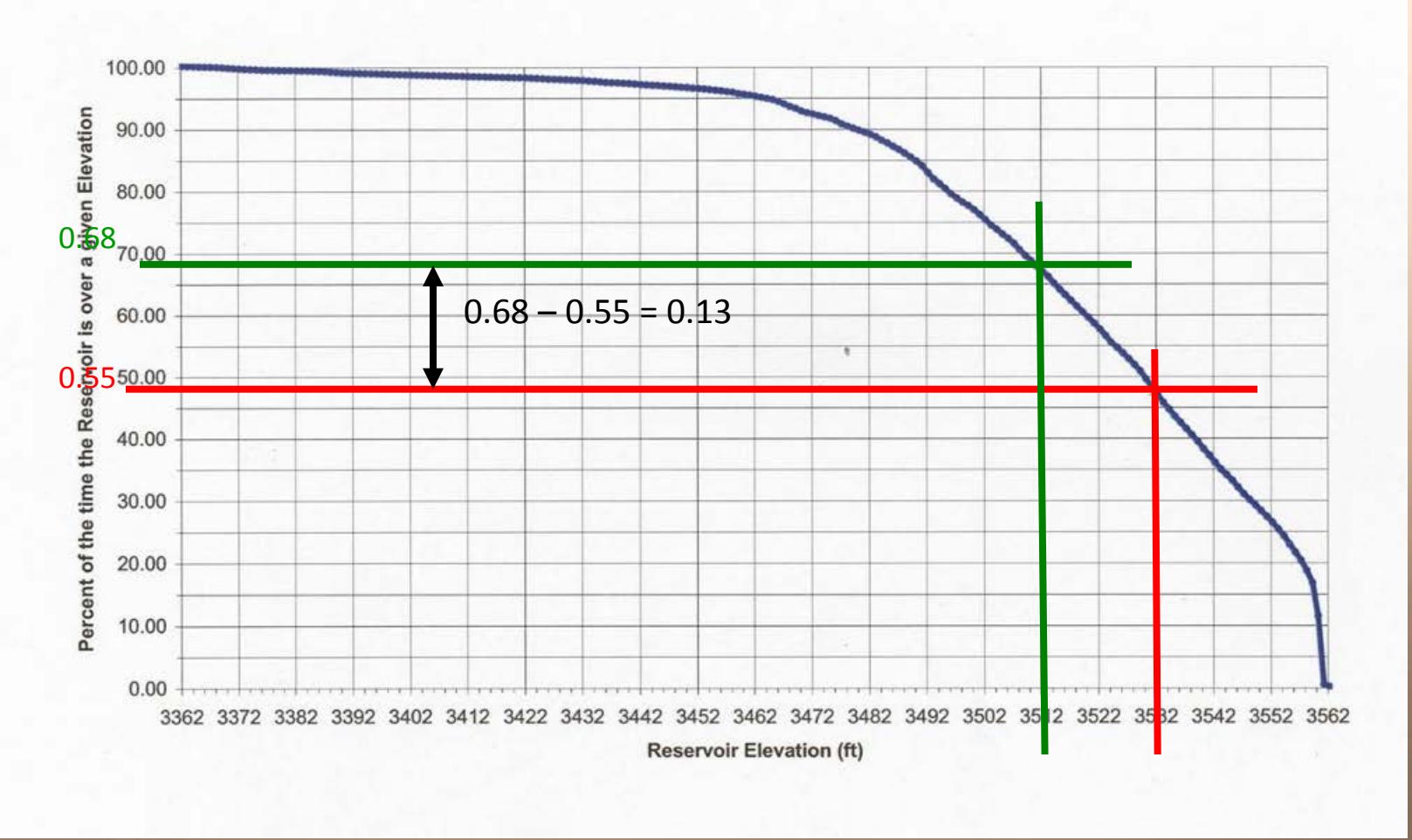
- Unedited (insufficient detail): Failure of the concrete dam during an earthquake

- Edited: (1) As a result of strong earthquake ground shaking during a period of high reservoir elevation, (2) cracking initiates at the change in slope on the downstream face of the concrete gravity dam at about elevation 3514. Due to cyclic "rocking" of the structure, the dam cracks completely through monoliths on either side of the spillway. Sliding initiates during the shaking, perhaps causing enough displacement to dilate the sliding plane and offset and shear the formed drains. This potentially leads to an increase in uplift on the cracked section and post-earthquake instability. (3) The dam breaches by sudden sliding of several monoliths down to elevation 3514.

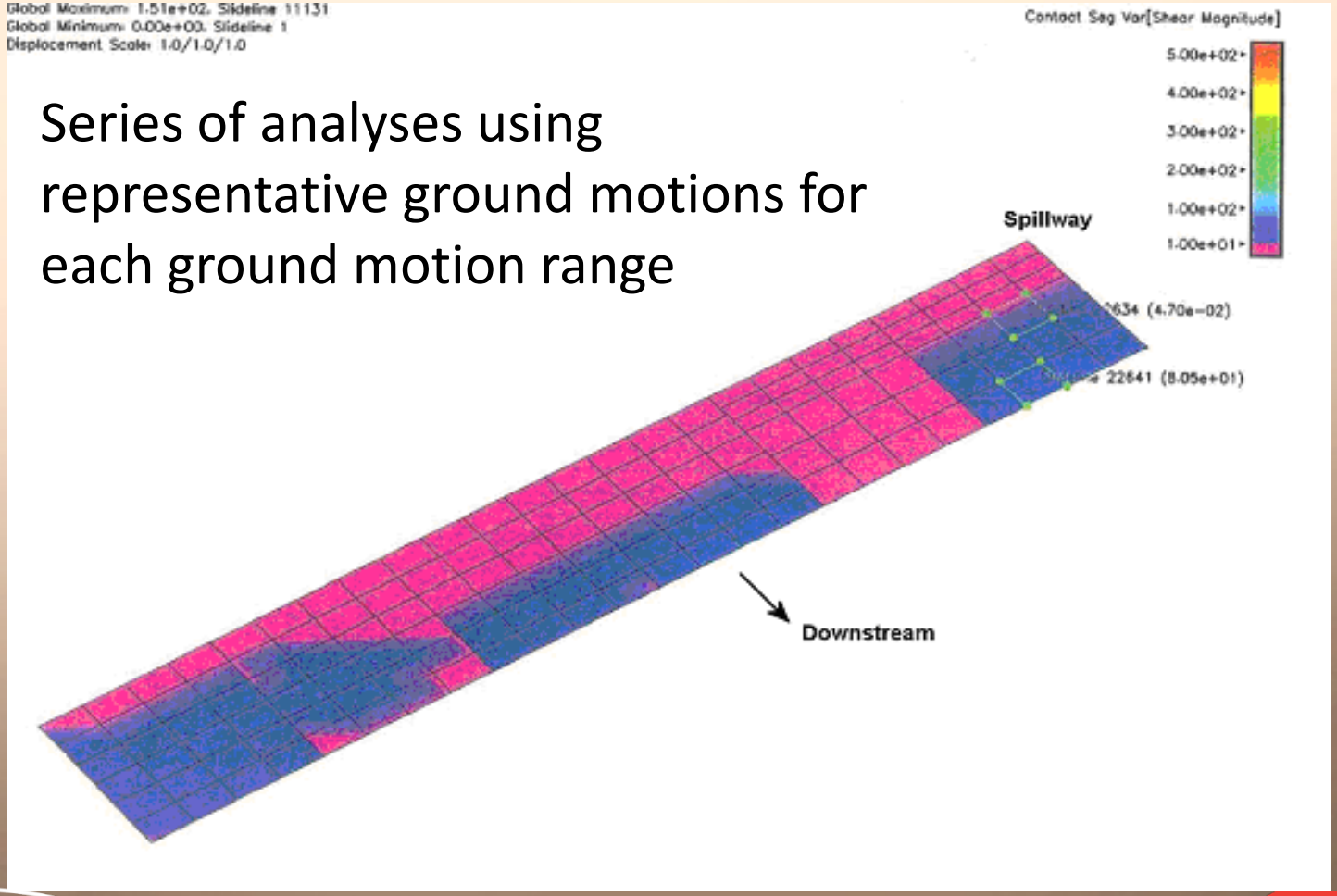
Event Tree


Can use system response curves to define conditional response nodes
Gravity Dam Seismic
Reservoir Load
7.26948E-06
Reservoir Range 5
1.0%
0
0.01
0
Reservoir Range 4
7.0%
0
0.07
0
<-Annualized Loss of Life (for one load range)
Reservoir Load Ranges
Reservoir Range 3
18.0%
0
4.0386E-05
Reservoir Range 2
27.0%
0
0.27
0
Reservoir Range 1
47.0%
0
0.47
0
Seismic Load Ranges
Seismic Load Range 6
0.0020%
0
3.65526E-06
0
Seismic Load Range 5
0.0020%
0
3.61728E-06
0
Seismic Load Range 4
0.0040%
0
Seismic Load Range 3
0.0070%
0
1.26545E-05
0
Seismic Load Range 2
0.0250%
0
4.49708E-05
0
Seismic Load Range 1
99.9600%
0
0.179927917
0
Section Cracks Through
Yes
40.0%
0
Section Cracks Through
1.011774237
No
60.0%
0
Sliding Disrupts Drainage
Yes
10.0%
0
Sliding Disrupts Drains
2.25
No
90.0%
0
Post E.Q. Instability
Yes
30.0%
30
8.62186E-08
30
Post E.Q. Instability
9
No
70.0%
0
2.01177E-07
0
Post E.Q. Instability
1.5
Yes
5.0%
30
1.29328E-07
30
No
95.0%
0
2.45723E-06
0
Post E.Q. Instability
0.186290396
yes
0.6%
30
2.67695E-08
30
no
99.4%
0
4.28416E-06
0
Annual Failure Prob ->
(for one load range)
2.42316E-07
Lower load range is threshold

Example, Load Range Probability from Exceedance Curve



Example Expert Elicitation, Likelihood of Cracking Through



Series of analyses using representative ground motions for each ground motion range

Likelihood of Cracking Through

- Adverse Factors
  - Tensile stress on u/s face exceeds estimated dynamic tensile strength for load ranges 5-6
  - Cracks may propagate more readily than nonlinear analysis accounts for
- Favorable Factors
  - Tensile stress on u/s face is less than estimated dynamic tensile strength for load ranges 2-4
  - Coring showed good bond at lift joints
  - Nonlinear analysis showed only one monolith would crack through at load range 6

Verbal Descriptors

Descriptor	Associated Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001*

*Use sparingly – Reagan's research showed that people are not well calibrated below about 0.01

Likelihood of Post E.Q. Instability, Probabilistic Stability Analysis Methodology

- Program “deterministic” analysis in Microsoft Excel
- Use @Risk – commercially available Macro add-in
- Instead of defining input parameters as single values, define them as distributions
- Perform “Monte-Carlo” analysis using @Risk to calculate many factors of safety by sampling input distributions
- Use the output distribution of safety factor to determine the probability of unsatisfactory performance (e.g. probability of F.S.<1.0)
- Prob F.S.<1.0 = (Number of F.S.<1.0) / (Total No. F.S.)

F.S. Output
(10,000 iterations)

@RISK Output Data Report

Output Data

Outputs	FS = ?K/?L = / (ft)
Simulation#	1
Iteration / Cell	B24

1	1.40282166
2	1.400596261
3	1.501422405
4	1.251672149
5	1.42097795
6	1.175672889
7	1.477007627
8	1.59830904
9	1.235151768
10	1.571461201
11	1.303617954
12	1.47099793
13	1.271955848
14	1.104541183
15	1.32243073
16	1.567054033
17	1.259018064
18	1.44313252
19	1.224726915
20	0.953297615
21	1.272130251

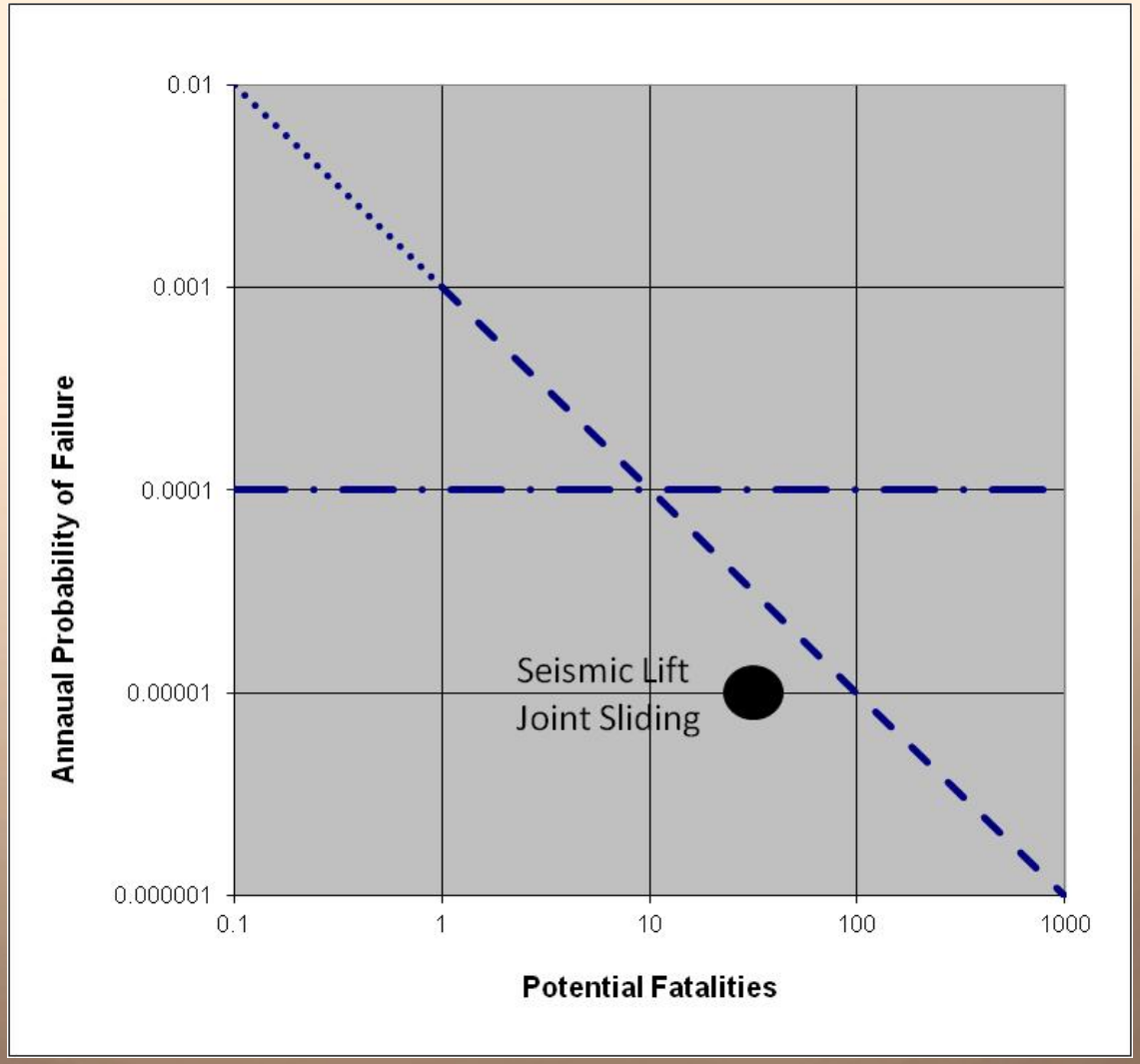
Summary Report | Outputs Data Report

	A	B
214		0.995250225
215		0.995401144
216		0.996119738
217		0.996244669
218		0.996596992
219		0.996732235
220		0.996939957
221		0.997377455
222		0.9976843
223		0.997831881
224		0.998167098
225		0.998627961
226		0.998666167
227		0.999451816
228		0.99964112
229		1.000186086
230		1.000269651
231		1.000651717
232		1.000991702
233		1.001196861
234		1.001266599
235		1.001507759
236		1.003768325
237		1.00380218
238		1.004098296
239		1.004418135
240		1.005377531
241		1.005683422
242		1.005916238

Consequences

- Based on an evaluation of
  - Population at risk
  - Flood wave travel and warning time
  - Warning effectiveness and mobilization rates
  - Evacuation routes
  - Flood severity (depth and velocity)
  - Non-breach flooding (to establish incremental consequences)
  - Economics (direct damages, lost benefits, replacement costs)

Results Relative to Risk Guidelines



Example of Building the Case

- Claim:
  - The lift joints near the spillway crest are well bonded and have significant strength. This leads to a low likelihood (0.1 or less) of cracking through the section at 1/10,000 AEP or smaller ground motions.
- Evidence:
  - All lift joints near the spillway elevation were recovered intact in core drilling
  - There were a large number of tests indicating high tensile strength across joints (report numbers)
  - Construction control procedures were excellent (describe)
  - Stresses are less than estimated strength (enumerate)