Simple Probabilistic Analysis of a Gravity Dam

FEDERAL ENERGY REGULATORY COMMISSION
OFFICE OF ENERGY PROJECTS
DIVISION OF DAM SAFETY AND INSPECTIONS

Traditional Deterministic Approach

- For Sliding of the structure of the Foundation
  - Fixed parameters
    - Weight of concrete: 150 lb/ft^3
    - Weight of water: 62.4 lb/ft^3
  - Variable parameters
    - Uplift
    - Foundation strength
    - Cohesion
    - Asperities

Traditional Analysis

- Little or no cohesion used
- Conservative shear strength estimate
- Full headwater to tailwater uplift used, or based on piezometer readings.
- Drain effectiveness must be estimated
- Results are expressed as a factor of safety with a pass/fail criterion.

Sources of Uncertainty

- "One of the main sources of uncertainty in the analysis of gravity dam stability is the amount of cohesive bond present at the dam foundation interface. The FERC recognizes that cohesive bond is present, but it is very difficult to quantify through borings and testing." FERC Engineering Guidelines Chapter 3

Sources of Uncertainty

Table 3

Typical Rock Shear Strength Parameters 1/

ROCK TYPE	TYPE OF ANALYSIS: CONC/ROCK INTERFACE		INTACT ROCK		COMPRESSIVE STRENGTH
	ϕ (deg)	C (psi)	ϕ(deg)	C(psi)	f'c(psi)
Basalt Range	-	-	31-61	3953-6340	24450-31850
Basalt Average			53.2	4931	28150
Granite Range	31-56	28-242	29-70	1040-5800	6190-40,000
Granite Average	47	105	56.1	2118	15,765
Limestone Range	39-52.5	28-71	33-60	1100-2950	6000-19320
Limestone Average	46	50	50.5	2282	12,230
Sandstone Range	30-53	13-115	25-60	600-6000	3000-30,000
Sandstone Average	41	53	49	2394	11670
Shale Range	23-63	10-100	27-69	1160-3390	5220-17770
Shale Average	49	38	53	2275	11,495
Schist Range	45-60	100-284	50.2-66.5	350-2090	2180-12010
Schist Average	51	217	59.6	1018	7100

43.5

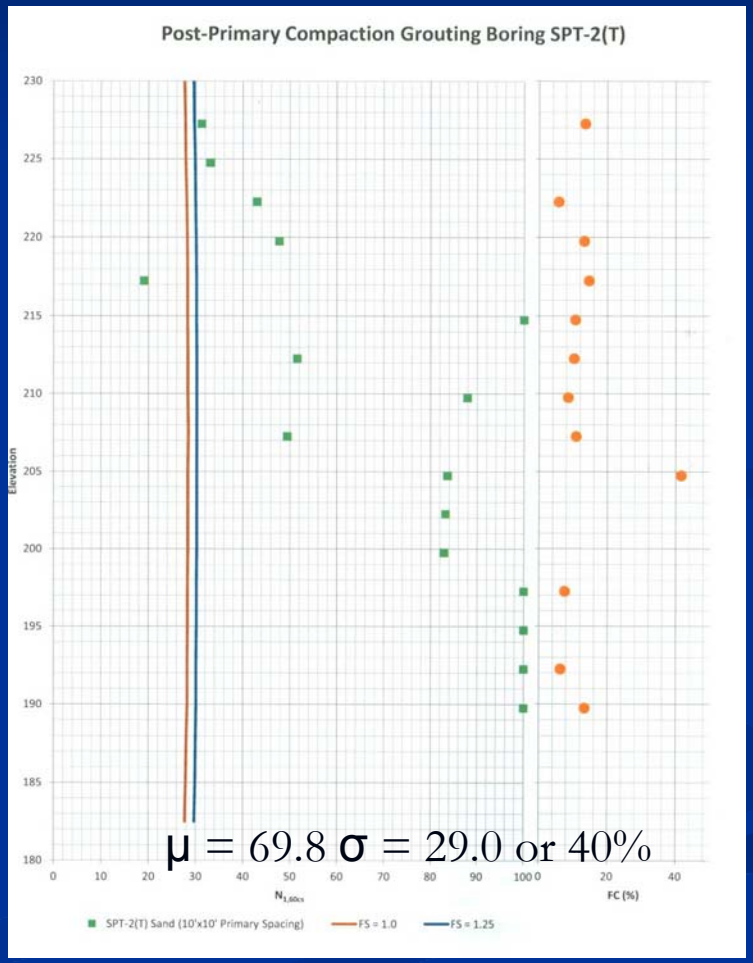
43

52.5

USACE "Gravity Dam Design" 1974

Sources of Uncertainty

- Foundation properties may not always be clear cut.
- This SPT test log shows blow counts from 20-100.
- What would be chosen based on engineering judgement?



Sources of Uncertainty

SPT Penetration, N-Value (blows/ foot)	**Density of Sand**	ϕ (degrees)
<4	Very loose	<29
4 - 10	Loose	29 - 30
10 - 30	Medium	30 - 36
30 - 50	Dense	36 - 41
>50	Very dense	>41

For Sand

SPT Penetration, N-Value (blows/ foot)	ϕ (degrees)
<4	25-30
4 - 10	27-32
10 - 30	30 - 35
30 - 50	35 - 40
>50	38 - 43

For Granular Soils

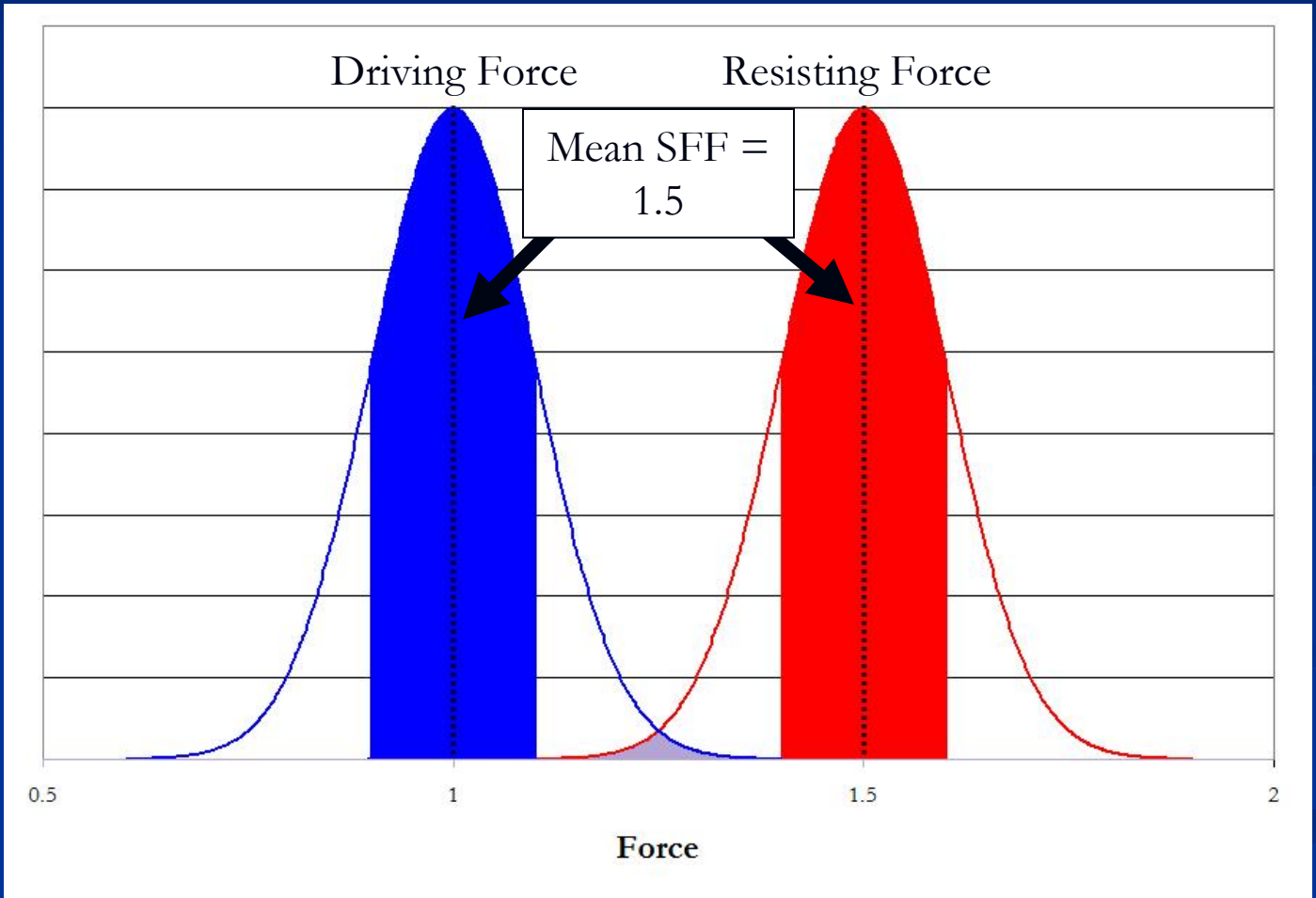
Traditional Analysis (cont.)

- Assumptions
  - C = 0
  - Full Uplift
  - Φ= 32°

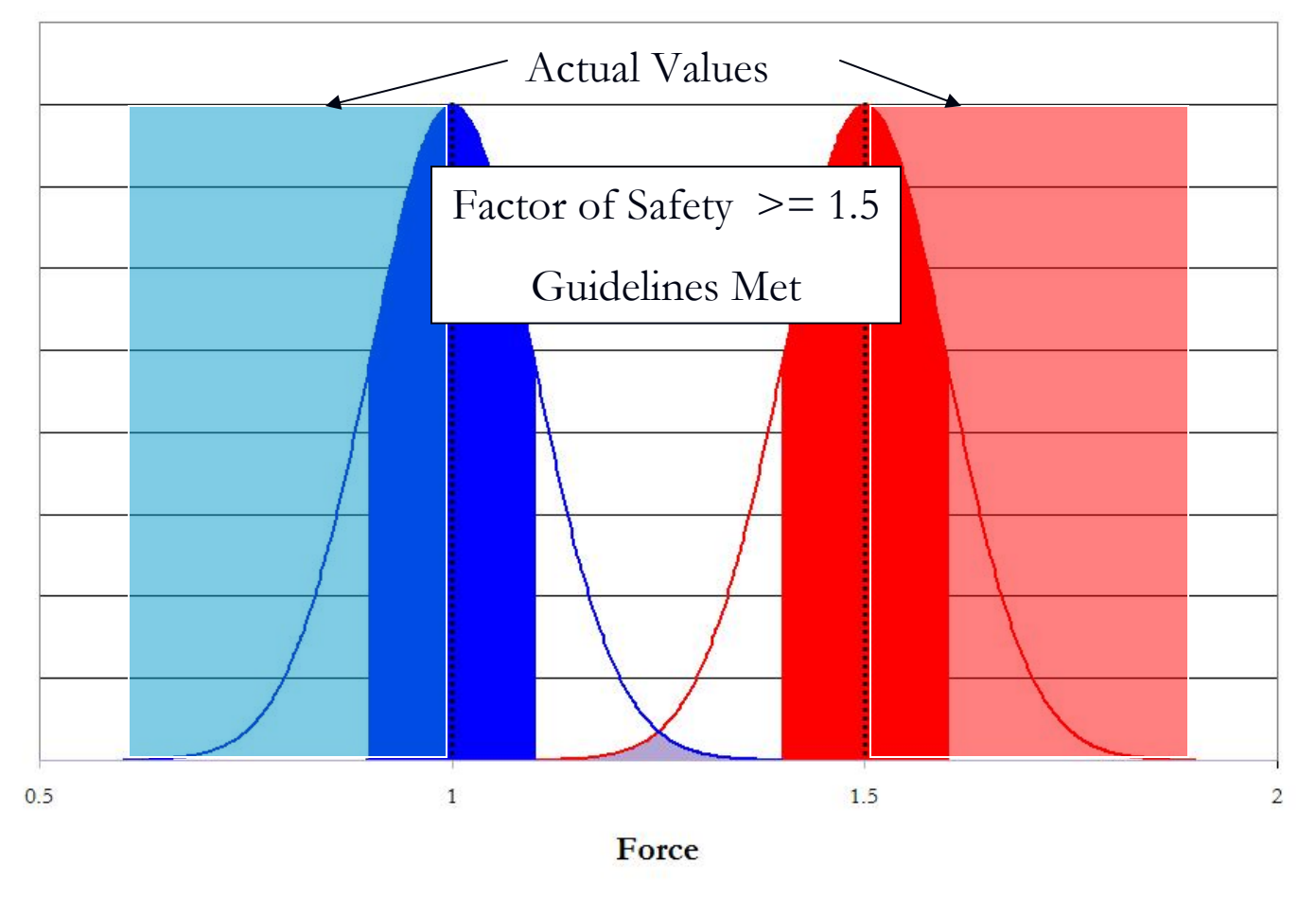
$$SFF = \frac{CA + \sum F_{Normal} \bullet \tan\phi}{\sum F_{Shear}}$$

SFF = 1.5

Deterministic Approach Meets Engineering Guidelines



Calculated SFF = 1.5



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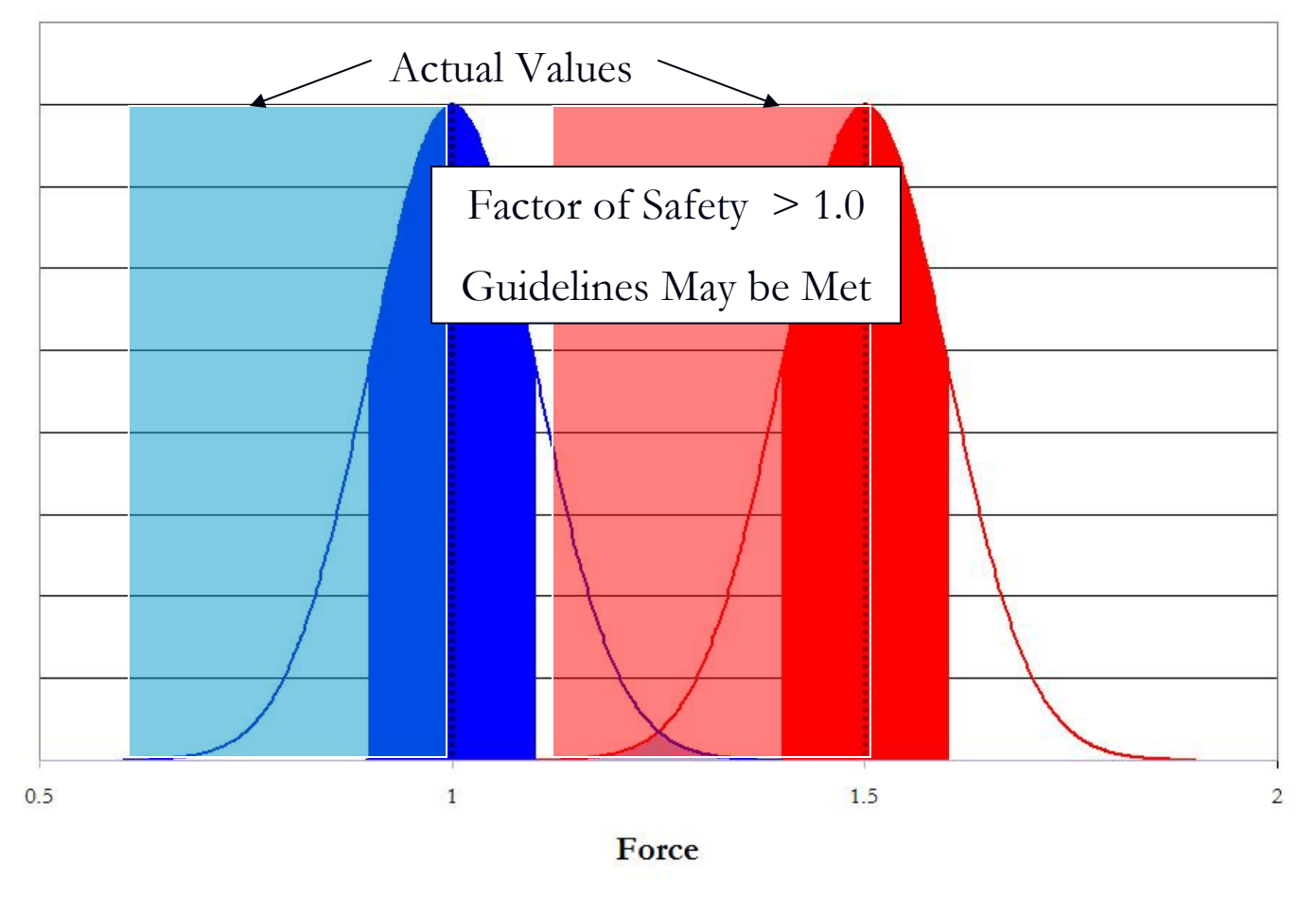
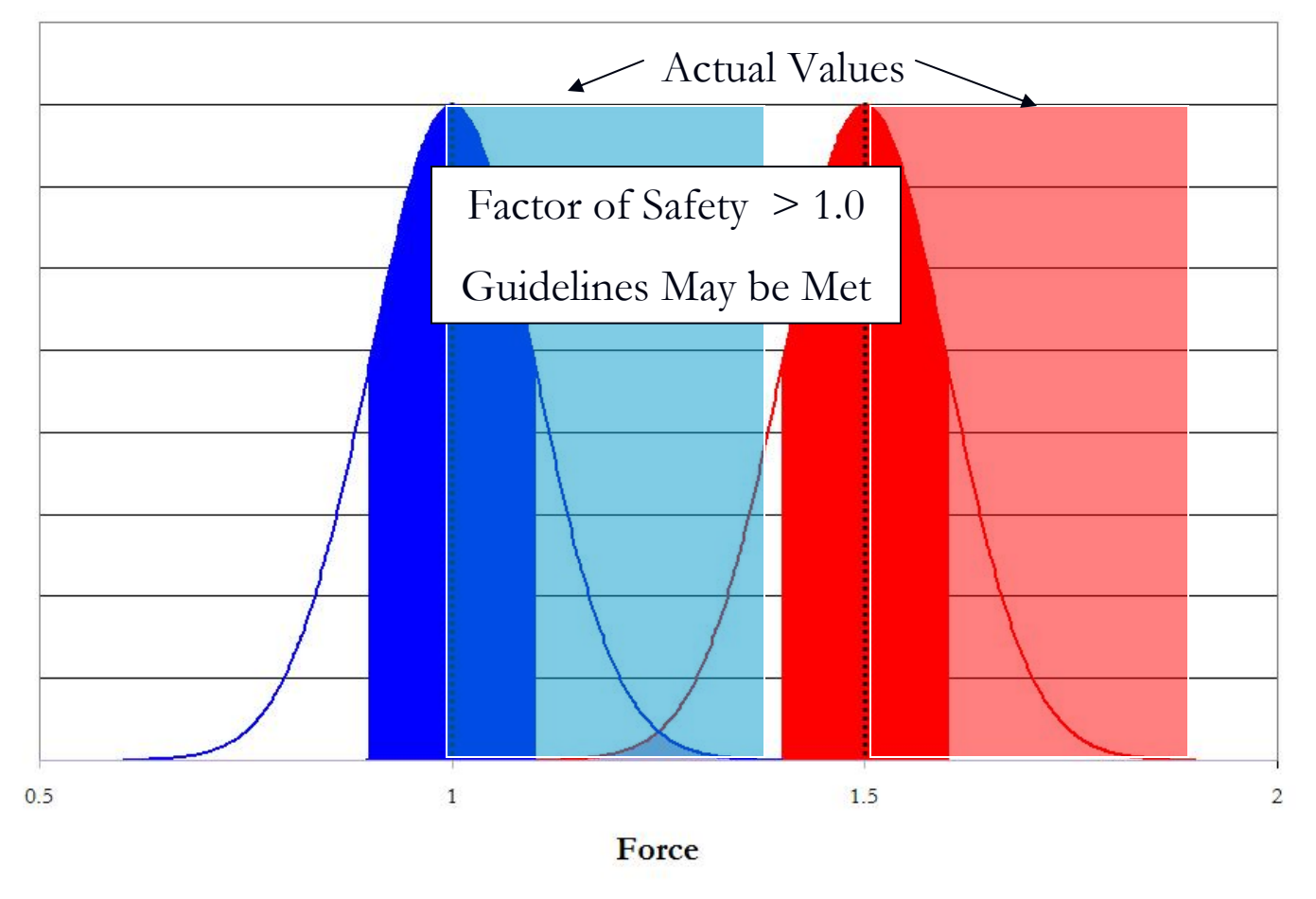
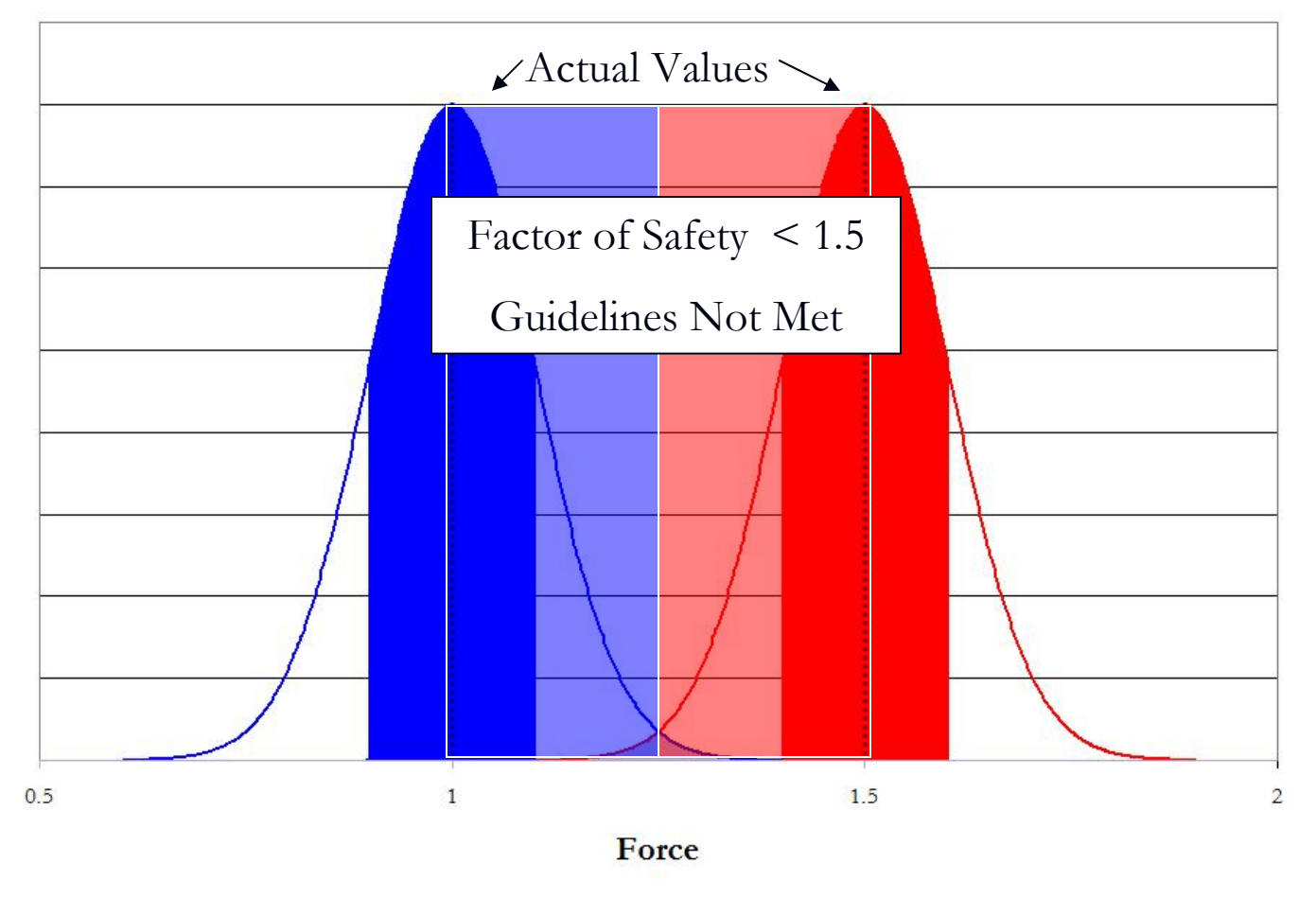


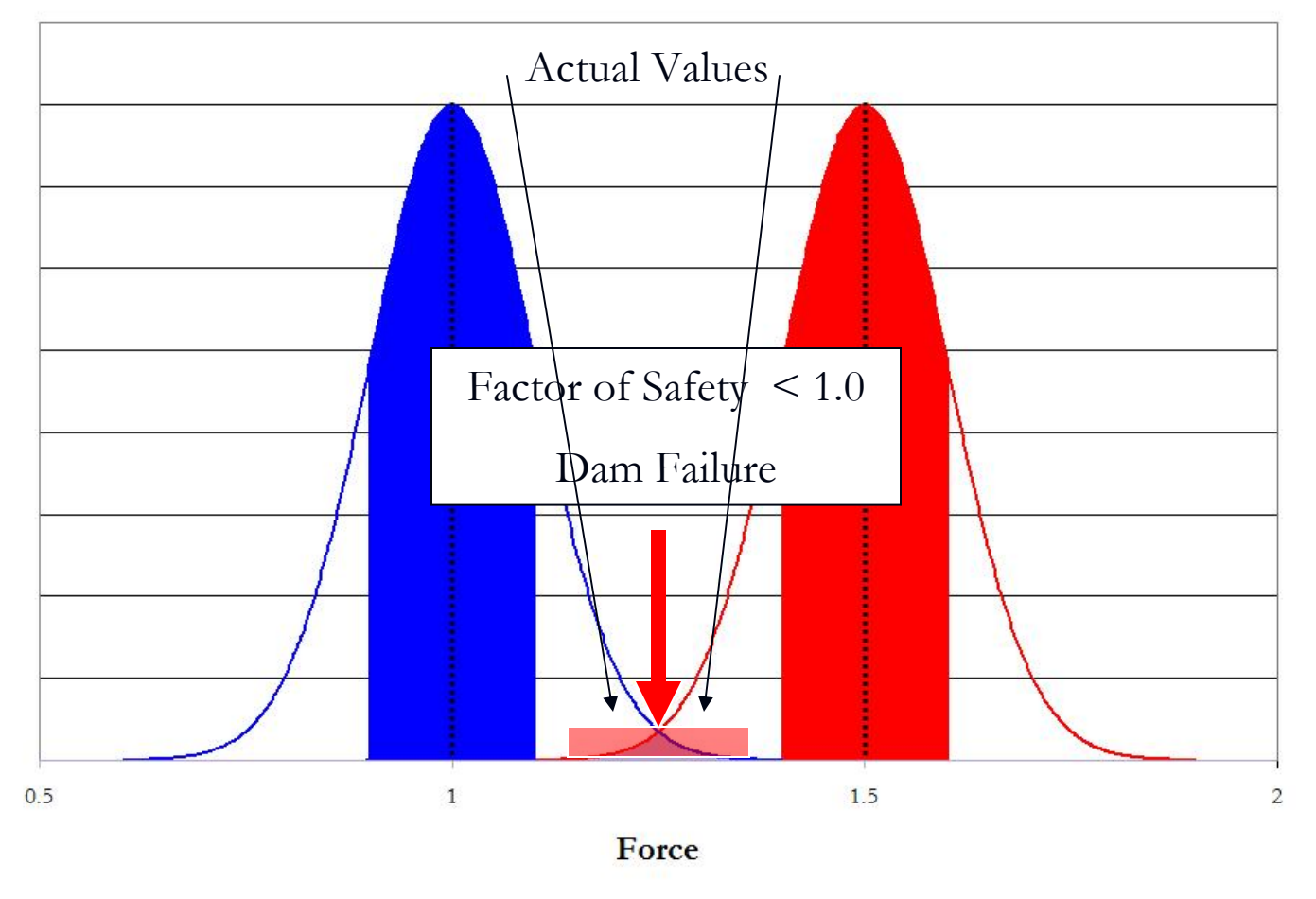
Calculated SFF = 1.5



Calculated SFF = 1.5



Calculated SFF = 1.5



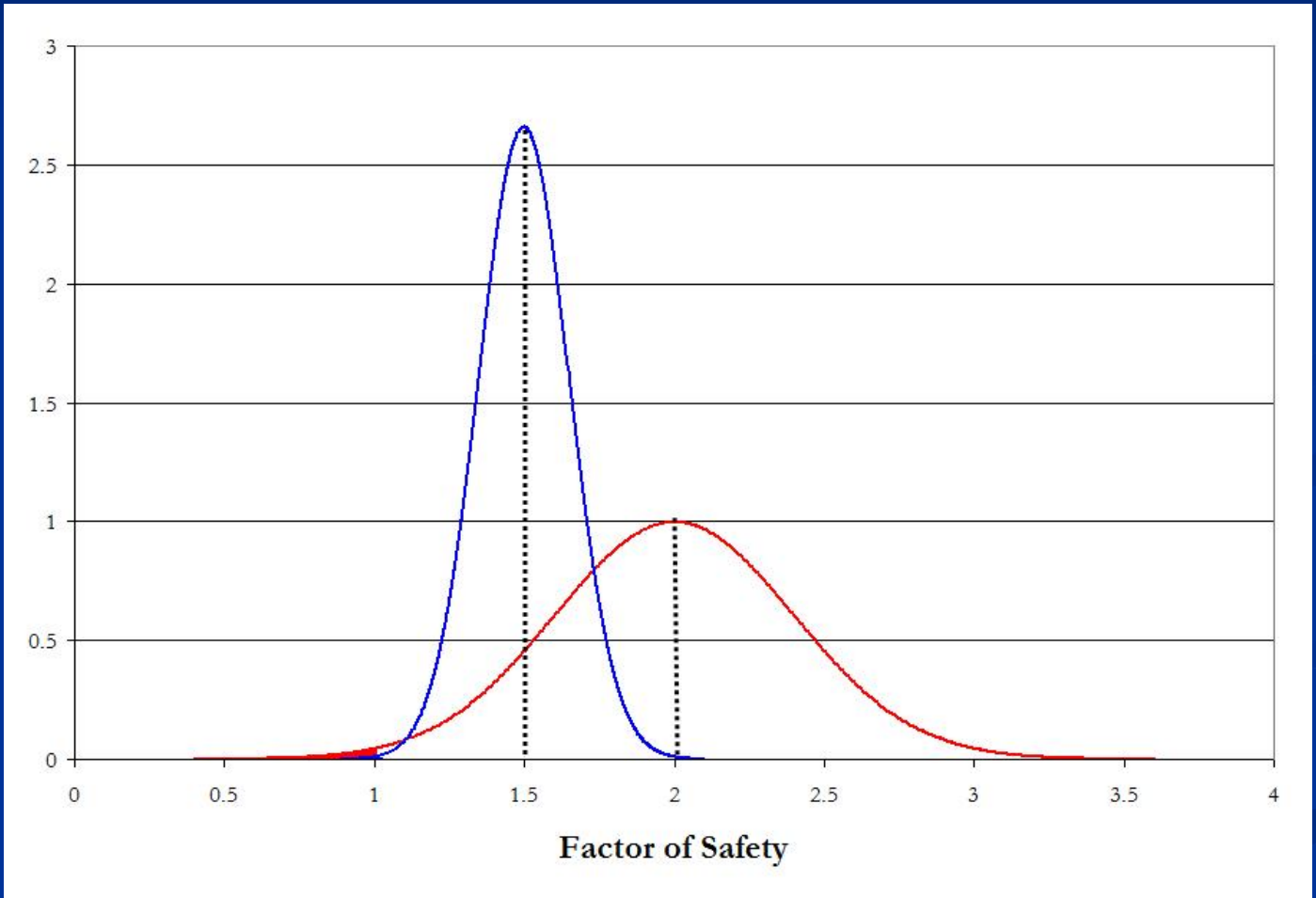
Which Dam is Safer?

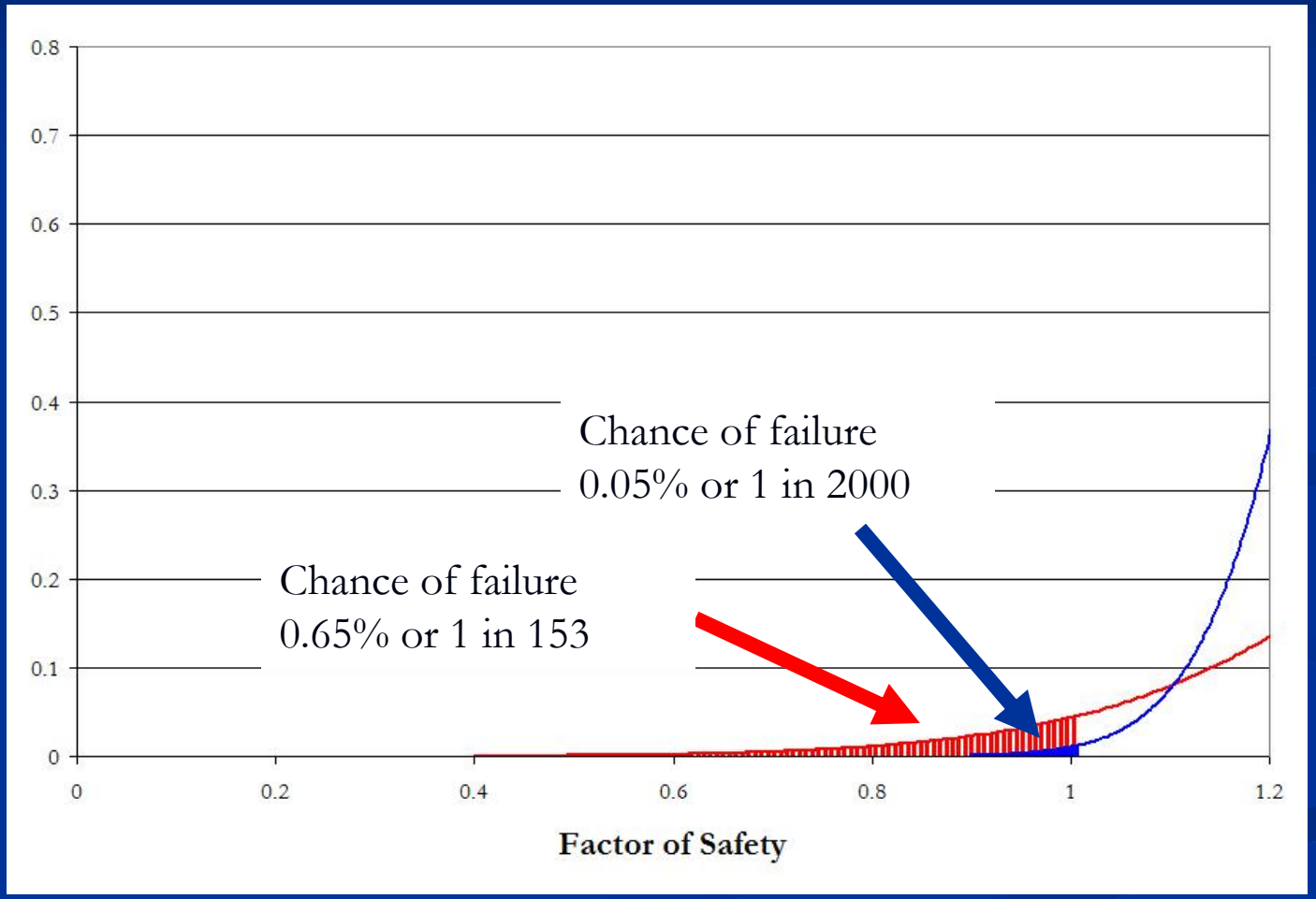
$$SFF = \frac{CA + \sum F_{Normal} \bullet \tan\phi}{\sum F_{Shear}}$$

- $\Phi = 32°$
- SFF = 1.5
- $\sigma_{SFF} = 0.15$
- C = 0

- $\Phi = 40°$
- SFF = 2.0
- $\sigma_{SFF} = 0.40$
- C = 0

Fenton and Griffiths, GeoRisk 2011


3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Factor of Safety


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Chance of failure
0.05% or 1 in 2000
Chance of failure
0.65% or 1 in 153
Factor of Safety

Methods to address uncertainty in Deterministic Analyses

- Sensitivity Analysis on parameters
- Use of Conservative estimates
- Better sampling program

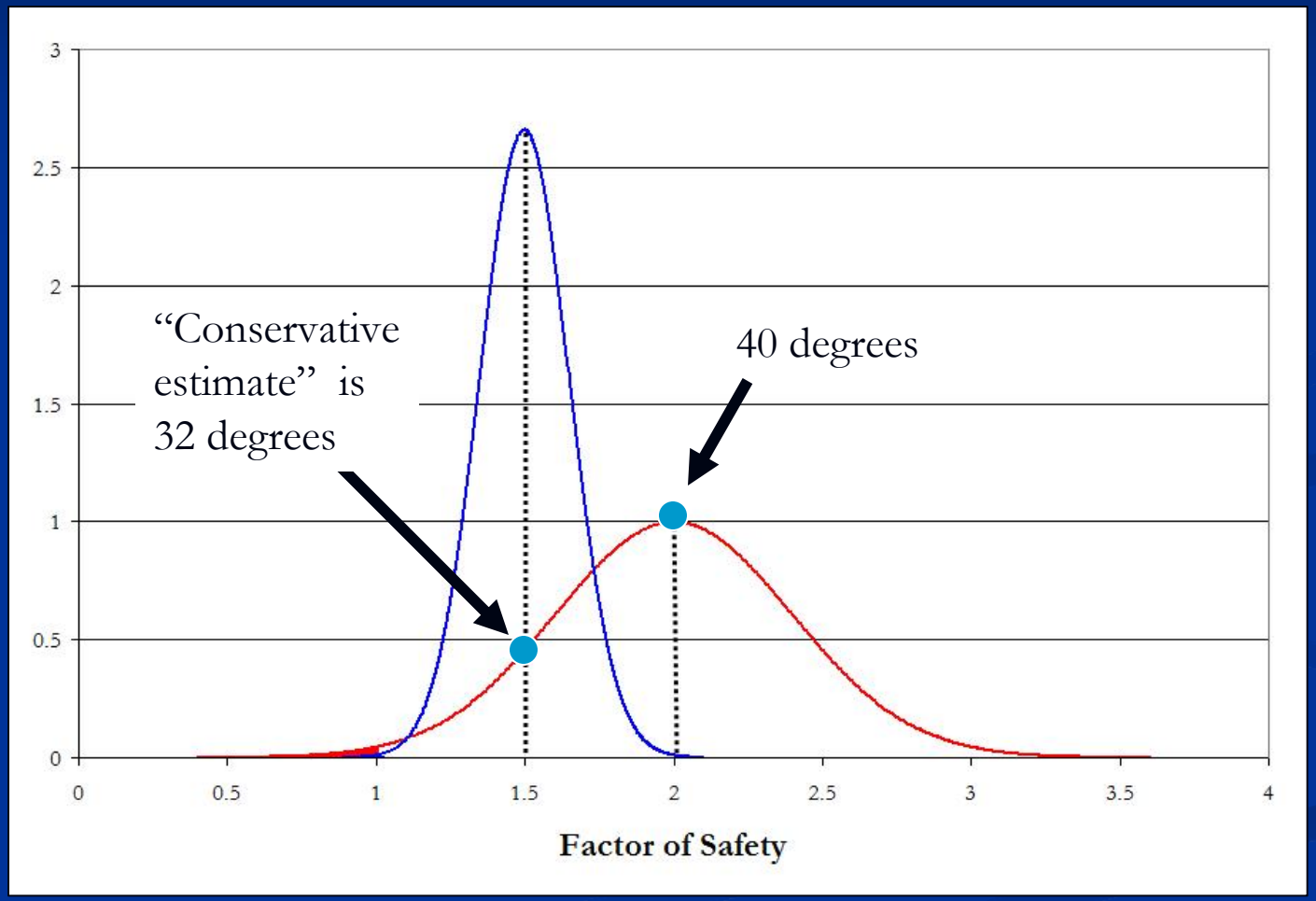
Sensitivity Analysis

- Sensitivity tells you if analysis is sensitive to the variable.
- Does not provide information about uncertainty of variable.

Conservatism vs. Probabilism

- The Phi angle for a certain foundation is listed as between 30 and 50 degrees. Is choosing 32 conservative?
- It depends…

Conservatism does not change Distribution



Key Points

- Just because you have a high SFF doesn't necessarily mean you have a safe dam.
- Reducing uncertainty can be more important than the shear strength.

Key Points

- Probabilistic analysis results expressed in Probability of Failure, not SFF.
- Best Estimates, not conservative values are used.
- Estimates of range of values needed (i.e. Standard Deviation or comparable).
- Please note: Gravity dams in particular are more susceptible to unknown weak seams than foundation material variability.