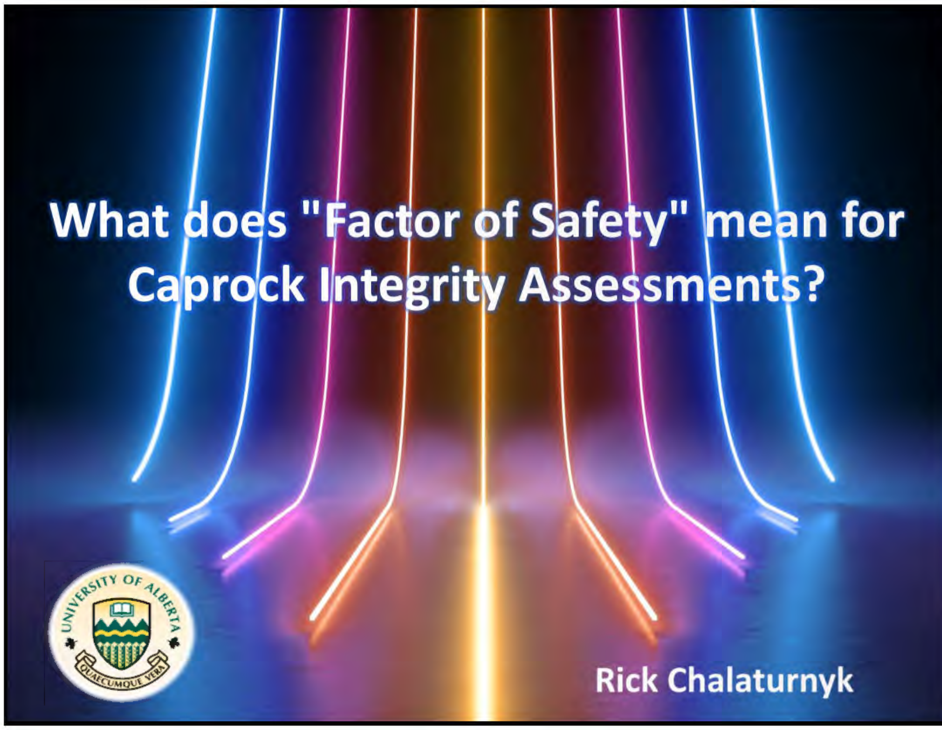


energi SIMULATION

# SUMMIT

Sep 30 – Oct 1 2021

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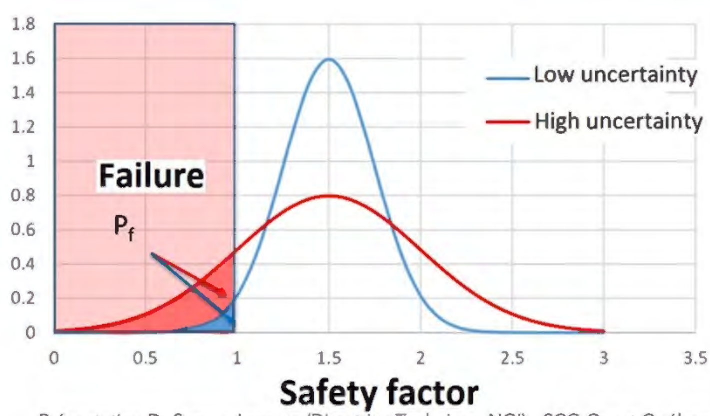
## Outline

- Overview of NSERC/Energi Simulation Industrial Research Consortium on Reservoir Geomechanics
- A Conversation about "Factor of Safety" for Caprock Integrity



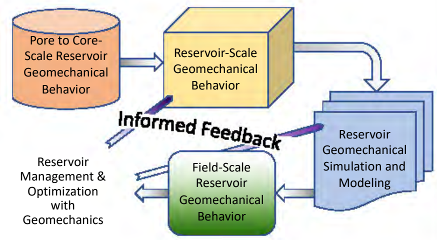

Présentation Dr Suzane Lacasse (Directrice Technique NGI) - SCG Ouest Québec



2

## NSERC/Energi Simulation Industrial Research Consortium on Reservoir Geomechanics (2019-2025)

- Tackle several key reservoir geomechanical challenges that currently impact industry's ability to continually improve the efficiency and sustainability of unconventional hydrocarbon development, including oil sands, shale caprocks, shale gas, tight oil & gas by pursuing research studies advancing our understanding of:
  - Theme 1: Pore to Core-Scale Reservoir Geomechanical Behavior
  - Theme 2: Reservoir-Scale Geomechanical Behavior
  - Theme 3: Reservoir Geomechanical Simulation and Modelling
  - Theme 4: Field-Scale Reservoir Geomechanics Behavior
  - Theme 5: Reservoir Management & Optimization with Geomechanics






3

## GeoSAFETY
## Geoscience for Subsurface Assurance oF Energy TechnologY

- The GeoSAFETY focusses on creating solutions to overcome the technical challenges of adopting subsurface formations for:
  - fluid storage and utilization (e.g., carbon dioxide, hydrogen), geothermal systems, nuclear waste repositories;
  - intermittent subsurface energy storage (associated with renewables such as wind and solar); and
  - the efficient and responsible development of hydrocarbon resources as we progress towards renewable energy systems.
- GeoSAFETY will deploy a new generation of experimental systems within our GeoInnovation Environments to advance new knowledge related to how at multiple scales (e.g., pore to fracture to reservoir scale), geomechanical processes impact multiphase fluid flow processes in subsurface environments deployed for current and future energy systems.
- GeoSAFETY complements and supports the outstanding research embodied in the NSERC/Energi Simulation Industrial Research Consortium on Reservoir Geomechanics and research conducted in the Reservoir Geomechanics Research Group [RG]2 over the last 20 years.



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## Designing to Prevent Failure – Factor of Safety

- In engineering, a factor of safety (FoS), also known as (and used interchangeably with) safety factor (SF), expresses how much stronger a system is than it needs to be for an intended load.
- FoS is a term describing the structural capacity of a system beyond the expected loads or actual loads - how much stronger a system is than it usually needs to be for an intended load.
  - Building ~ 2
  - Pressure vessels ~ 3.5 to 4.0,
  - Landing gears on airplanes ~ 1.5





## Subsurface Processes and Factor of Safety

- Factors of safety consider uncertainties such as:
  - Magnitude of damages (loss of life and property damage)
  - Relative cost of increasing or decreasing the factor of safety
  - Relative change in probability of failure by changing the factor of safety
  - Reliability of soil data
  - Construction tolerances
  - Changes in soil properties due to subsurface operations
  - Accuracy (or approximations used) in developing design/analysis methods

## Motivation – Caprock Failure

- Failure?
  - The inability of a system or system component to perform a required function within specified limits
  - A cessation of proper functioning or performance: e.g. a power failure.
  - Nonperformance of what is requested or expected
  - A decline in strength or effectiveness.

Joslyn SAGD Steam Release Incident

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## Caprock Integrity and $CO_2$ Geological Storage ($H_2$ Storage, etc.) – Time for Factor of Safety?

- Compendex: Subject/Title/Abstract searches for "caprock integrity" and "factor of safety"
  - "caprock integrity" – 229 records
  - "caprock integrity" AND "factor of safety" – 3 records – ALL SAGD
  - "caprock integrity" AND "safety factor" – 5 records – still ALL SAGD
  - "caprock integrity" AND "$CO_2$" – 121 records (essentially the same with "carbon"
  - "caprock integrity" AND "$CO_2$" AND "safety factor" – 0 records (but one did exist! - Victor Vilarrasaa, V. et al., 2010. Coupled hydromechanical modeling of CO2 sequestration in deep saline aquifers. IJGHTC, Vol. 4, Issue 6, pp 910-919.)..but for the 70 papers that have cited this work since 2010, no one has adopted anything even remotely like "safety factor"…
- Should we have a factor of safety against exceeding an induced seismic event < 3, <2, <1????

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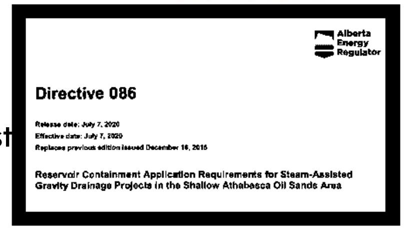
## How did FoS become part of SAGD Caprock Integrity Assessments?

- Over the last approximately 15 years, regulatory requirements have specified that project proponents **compute the factor of safety** (margin of safety) against tensile and shear failure within the caprocks associated with their projects.
- Dir 086 establishes a Maximum Operating Pressure.
  - Identifies that there are two mechanisms by which a caprock can fail: tensile and shear.
  - Applicants must determine a MOP that considers both failure mechanisms


Alberta Energy Regulator

**Directive 086**

Release date: July 7, 2020
Effective date: July 7, 2020
Replaces previous edition issued December 16, 2016

**Reservoir Containment Application Requirements for Steam-Assisted Gravity Drainage Projects in the Shallow Athabasca Oil Sands Area**

- Minimum thickness of 10 m
- Clay-rich bedrock of Clearwater Formation – Gamma ray value greater than 75 API units…or a demonstrated equivalent
- Laterally continuous across the project area (the boundaries within which bitumen recovery may occur over the life of the project
- Lower Clearwater shale MUST still be present…unless the applicant can demonstrate an equivalent caprock is present.

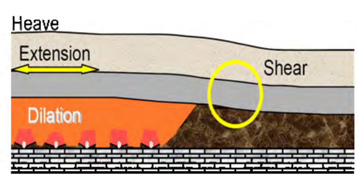


## Tensile Failure – Dir. 086

- To address potential tensile failure of the caprock, applicants must determine the MOP by using the following formula:

$MOP_{(bottomhole)}$ (kPa) = Safety factor of 0.8 ×
Caprock fracture closure gradient (kPa/m) ×
Depth at shallowest base of caprock (m TVD),

where kPa is kilopascals and m TVD is metres true vertical depth.

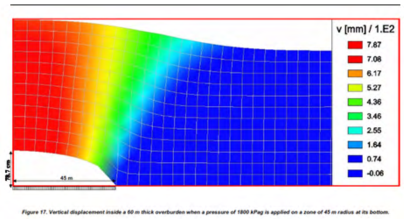



$$\text{Safety Factor} = \frac{\sigma_{min}}{p_{inj}} \qquad MOP\ (P_{inj}) = \frac{(\sigma_{min}) * (depth)}{FoS} \qquad FoS_{tensile} = \frac{\sigma_3}{P_{inj}}$$

where $\sigma_3$ is the minimum total principal stress and $P_{inj}$ is the steam injection pressure

$\therefore FoS = 1.25$

## Shear Failure – Dir. 086

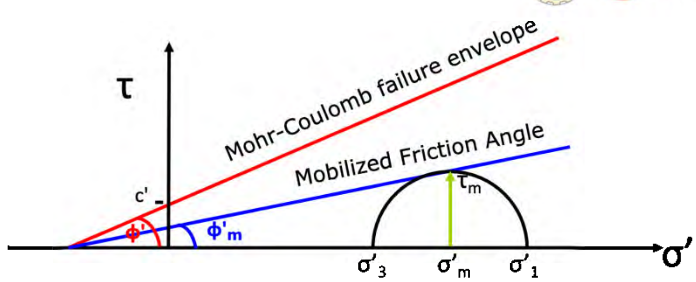



- To address potential shear failure of the caprock, applicants must conduct geomechanical modelling.
- Application must provide:
  - input data files and source of data;
  - the name and version of the modelling software;
  - a discussion of the methodology used in the modelling (e.g., boundary conditions, material failure criteria, rock constitutive model, material properties, coupling of the geomechanical model to the reservoir model);
  - a discussion of the results predicted by the modelling, **including the pressure at which shear failure of the caprock is predicted to occur** and how the results support the proposed operating pressure;
  - an assessment of the sensitivity of the results from the modelling to the input parameters and a discussion of the uncertainties in the predicted results; and
  - A discussion of the frequency at which the modelling will be updated with the results of the project's monitoring program.



## Factor(s) of Safety against Shear Failure

- Most equations are reasonable but are usually only applied element by element and don't provide clues as to how the "caprock system" is behaving and what the margin of safety or safety factor is for the entire caprock interval



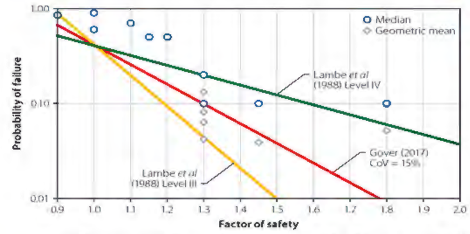

$$\text{Safety Factor} = \frac{\tan \phi'}{\tan \phi'_m}$$

*So, should this also be ∴ FoS = 1.25 ?*

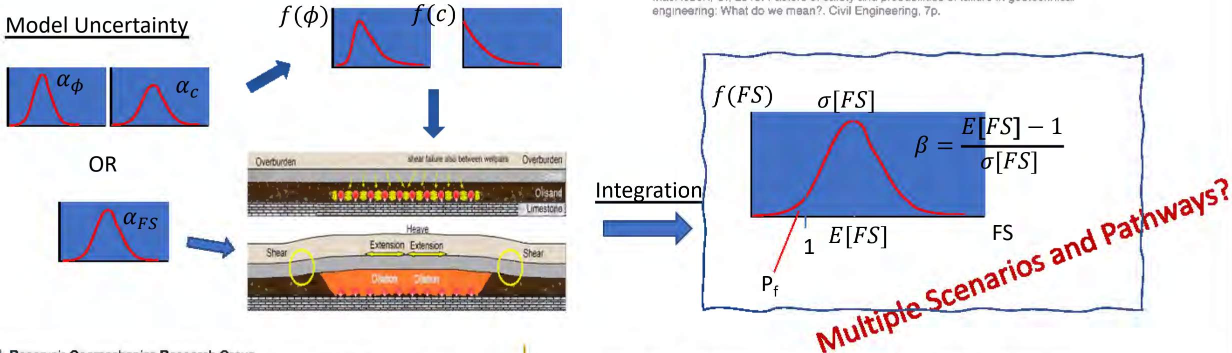
where $$\tan\varphi'_m = \frac{\tau_m}{c' \cdot \cot\varphi' + \sigma'_m}$$

## Probability of Failure instead of Factor of Safety?

*Should we be using "Probability of Unsatisfactory Performance"?*




MacRobert, C., 2018. Factors of safety and probabilities of failure in geotechnical engineering: What do we mean?. Civil Engineering, 7p.

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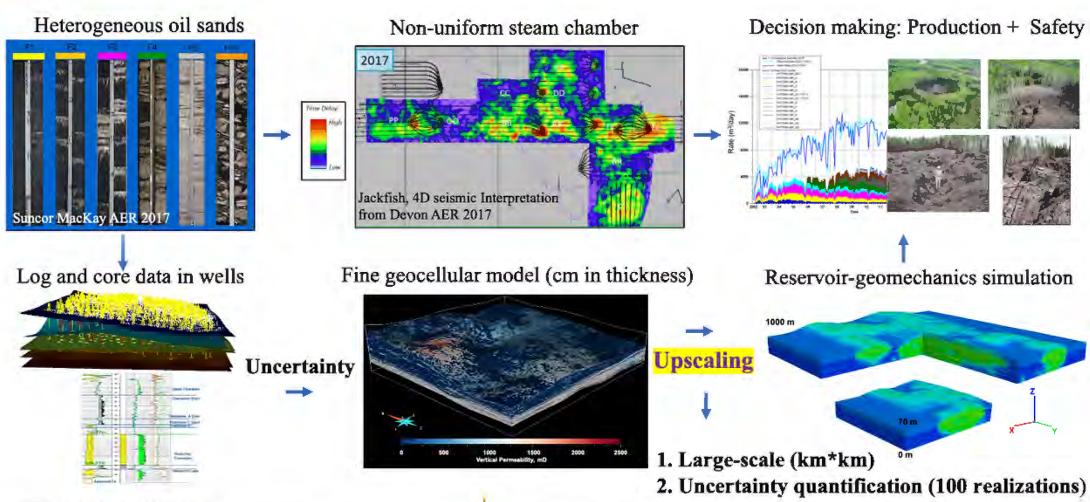
## Upscaling (PhD work of Bo Zhang)

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## Potential Pathways (Modes of Failure?) (Dir. 086 Risk Assessment)

- Provide the details of the risk assessment and risk management plan regarding reservoir containment, including:
  - any assumptions used in the assessment;
  - **a description of the potential pathways by which reservoir containment could be lost and identify the potential receptors;**
  - **an assessment of the likelihood of occurrence and consequence of loss of reservoir containment by each of the potential pathways;**
  - a discussion of how the risks would be mitigated;
  - a discussion of the uncertainties associated with the assumptions made in the risk assessment and management plan; and
  - a discussion of why the assessed level of risk and management plan are acceptable to allow the project to proceed.

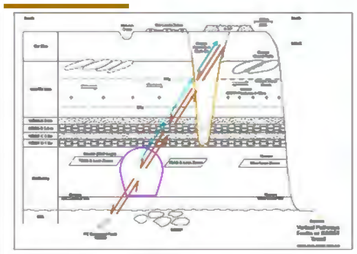
Not just SAGD!!!

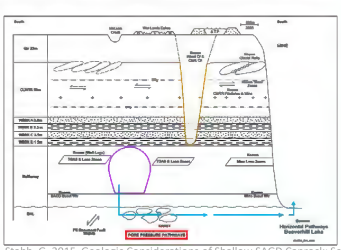
Could be any subsurface energy process (CCUS, $H_2$, salt caverns, geothermal, etc.)

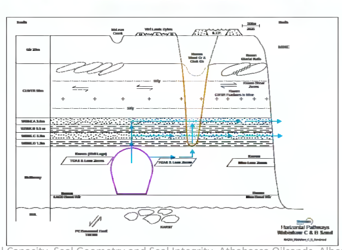


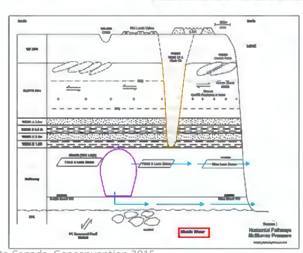


## Potential Pathways (Modes of Failure?)



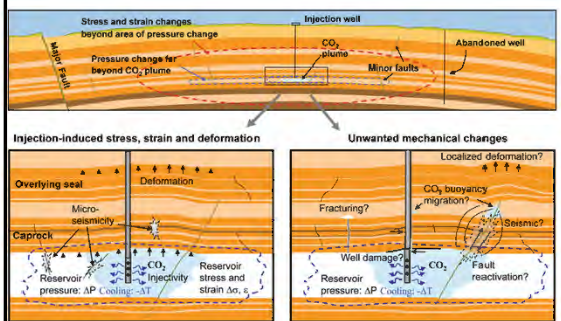






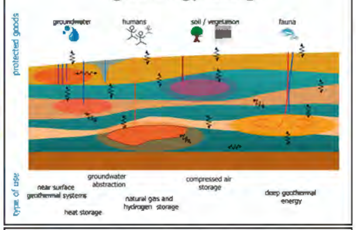
Stabb, G. 2015. Geologic Considerations of Shallow SAGD Caprock; Seal Capacity, Seal Geometry and Seal Integrity, Athabasca Oilsands, Alberta Canada. Geoconvention 2015.

## Subsurface Pathways

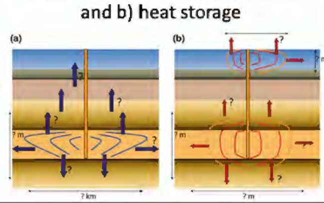



Rutqvist, J., 2012. The geomechanics of CO2 storage in deep sedimentary formations. J. Geotechnol. Geol. Eng., 30 (3), pp. 525-551.

Types of subsurface use and geoenergy storage




Induced effects of a) gas injection and b) heat storage




Induced effects for typical subsurface use options

(Bauer et al., 2013)
Environ Earth Sci (2013) 70:3935–3943
DOI 10.1007/s12665-013-2883-0

- – typically no effect
- x site specific assessment
- X typically effect

| | large scale pressure change | brine movement | liquid phase movement | induced seismicity | land subsidence | temperature changes | chemical and microbial reactions |
|---|---|---|---|---|---|---|---|
| groundwater production | x | - | - | - | x | - | x |
| near surface geothermal energy | - | - | - | - | - | X | X |
| hydrocarbon production | X | x | X | x | x | x | x |
| salt production | x | X | - | - | x | - | X |
| mining | X | x | - | X | X | x | x |
| deep geothermal energy | X | X | - | X | - | X | X |
| natural gas storage | x | X | X | x | X | x | x |
| heat storage | - | - | x | x | x | X | X |
| compressed air storage | - | - | - | x | X | X | x |
| storage of synthetic methane | X | X | X | x | X | x | x |
| storage of hydrogen | X | X | X | x | X | x | x |
| brine / liquid waste disposal | X | X | - | X | x | x | X |
| $CO_2$ disposal | X | X | X | X | x | x | X |



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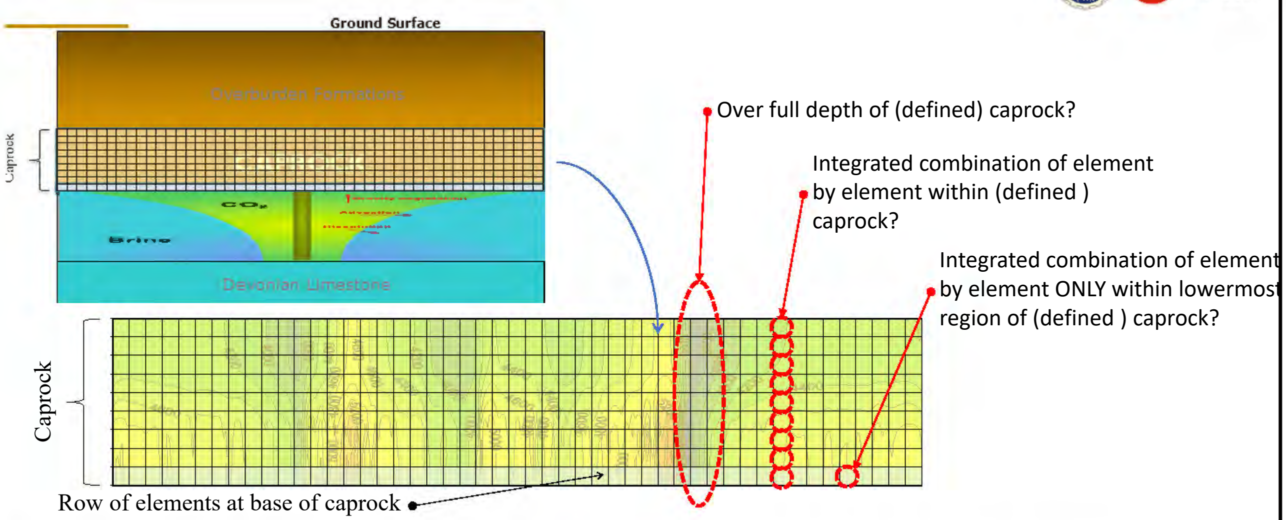
## How is FoS defined for a Caprock?



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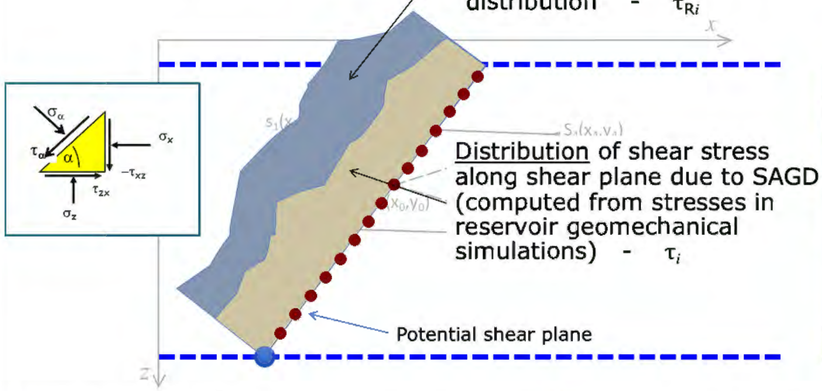
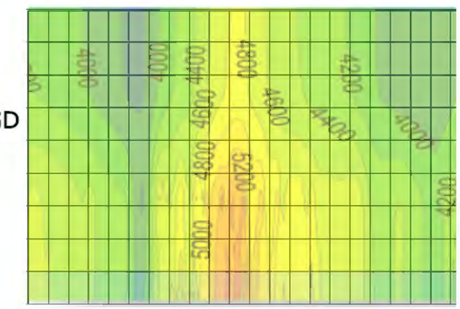
## FoS is defined relative to a "Failure Mechanism"

$$\Rightarrow \begin{cases} \sigma_\alpha = \frac{\sigma_z + \sigma_x}{2} + \frac{\sigma_z - \sigma_x}{2}\cos(2\alpha) + \tau_{xz}\sin(2\alpha) \\ \tau_\alpha = \frac{\sigma_z - \sigma_x}{2}\sin(2\alpha) - \tau_{xz}\cos(2\alpha) \end{cases}$$

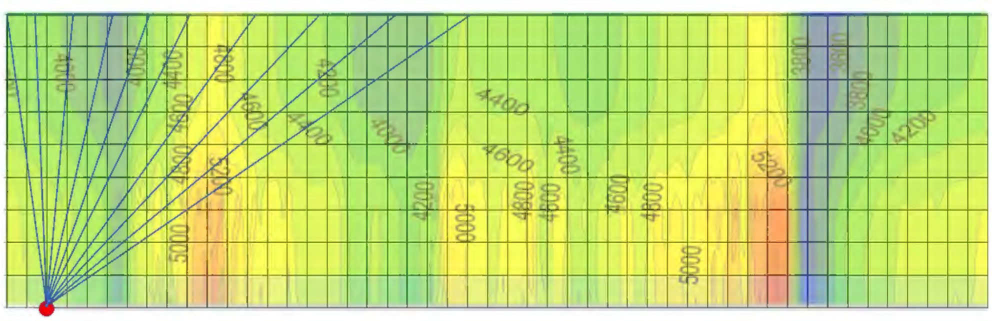




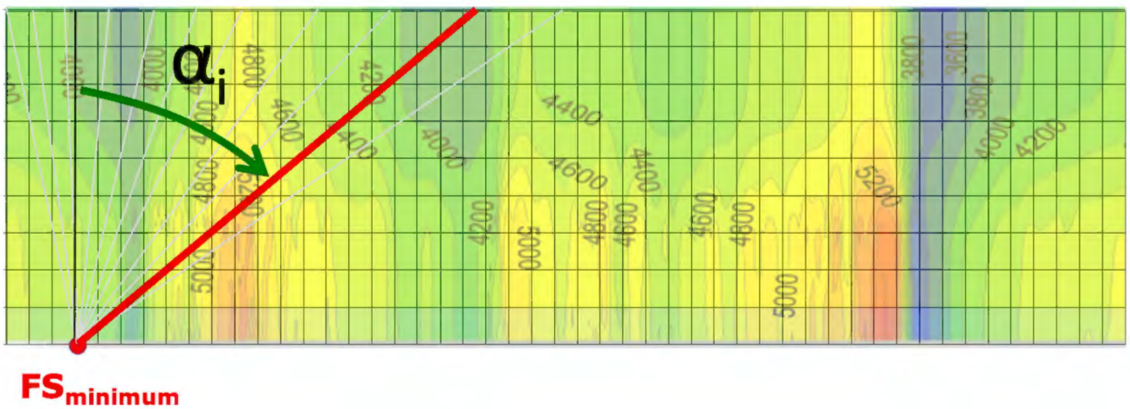


## Search for Critical "POTENTIAL" Planes of Shear through the caprock



- Sampling points are selected along the base of the caprock from which a linear shear plane is drawn through the caprock at various inclinations.
- The position of the *potential* shear plane will move along the lower boundary (from left to right side) with different values of a. Within this zone, sampling points are selected along the base of the caprock from which a linear shear plane is drawn through the caprock at various inclinations.

## Search for Critical "POTENTIAL" Planes of Shear through the caprock



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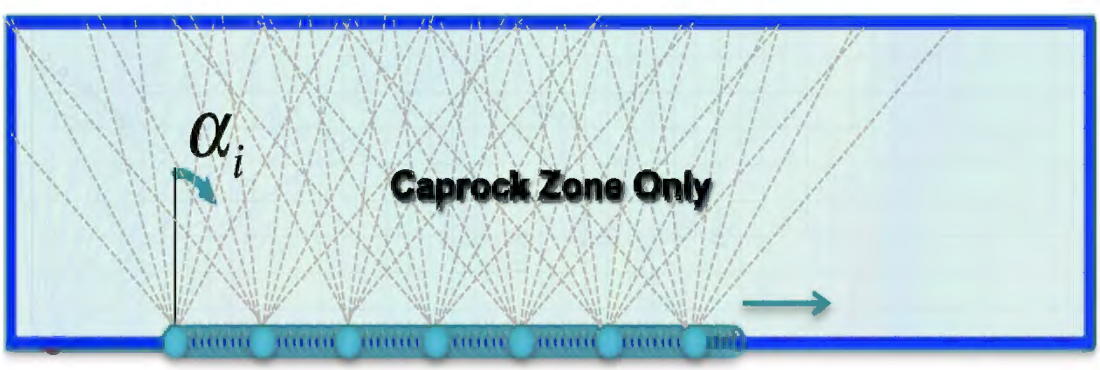
## Search for Critical "POTENTIAL" Planes of Shear through the caprock




- The position of the *potential* shear plane will move along the lower boundary (from left to right side) with different values of $\alpha_i$.



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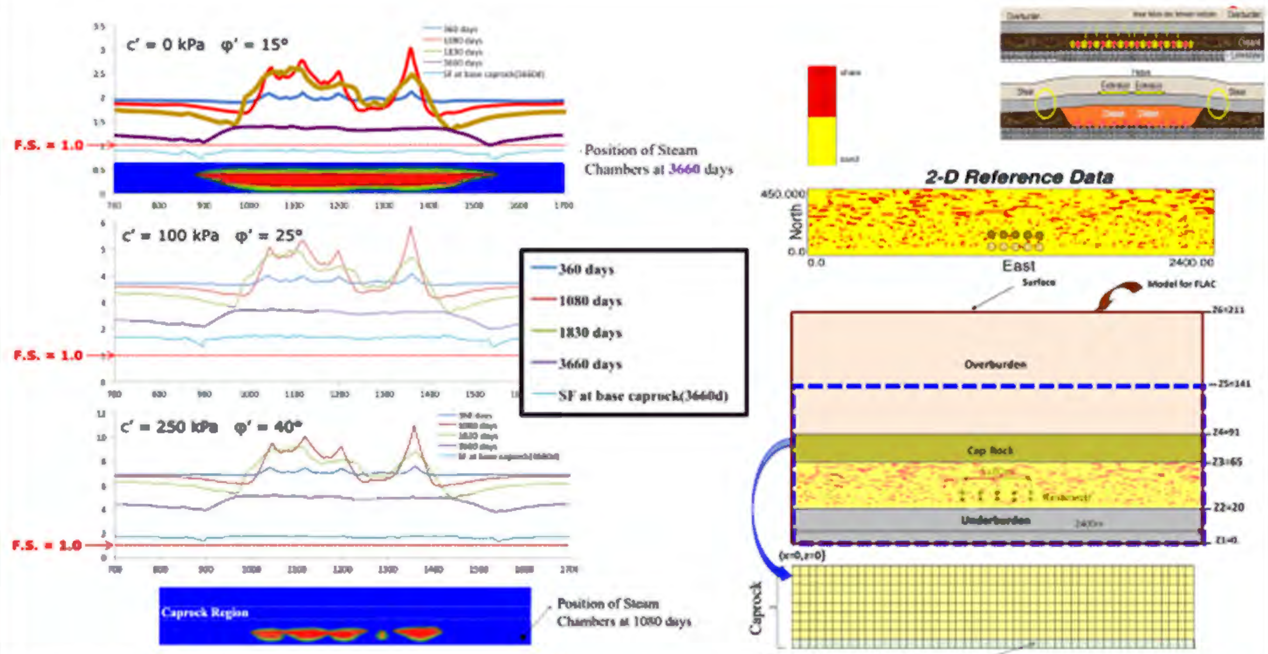
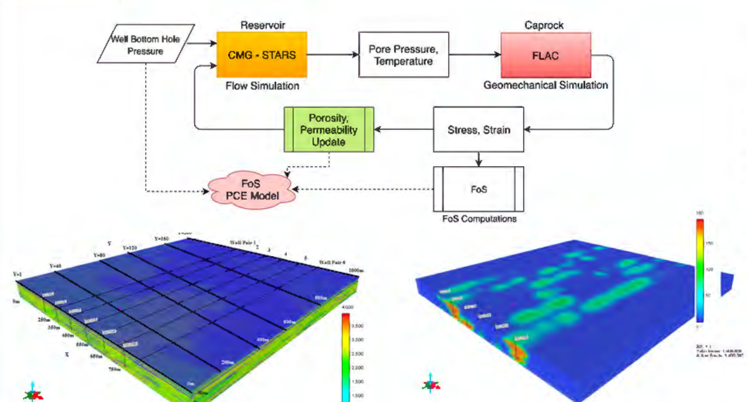


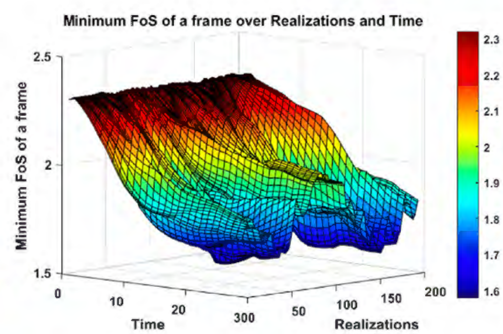





# Uncertainty quantification of the factor of safety in a steam-assisted gravity drainage process




(c) Steam chamber growth across the reservoir at t=25.




$$\tau_{strength} = (\sigma - P_p)sin(\phi) + Ccos(\phi) \qquad \tau = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$FoS = \frac{\tau_{strength}}{\tau}$$

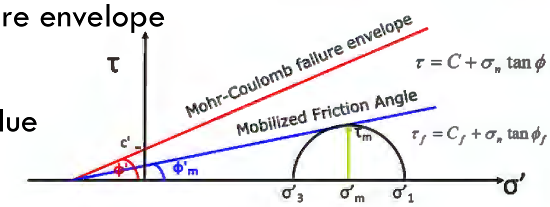
Ganesh, A., B. Zhang, R. Chalaturnyk and V. Prasad, 2020. Uncertainty quantification of the factor of safety in a steam-assisted gravity drainage process through polynomial chaos expansion. Computers and Chemical Engineering Vol. 133, https://doi.org/10.1016/j.compchemeng.2019.106663

## Shear Strength Reduction (SSR) Method to compute Factor of Safety?

- Utilize numerical simulation tools that are employed in almost all caprock integrity assessments
- Trial of Strength Reduction Factors (SRF)
- The SRF is then iteratively increased at a constant user-defined rate, thereby reducing cohesion and friction angle parameters until the failure envelope intercepts the final failure envelope which is defined by $c_f$ and $\phi_f$.
- The Final Factor of Safety of the system is the value of this final Strength Reduction Factor.

$$C_f = \frac{C}{SRF}$$

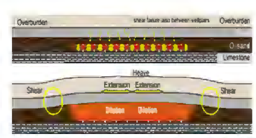
$$\phi_F = \tan^{-1}\left(\frac{\tan\phi}{SRF}\right)$$



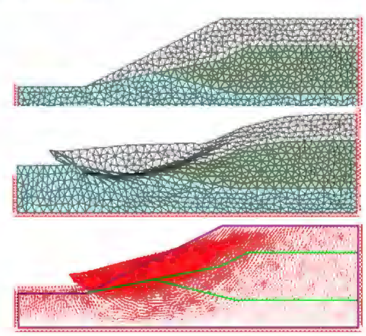


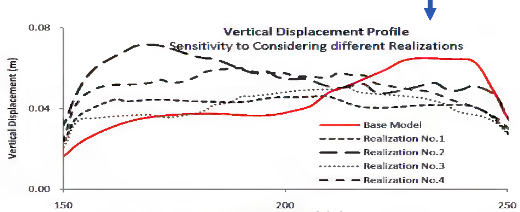



## Shear Strength Reduction Method



- Three possible criteria can be used as a primary mechanism for determining failure and a corresponding FoS:
  - Development of plastic zones from the toe to head of the slope
  - Large deformation
  - Solution non-convergence






Stable Slope
FoS ~ 1.4

| Janbu Corrected | Bishop | Spencer | GLE | Phase[2] (T6) | Phase[2] (Q8) |
|---|---|---|---|---|---|
| 1.393 | 1.410 | 1.380 | 1.398 | 1.385 | 1.389 |

Unstable Slope
FoS ~ 1.0

| Janbu Corrected | Bishop | Spencer | GLE | Phase[2] (T6) | Phase[2] (Q8) |
|---|---|---|---|---|---|
| 1.005 | 0.988 | 0.987 | 0.987 | 0.997 | 1.018 |

## Potential Benefits of Shear Strength Reduction Approaches to Assessment of Safety

- Numerical methods used in SSR inherently accommodate stress-strain relationships and avoid arbitrary assumptions regarding simplifying assumptions of analytical/semi-analytical methods.
- SSR analysis does not require a priori assumptions on failure surface types, shapes, and location. Rather, it automatically establishes critical failure mechanisms. The method can automatically monitor the development of failure zones, ranging from localized instabilities to total collapse.
- Given realistic deformation properties of materials (Young's moduli in particular), the SSR method can predict expected deformations at failure. Although deformation properties may not change safety factor values by much, they can alter failure mechanisms. This aspect can significantly improve our ability to support and monitor subsurface processes.
- The SSR technique can accommodate both the peak and residual strengths of materials in the same analysis. This feature much better captures the real-world behaviour of geological materials.



## Summary

- For SAGD, need to better understand exactly what a "factor of safety" means relative to operations and to a specific mechanism of "failure" or "unsatisfactory performance".
- Rapid rise of interest in CCUS for energy transition will require our simulations to be "less science" and "more engineering" to provide effective input to operational decisions - we need to understand how far from "acceptable performance" we are.
- Same is true for other subsurface energy options, e.g. hydrogen.
- Requires better understanding of how to utilize sophisticated simulations to model "failure" or "unsatisfactory performance".
- Family of ES Chairs working in key areas to allow faster reservoir geomechanical simulations, so uncertainty can be robustly captured in "failure mechanisms".

## Acknowledgment

energi SIMULATION
NSERC CRSNG
nwmo NUCLEAR WASTE MANAGEMENT ORGANIZATION SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES
SUNCOR ENERGY
cenovus ENERGY
RIPED
ConocoPhillips
CMG COMPUTER MODELLING GROUP LTD.