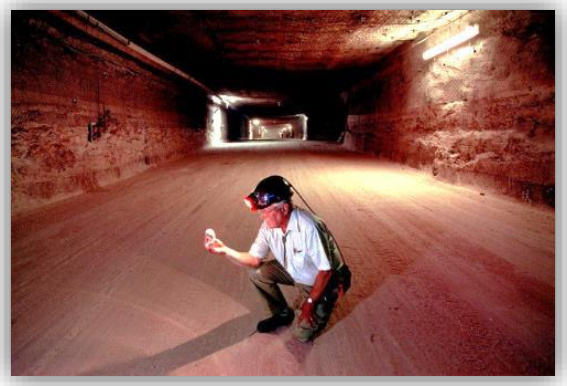
Introducing a probabilistic-based method for analyzing dilation in salt caverns

Mechanical Behavior of Salt VIII

South Dakota School of Mines
RESPEC

May 26, 2015



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Introduction

Three geomechanical criteria govern salt cavern designs:

- Time-dependent behavior
- Tension
- Dilation

With respect to dilation:

- Must maintain stress conditions below the dilation threshold
- Dilation threshold is determined from laboratory testing

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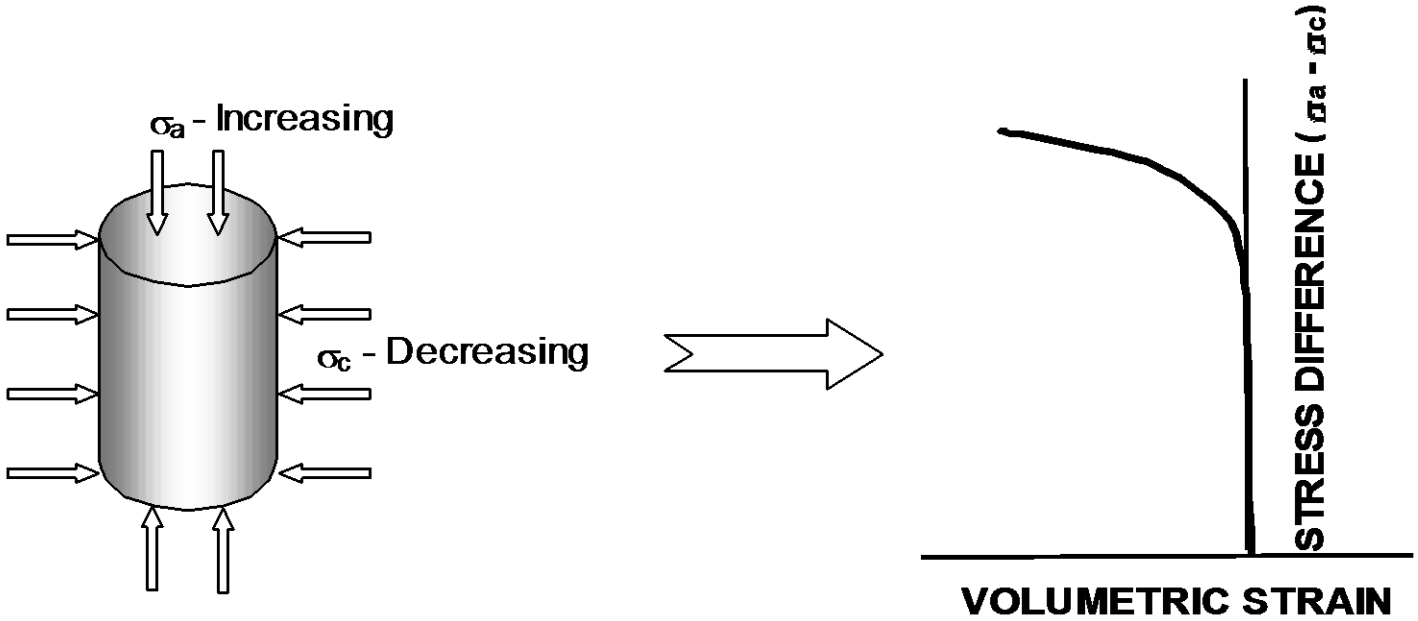
Constant Mean Stress Test

- Specimen subjected to hydrostatic confinement
- Deviatoric stress on specimen is increased while the confining pressure is decreased such that the mean stress on the specimen remains constant
- Volumetric strain is computed and monitored during the test



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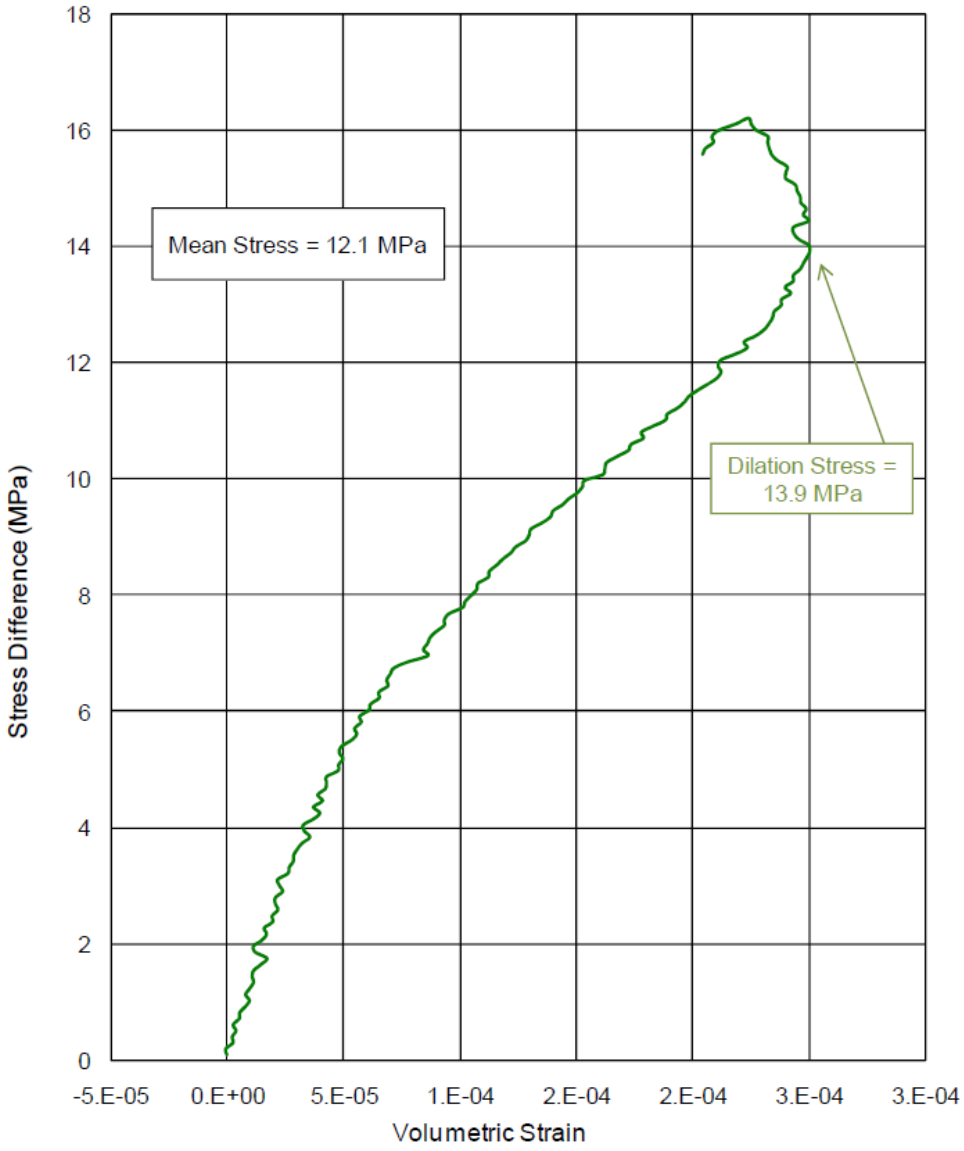
Constant Mean Stress Test



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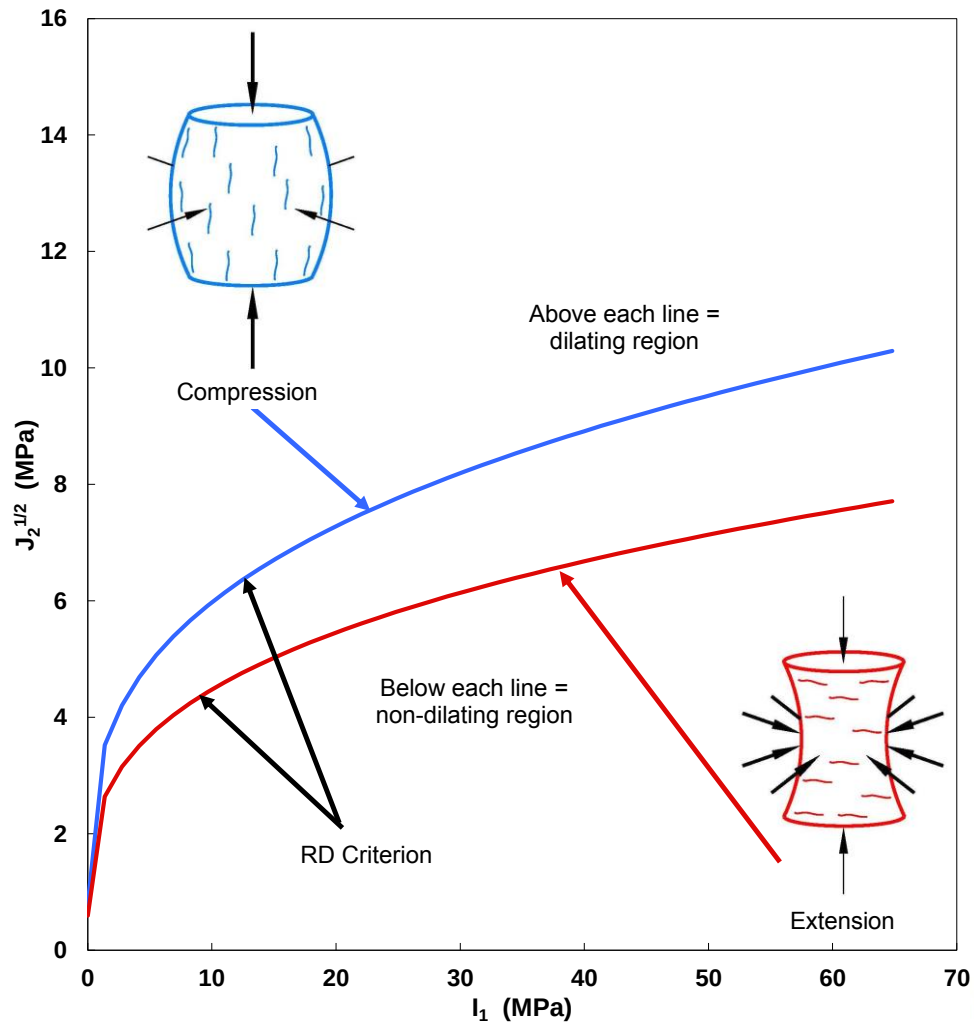
Dilation Limit

- CMS tests conducted in both compression and extension
- Dilation limit from each test plotted with respect to stress invariants
- Various criteria used to fit the data
- Ideally, limit stresses within cavern to levels below the dilation criteria line

$$\sqrt{J_{2,\mathrm{dil}}} = \left(D_1\left(I_1/\sigma_0\right)^n + T_0\right) \Big/ \left(\sqrt{3}\cos\psi - D_2\sin\psi\right)$$



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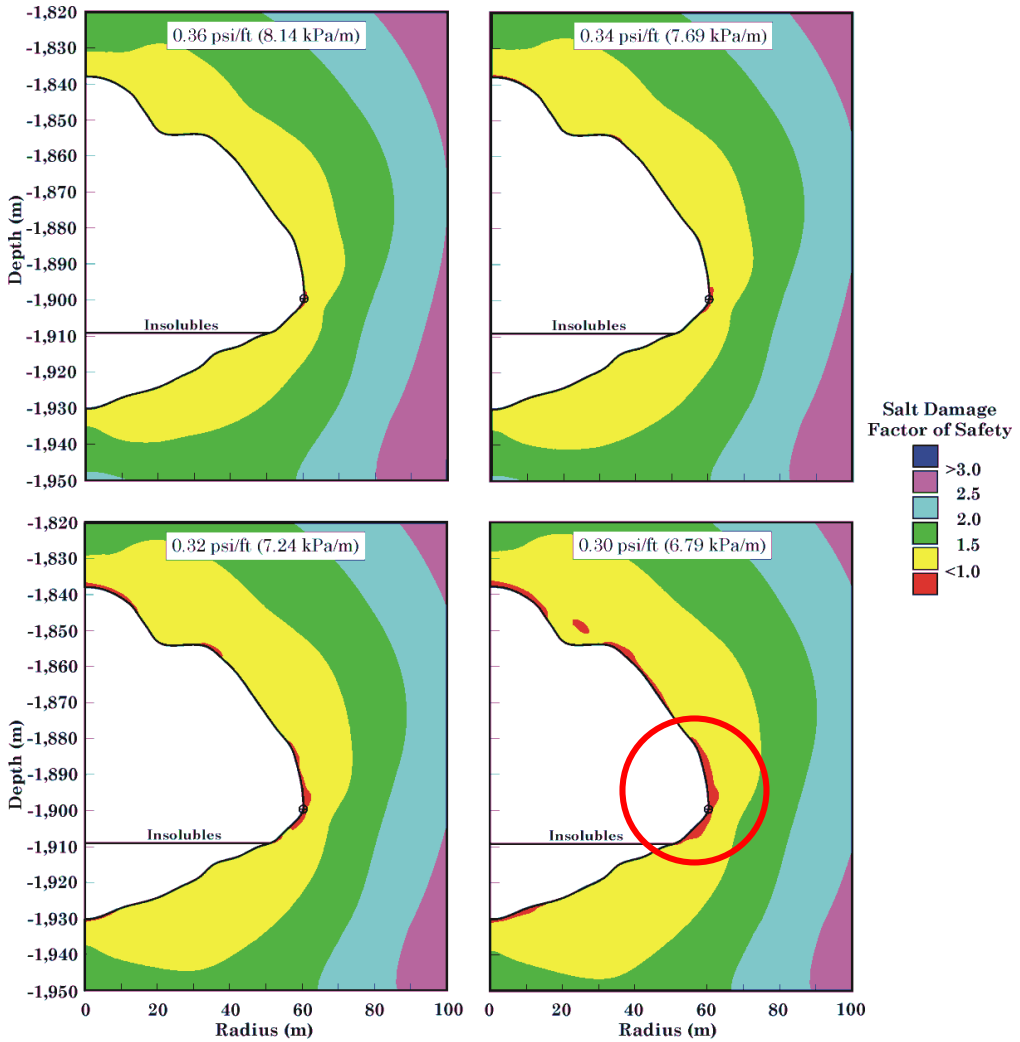
Dilation Limit



Axisymmetric cavern analysis showing dilation under minimum pressure conditions.

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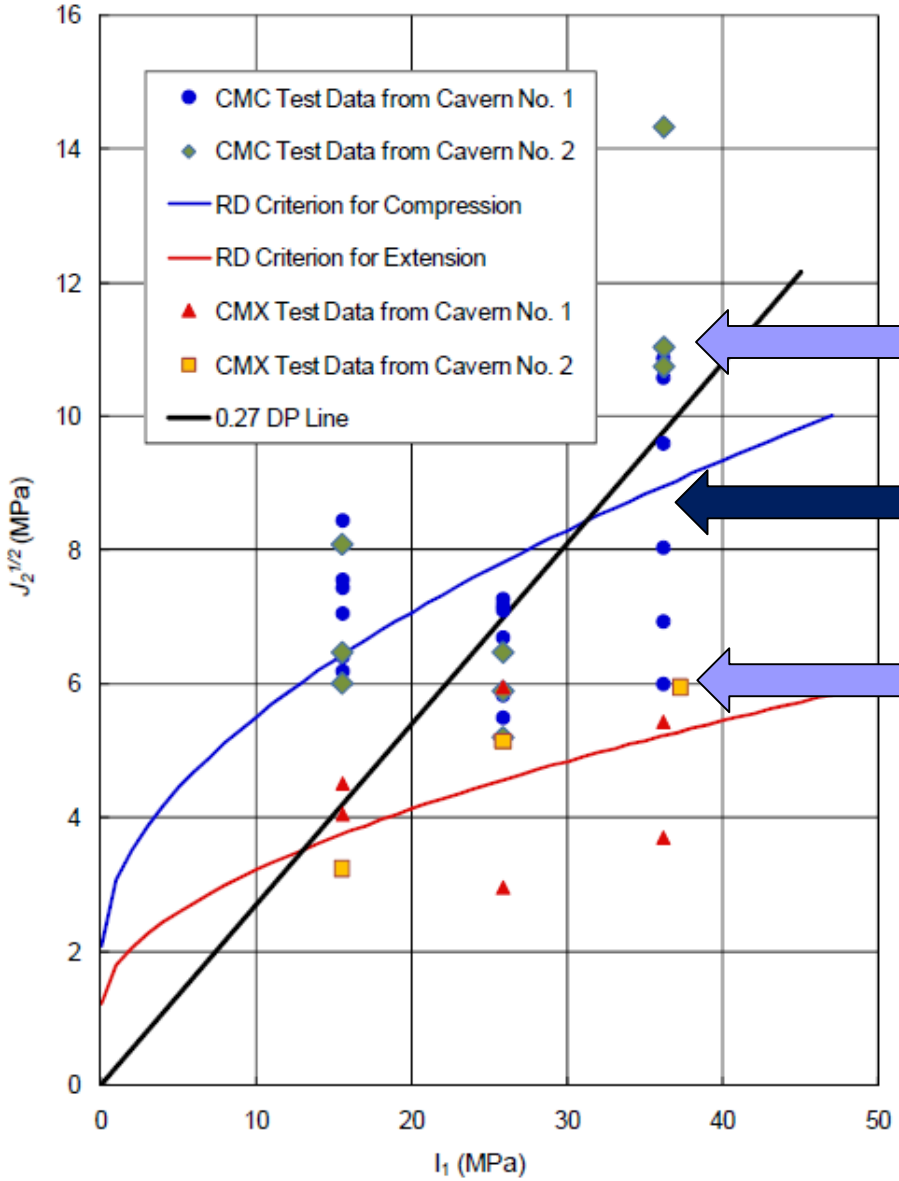
Variability of Dilation Limit



Maximum dilation stress

Average dilation stress

Minimum dilation stress

What value of the dilation stress should be used in design?

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Introduction to Probabilistic-Based Design

- Uncertainty in geotechnical design is the result of several sources (Phoon et al. 1995):
    1. Inherent variability
    2. Measurement errors
    3. Transformation uncertainties / scale effects

- A global factor of safety approach can only indirectly account for these uncertainties – "factor of ignorance". Therefore, a probabilistic-based design method is desired.

- Probabilistic-based design methods employ random variables and Latin Hypercube sampling to generate thousands of possible outcomes.

Methodology

- RESPEC has developed a large database of dilation strength for both bedded and domal salt.
- RD criterion contains three fitting variables: D_1, D_2, and n.

$$\sqrt{J_{2,\mathrm{dil}}} = \left(D_1\left(I_1/\sigma_0\right)^n + T_0\right) \Big/ \left(\sqrt{3}\cos\psi - D_2\sin\psi\right)$$

- Examine range in variability of dilation strength by fitting RD criterion to maximum, minimum, and average within laboratory data.
- This can be accomplished by changing the fitting variables.

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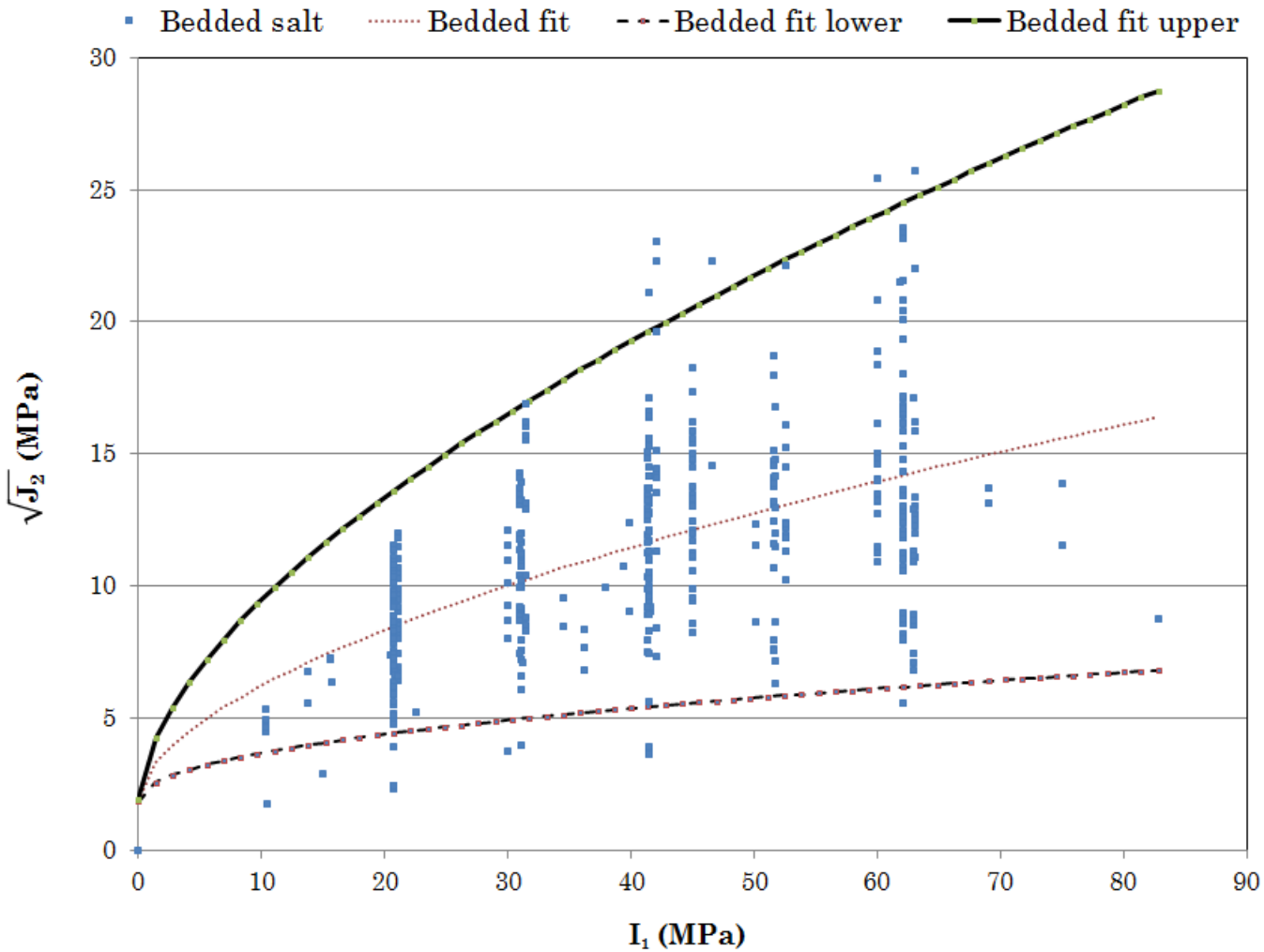
Methodology



Variability in dilation strength for bedded salt

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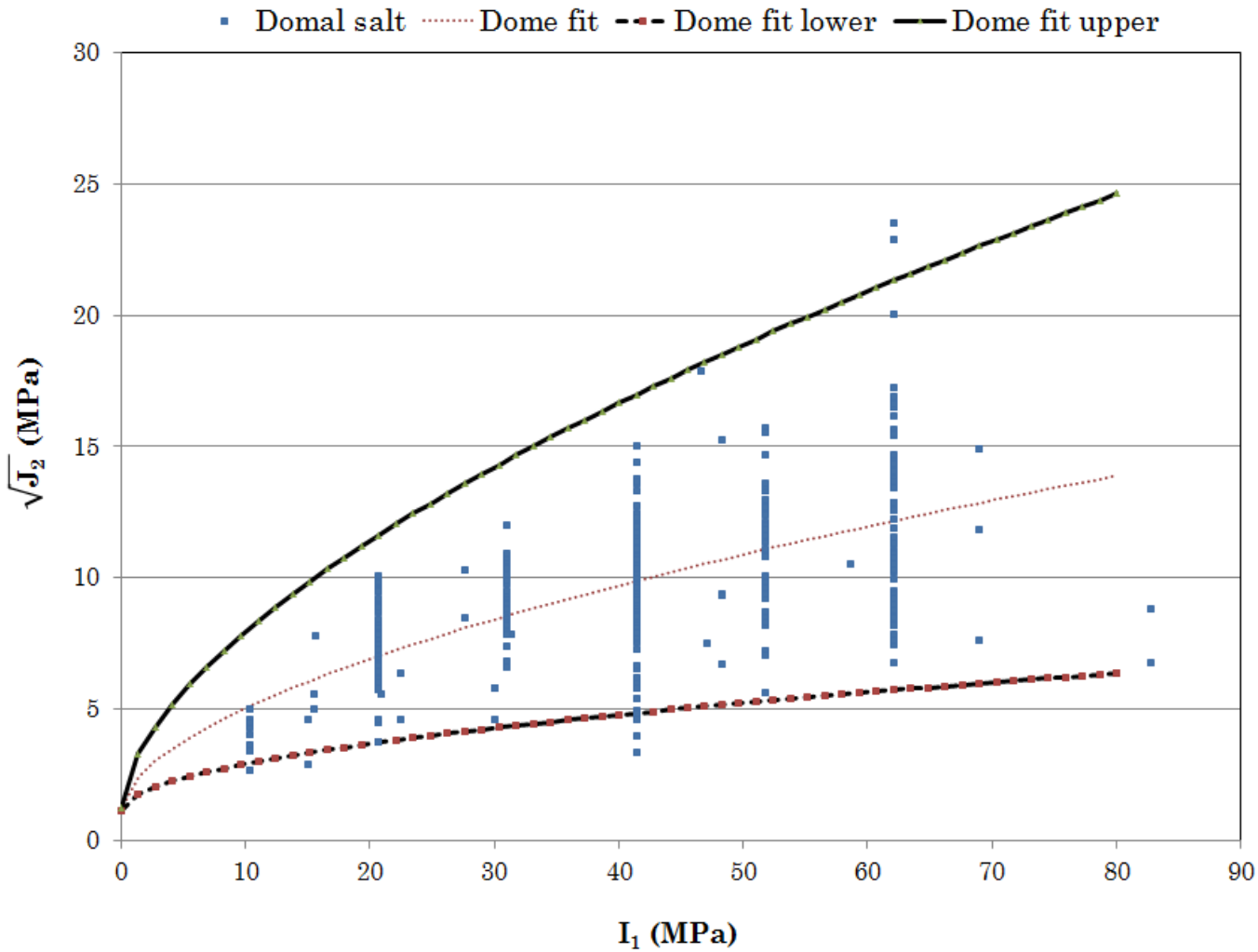
Methodology



Variability in dilation strength for domal salt

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Methodology

		D_1 (MPa)	D_2	n	T_o (MPa)
Bedded	Minimum	0.66	0.90	0.47	_
	Mean	1.19	0.96	0.57	1.92
	Maximum	1.90	1.00	0.60	_
Domal	Minimum	0.66	0.55	0.52	_
	Mean	1.23	0.61	0.57	1.40
	Maximum	1.90	0.75	0.60	_

Coefficient of variation (COV) for fitting variables for bedded salt:

D_1 = 20%

D_2 = 3%

n = 5%

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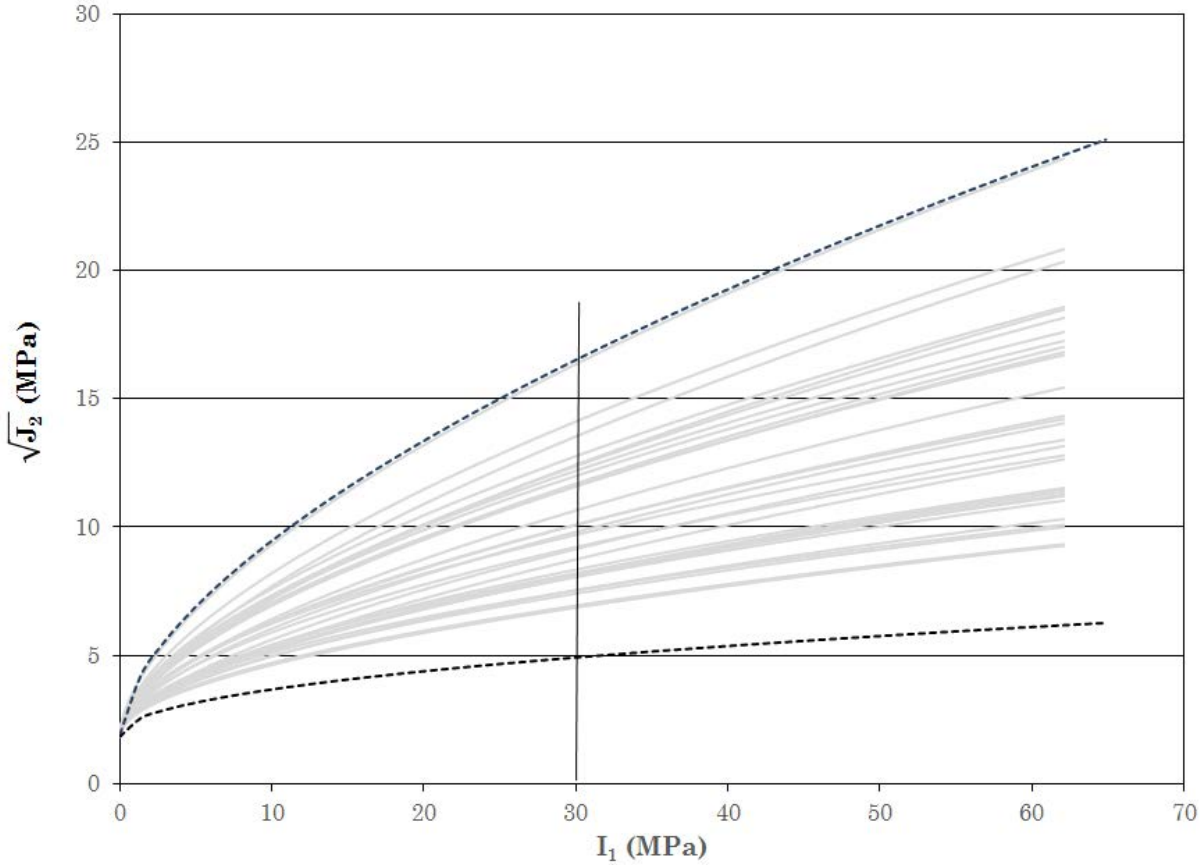
Latin Hypercube

- Now, conduct a Latin Hypercube simulation using the RD criterion and COV of the fitting variables. This will result in the generation of thousands of dilation strength curves:



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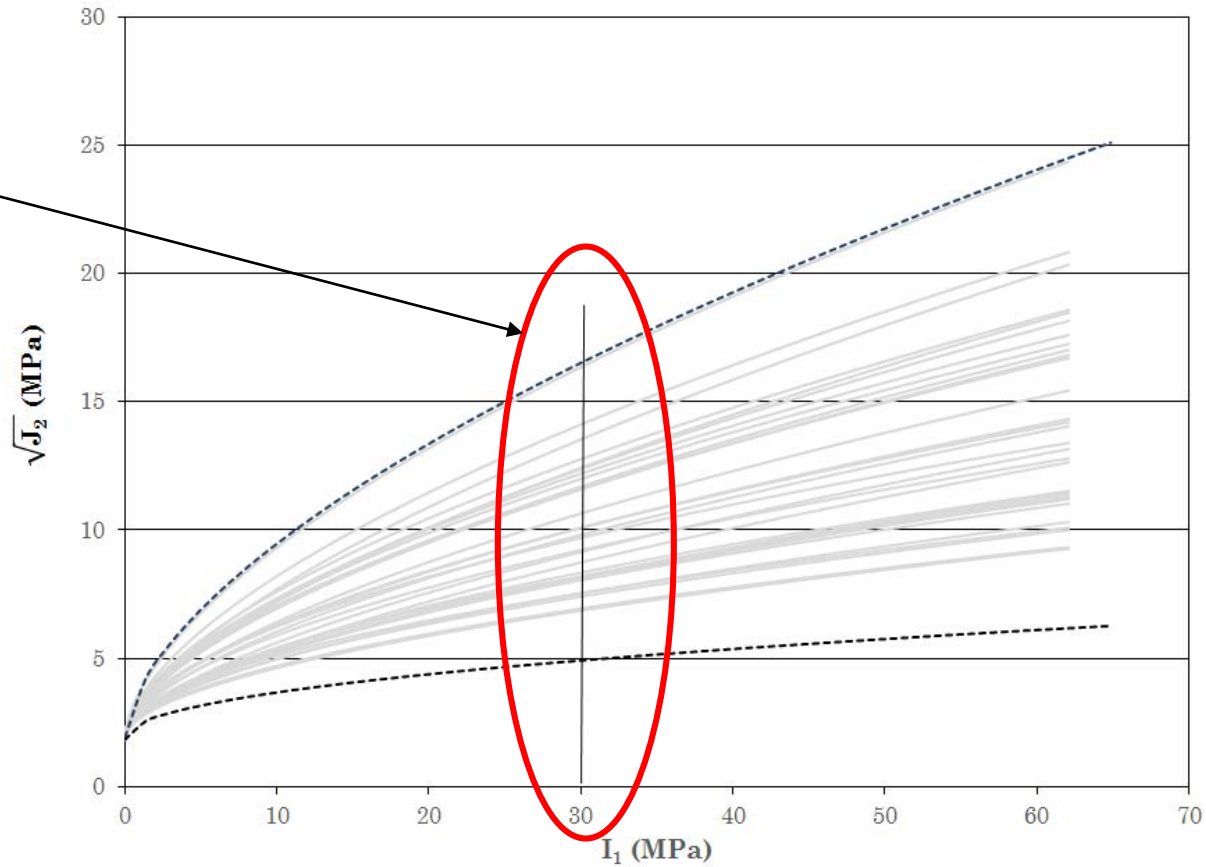
Analysis of RD Criterion Curves

- Once the curves are generated, it is possible to "cut" the curves at a value of I_1 (mean stress):

Dilation curves cut at I_1 = 30 MPa. This results in a range of values for $\sqrt{J_2}$.



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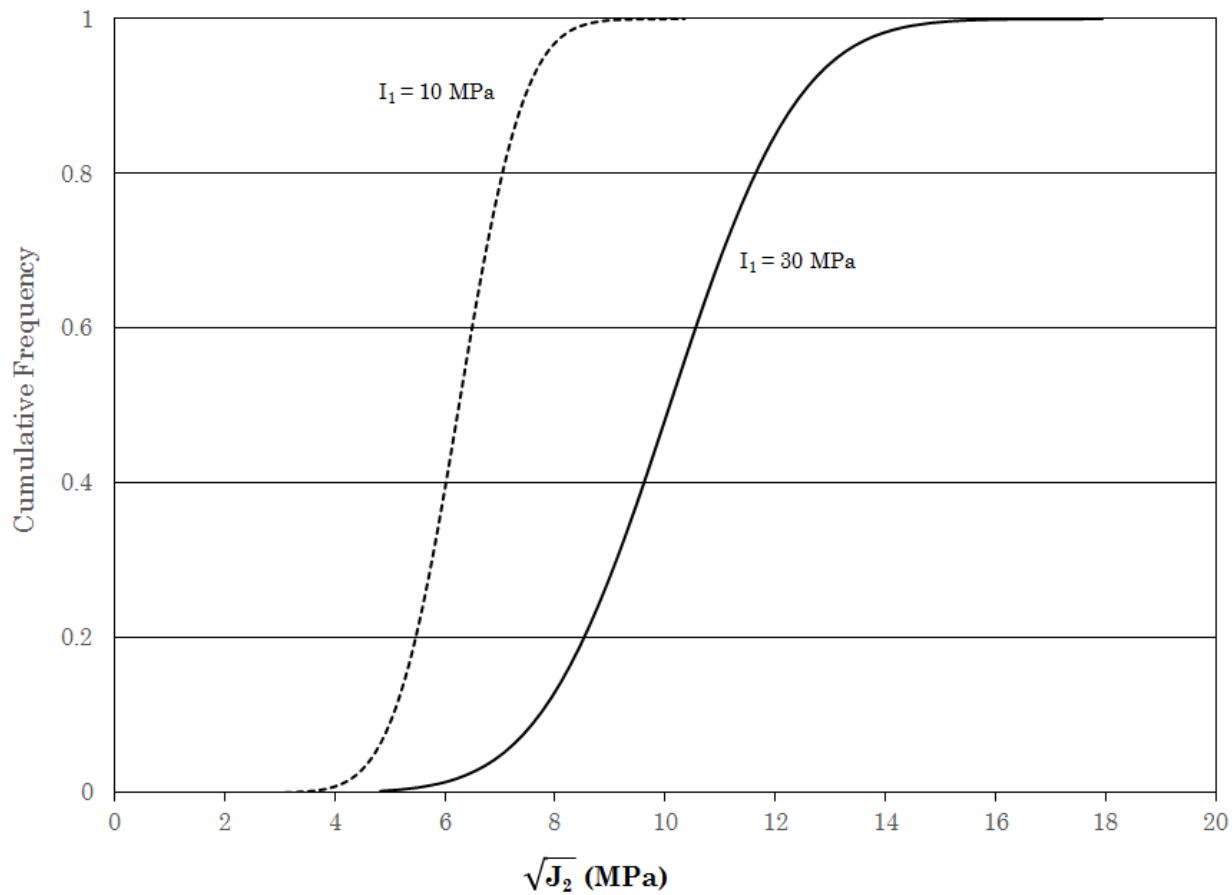
Analysis of RD Criterion Curves

- The range of values for $\sqrt{J_2}$ can be visualized as a cumulative distribution function and the statistics can be computed:

<u>Statistics (30 MPa)</u>

μ = 10.08 MPa

σ = 1.84 MPa



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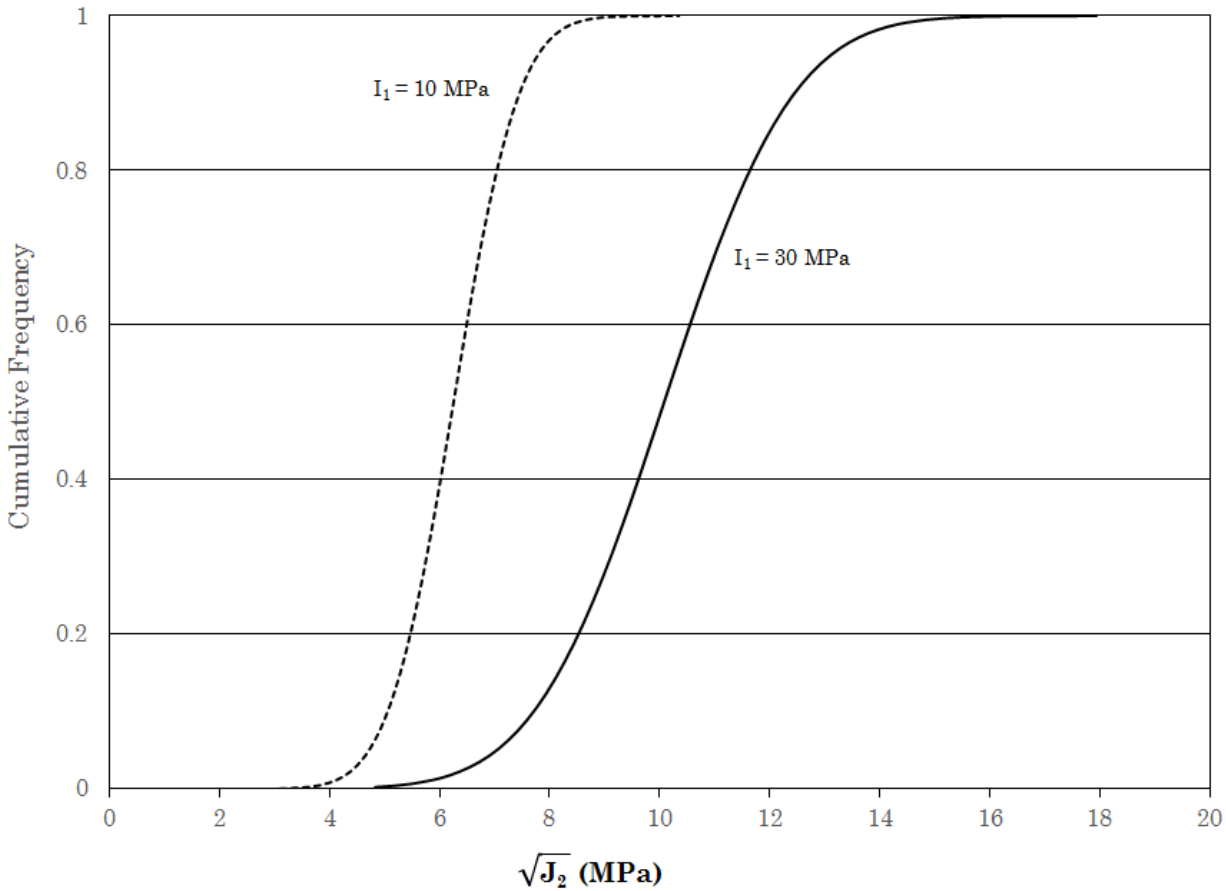
Analysis of RD Criterion Curves

- The last step is to determine a "probability of exceedance" given a value of $\sqrt{J_2}$ within an element of interest:

<u>Example</u>

$\sqrt{J_2}$ = 8.25 MPa
Exceedance = 16%

$\sqrt{J_2}$ = 6.05 MPa
Exceedance = 2%



Probability of exceedance = likelihood of exceeding the dilation criterion.

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Probability of Exceedance

- The probability of exceedance, p_f, can be related to a target reliability index, β_T, or expectation of performance:

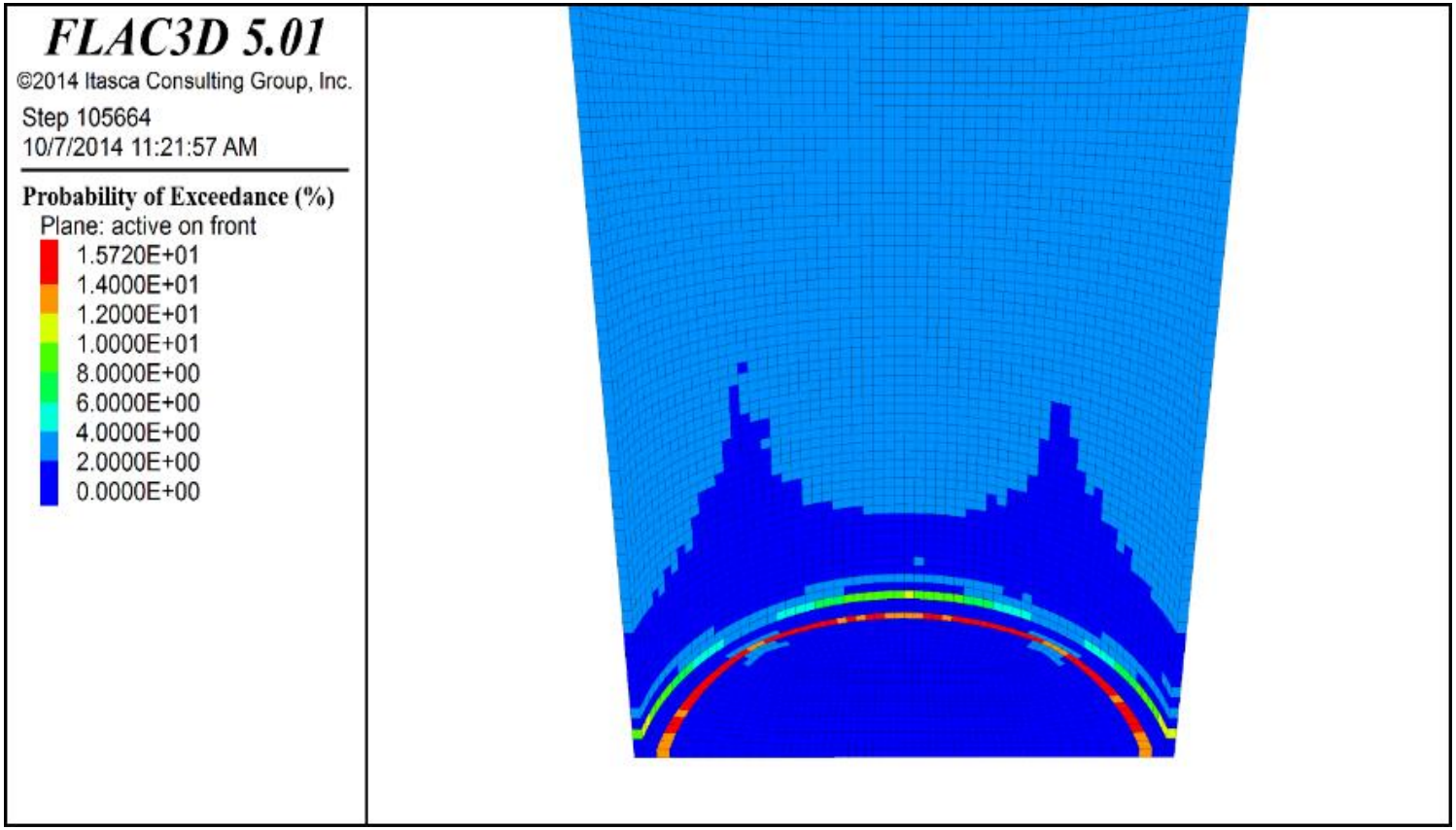
β_T	p_f	Expected Performance
0	0.500	-
0.5	0.309	-
1.0	0.159	Hazardous
1.5	0.067	Unsatisfactory
2.0	0.023	Poor
2.5	0.006	Below average
3.0	0.001	Above average
3.5	0.0002	-
4.0	0.00003	Good
4.5	0.000003	-
5.0	0.0000003	High

Typical range

Adapted from U.S. Army Corps of Engineers 1997, Table B-1

Example

- The approach can be used to determine the probability of exceedance for elements surrounding a cavern:



Probability of exceedance for the cavern floor.

Conclusion

- A probabilistic-based method has been developed to assess the potential for dilation in a salt cavern.
- The probabilistic method replaces the traditional factor of safety approach and can implicitly account for uncertainties.
- Through the use of the Latin Hypercube sampling method, hundreds of RD dilation criterion curves were generated.
- The curves can be analyzed at a value of I_1 to determine a "probability of exceedance" at a corresponding value of $\sqrt{J_2}$.
- Research continues to incorporate the process based on compression and extension states of stress.

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Questions?

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