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Numerical Simulation Evaluating the Standoff Distance of SPR Caverns from the Edge of the Big Hill Salt Dome, USA

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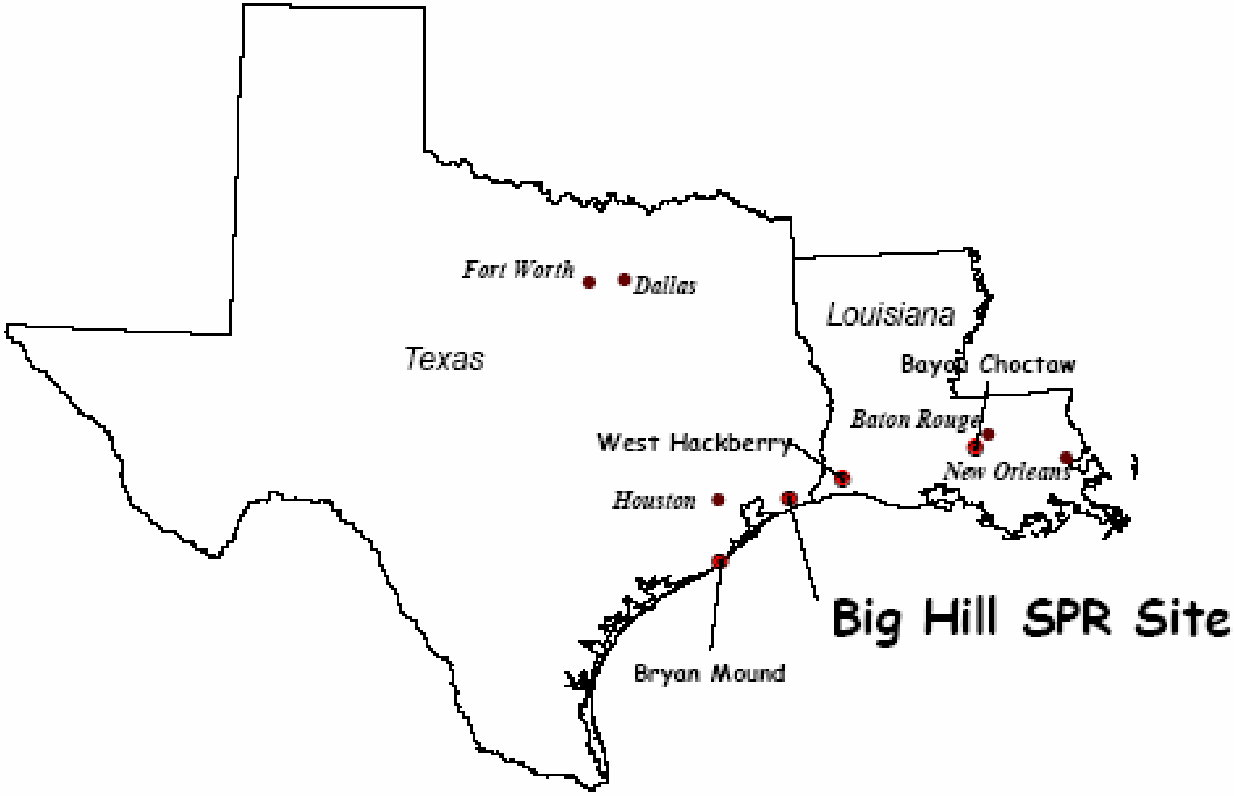
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Background

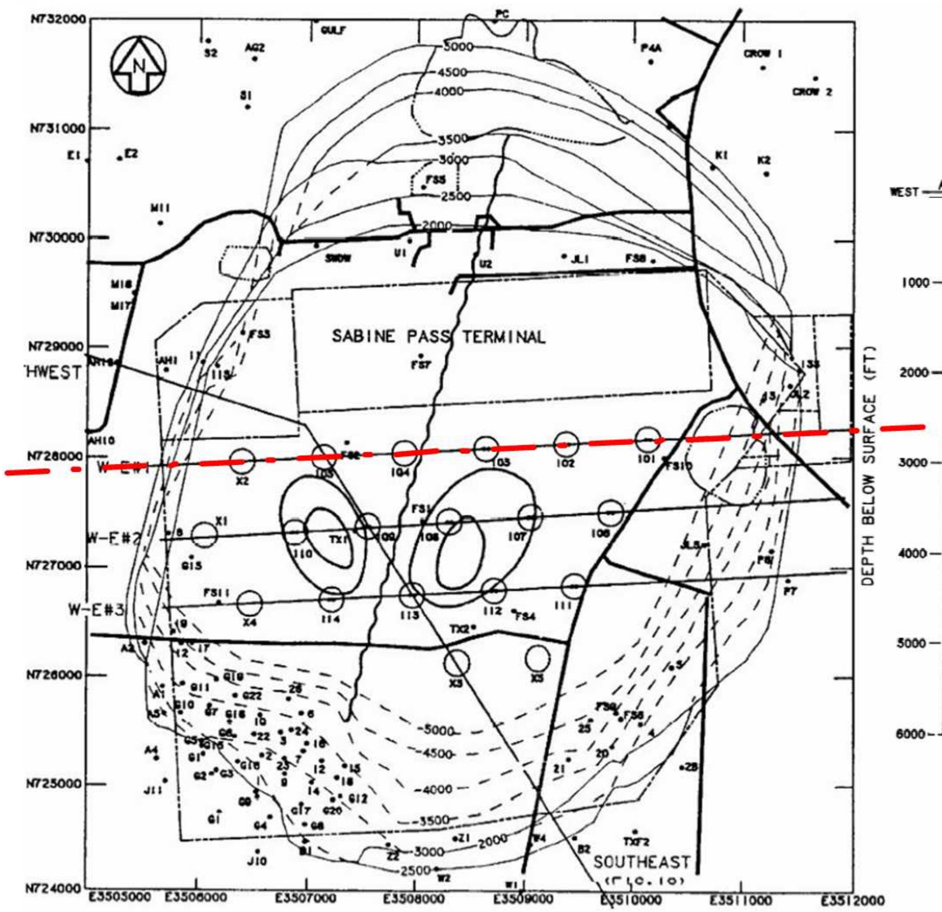
- Solution-mined caverns in salt have provided a means to safely store liquid and gas hydrocarbons in the USA for more than 60 years.
- In the Gulf Coast, salt domes have become excellent hosts for numerous storage caverns due to their favorable geologic properties.
- To develop new caverns, companies are increasingly turning toward marginal locations near the peripheries of domes where geologic uncertainty increases.
- Thus the sizes of caverns have increased and cavern fields have expanded towards the lateral edge of dome.
- This paper attempts to model further expansion of the SPR cavern field at Big Hill and addresses the resulting performance and stability issues.

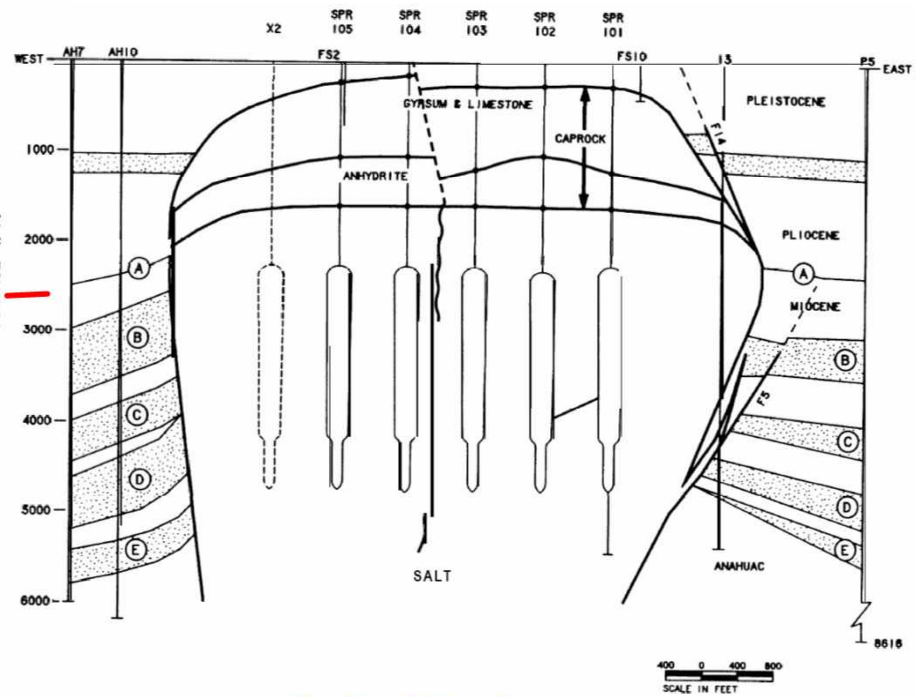
Location of Big Hill SPR Site

- Big Hill SPR facility located near Winnie, TX.
- The storage capacity of the Big Hill facility is currently 170 million barrels of oil.



Big Hill Salt Dome, Texas





Vertical Section

Plan View

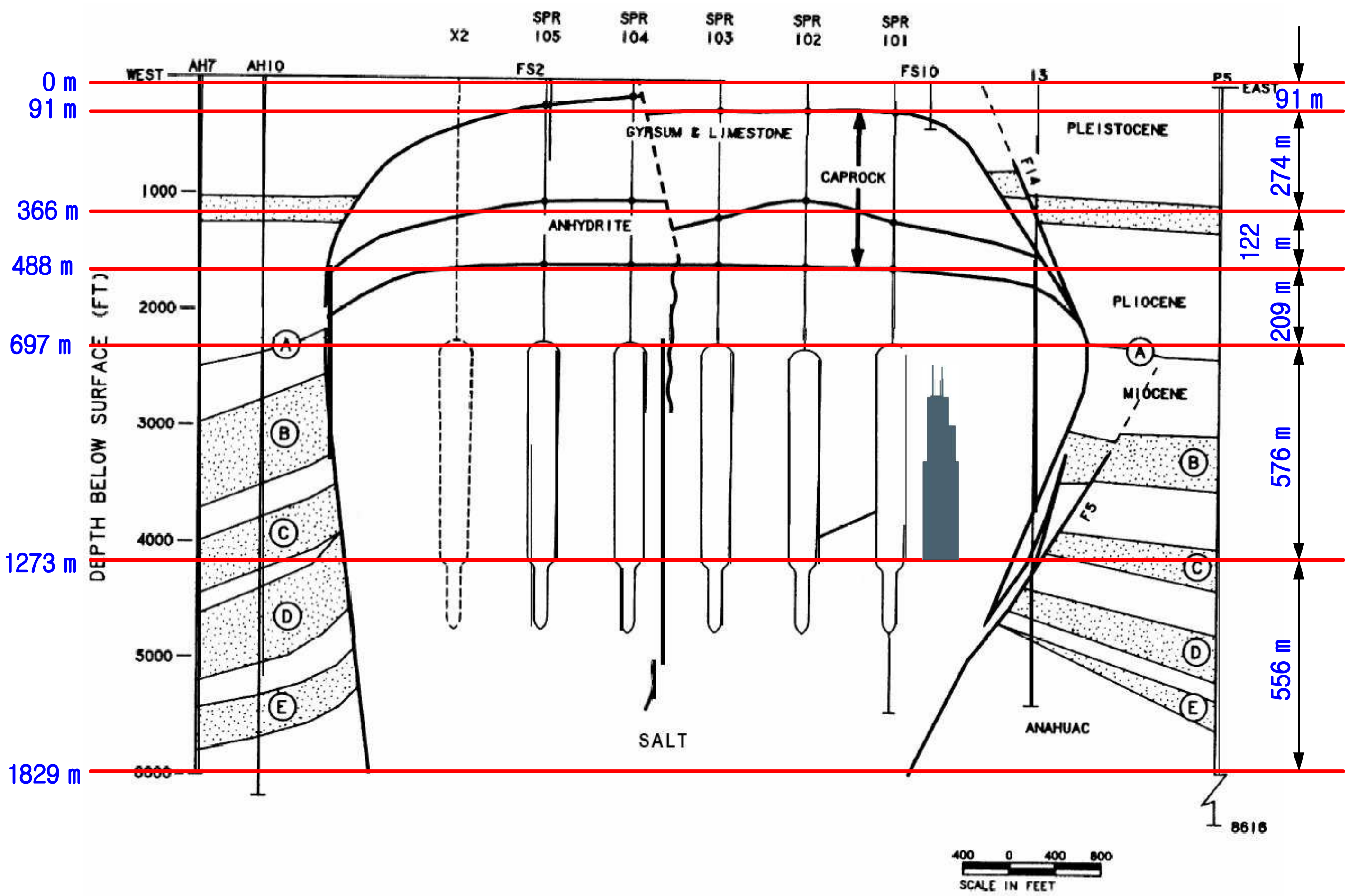
Why SD?

- The standoff distance (SD) is considered a key parameter for checking the structural integrity of the caverns in the dome.
- If the salt in the SPR facility forms discontinuities due to unstable stresses, oil might be released to the porous sandstone surrounding the salt dome.
- To estimate how many more caverns can be constructed in the existing salt dome, it is necessary to define the allowable SD for a cavern to the edge of the dome based on mechanical integrity of the cavern.

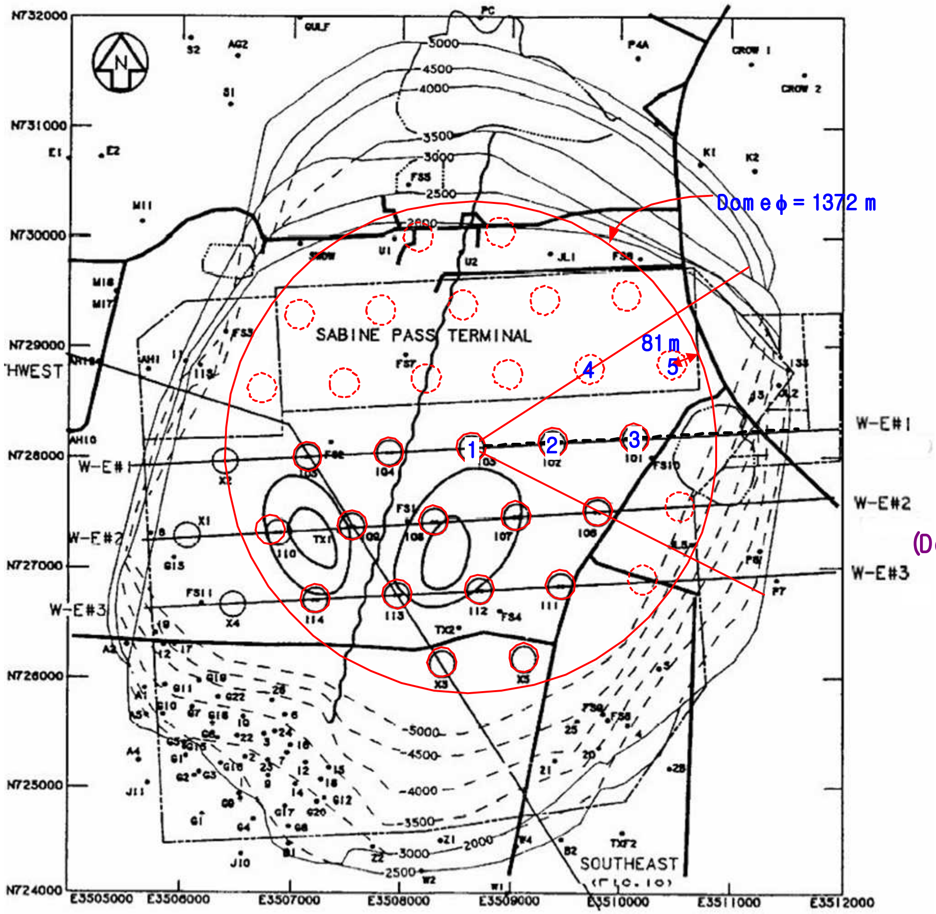
Objectives of Analysis

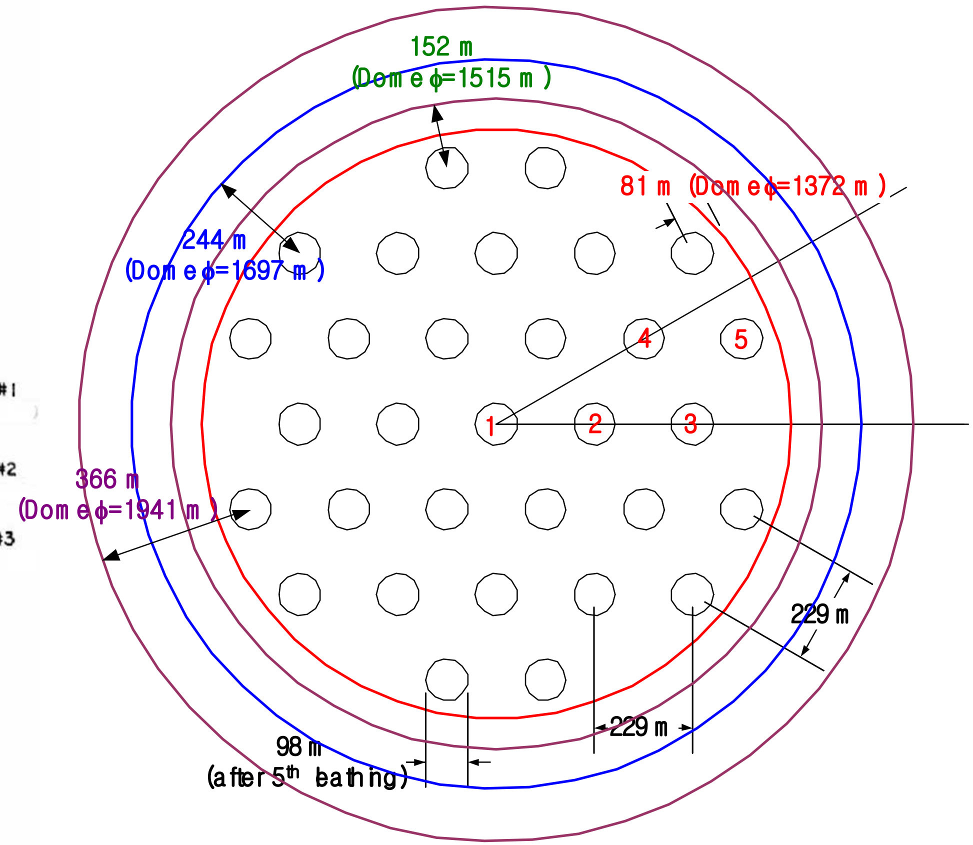
- To determine the allowable standoff distance based on mechanical integrity of the salt and caverns,
  - Evaluate the structural stability of the salt dome
    - By checking the minimum compressive stress distribution
    - By checking the minimum safety factor against dilatant damage

Stratigraphy and Thickness of Each Layer

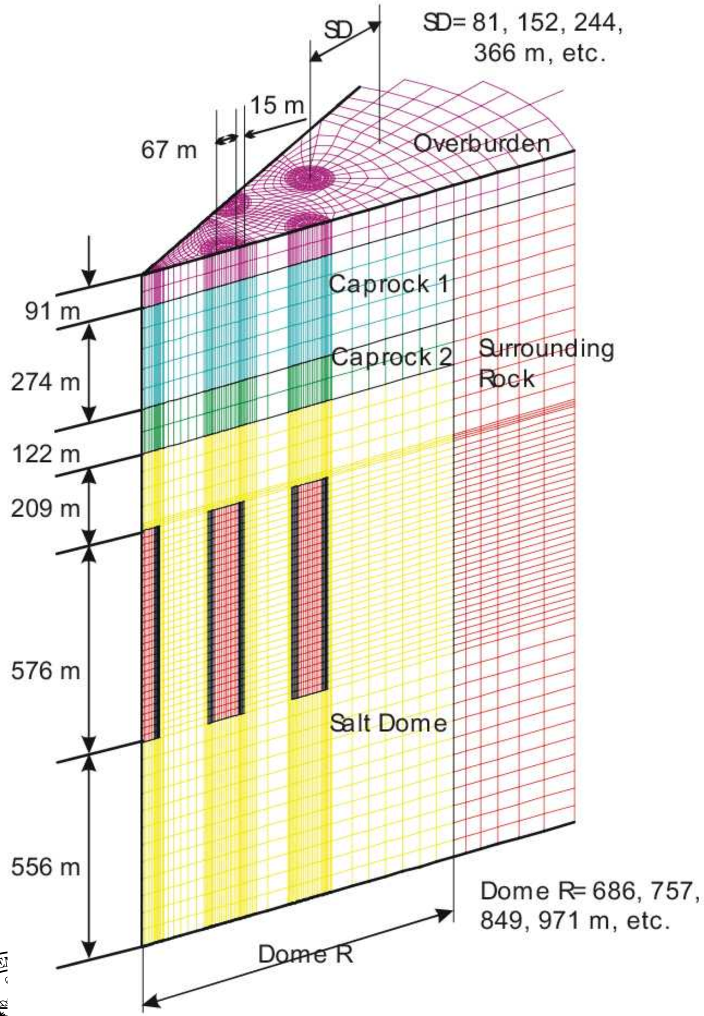


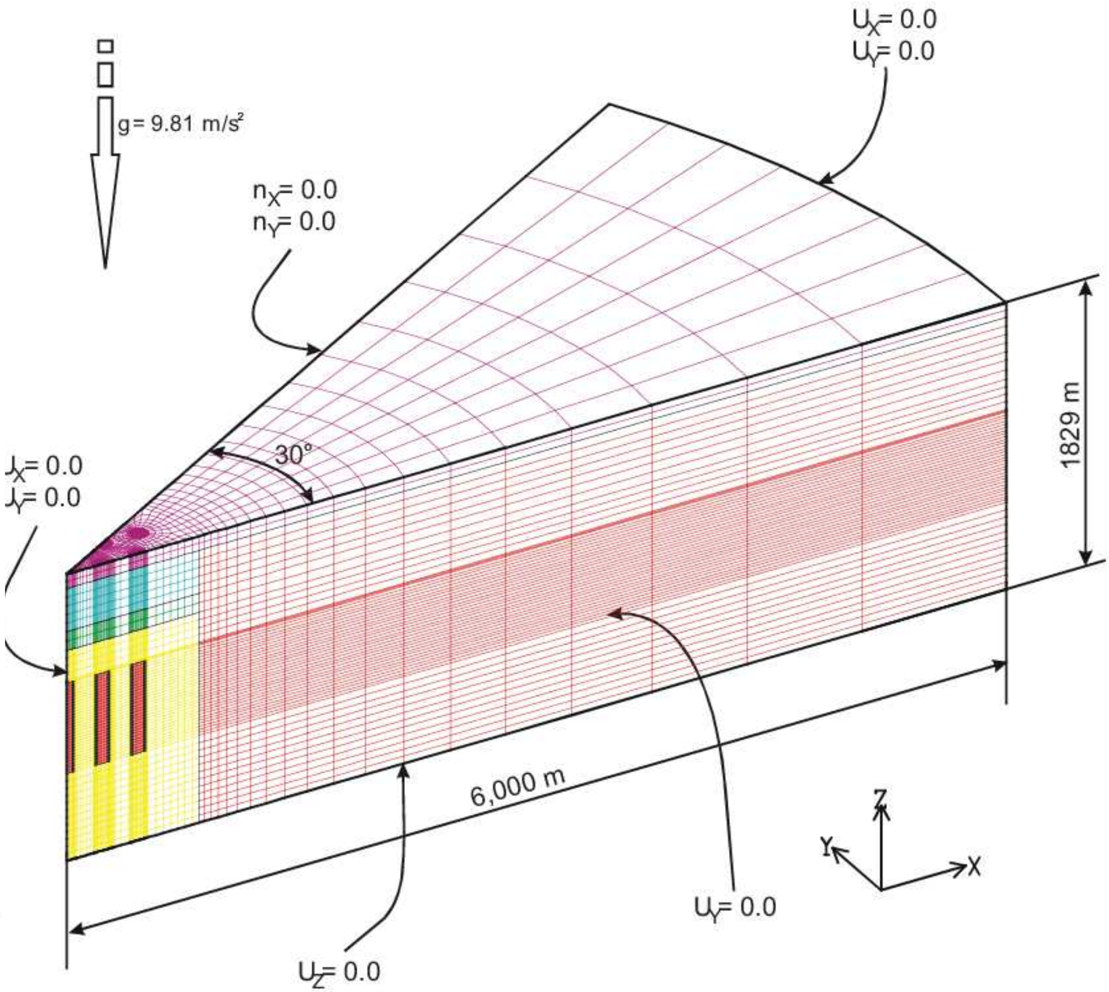
Cavern Layout





Mesh and Boundary Conditions
(31 Caverns, 5 Drawdowns by Leaching)





Solver

- JAS3D, 3D FEM structural analysis code, is used for this study
- "Power Law Creep Model" is used for the salt dome
- "Elastic Model" is used for overburden (sand), caprock 1 (gypsum and limestone), and lithologies surrounding the dome (sandstone)
- "Soil and Foams Model" is used for caprock 2 (anhydrite)

Model History

❑ Overall

- The simulated caverns are assumed to be leached to full size over a one year period.
- The caverns are filled with petroleum at one year
- The caverns are allowed to creep for 20 years.
- Starting at 21 years, and subsequently every 5 years, the caverns were instantaneously leached to produce a volume increase of 16% during each leach.
- Leaching was assumed to occur uniformly along the entire height of the caverns but was not permitted in the floor or roof of the caverns
- Simulation lasts 46 years (5 leaches)

Model History

- Internal Pressure in the Caverns
  - Both normal cavern operating conditions and workover conditions are simulated.
  - For normal operating conditions, the cavern pressure is based on a wellhead pressure of 6.24 MPa.
  - For workover conditions, zero wellhead pressure is used.
  - Workover durations are 3 months.
  - This workover cycle is repeated for every 5 year.

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Thermal Condition

- The FEM model includes a depth-dependent temperature gradient which starts at 24.8ºC (76.7ºF) at the surface and increases by 0.0257ºC/m of depth.
- The temperature profile is based on the average temperature data from well logs from Big Hill prior to leaching.
- The second order temperatures (radial temperature gradients) were not considered in the analyses.

Material Properties of Salt used in the Analyses

Parameter	Unit	Value	Reference
Young's modulus (E)	GPa	31	Kreig, 1984
Density (ρ)	kg/m^3	2300	Kreig, 1984
Poisson's ratio (v)	-	0.25	Kreig, 1984
Elastic modulus reduction factor (RF)	-	12.5	Magorian & Krieg, 1990
Bulk modulus (K)	GPa	1.653	from E and v
Two mu (2μ)	GPa	1.984	from E and v
Structure factor (A)	$Pa^{-4.9}/s$	5.79×10^{-36}	Kreig, 1984
Structure multiplication factor (SMF)	-	1.5	Park et al., 2005
Calibrated creep constant	$Pa^{-4.9}/s$	8.69×10^{-36}	Park et al., 2005
Stress exponent (n)	-	4.9	Kreig, 1984
Activation energy (Q)	cal/mol	12000	Kreig, 1984
Universal gas constant (R)	cal/(mol·K)	1.987	-
Input thermal constant (Q/R)	K	6039	-

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Material Properties of Lithologies around Salt Dome

	Unit	Overburden (Sand)	Caprock 1 (Limestone)	Caprock 2 (Anhydrite)	Surrounding Rock (Sandstone)
Young's modulus	GPa	0.1	21	75.1	70
Density	kg/m^3	1874	2500	2300	2500
Poisson's ratio	-	0.33	0.29	0.35	0.33
Bulk modulus	GPa	N/A	N/A	83.44	N/A
Two mu	GPa	N/A	N/A	55.63	N/A
A_0	MPa	N/A	N/A	2338	N/A
A_1	-	N/A	N/A	2.338	N/A
A_2	-	N/A	N/A	0	N/A

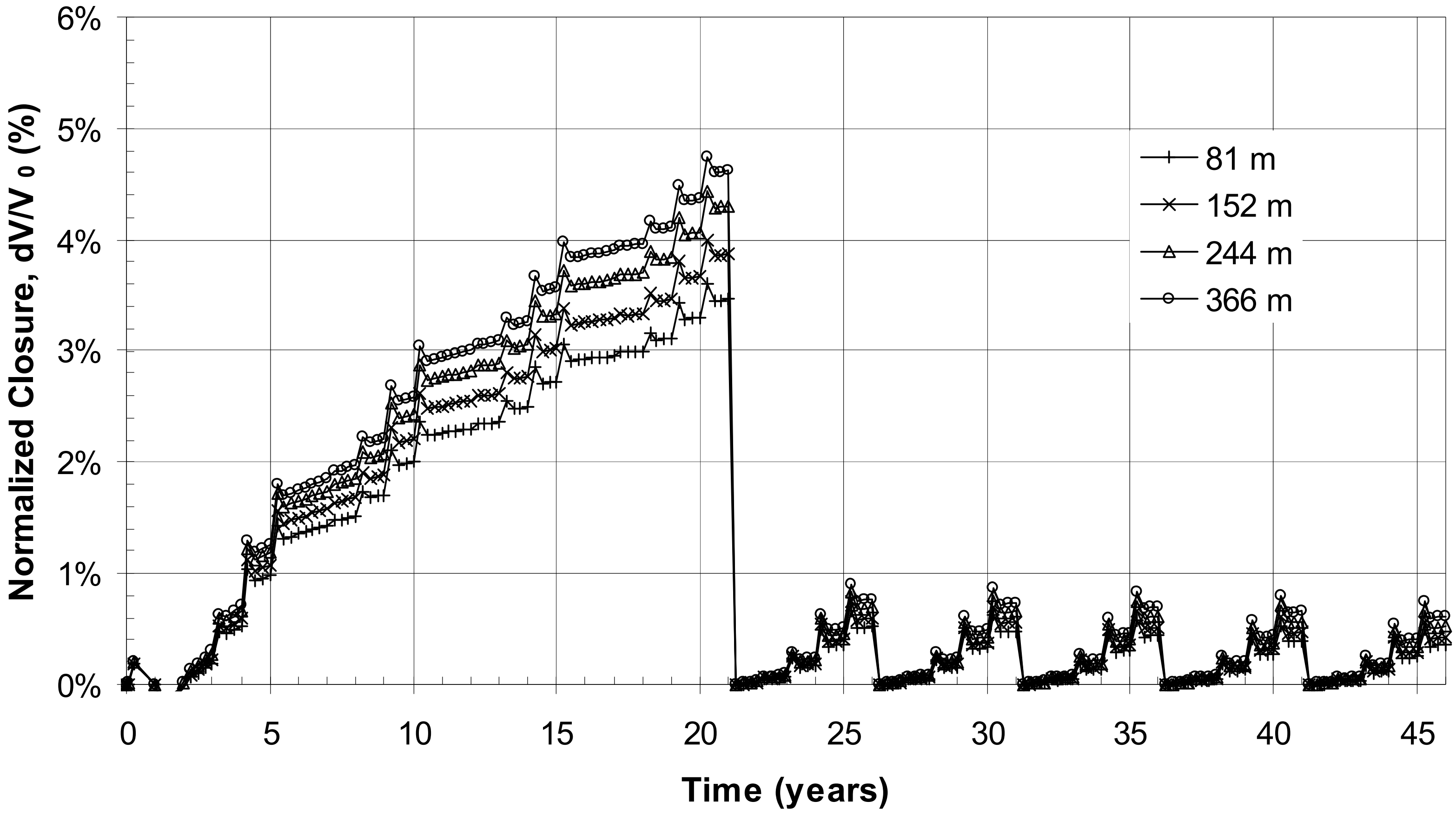
Failure Criteria

- **Structural Stability of Salt Dome:**
  - **Tensile failure**
  - **Dilatant damage**

$$\sqrt{J_2}\,(\text{psi}) = 1746 - 1320.5 \cdot e^{-0.00034 \cdot I_1\,(\text{psi})}$$

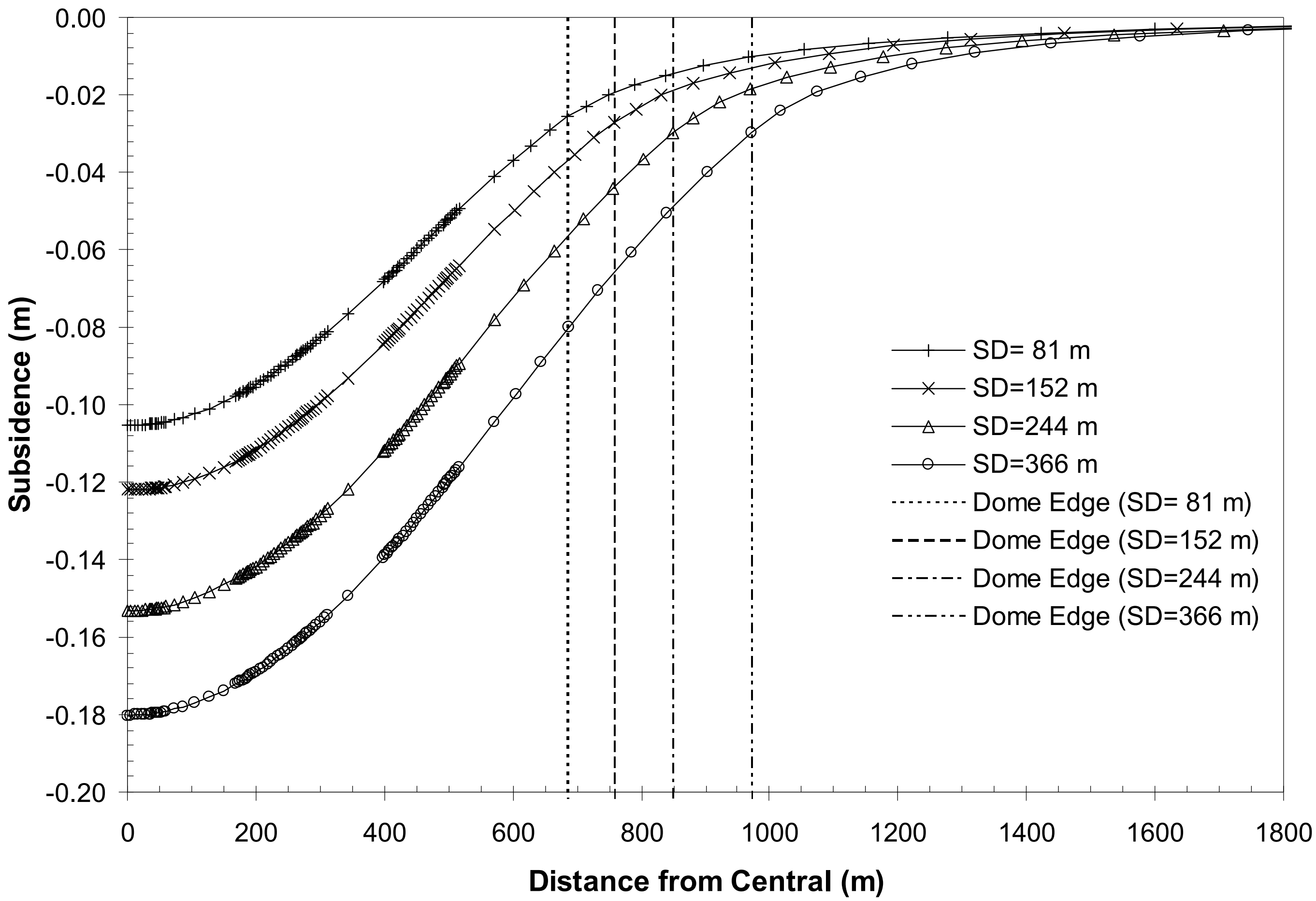
$$J_2, I_1 = \text{Stress Invariants}$$

Storage Loss



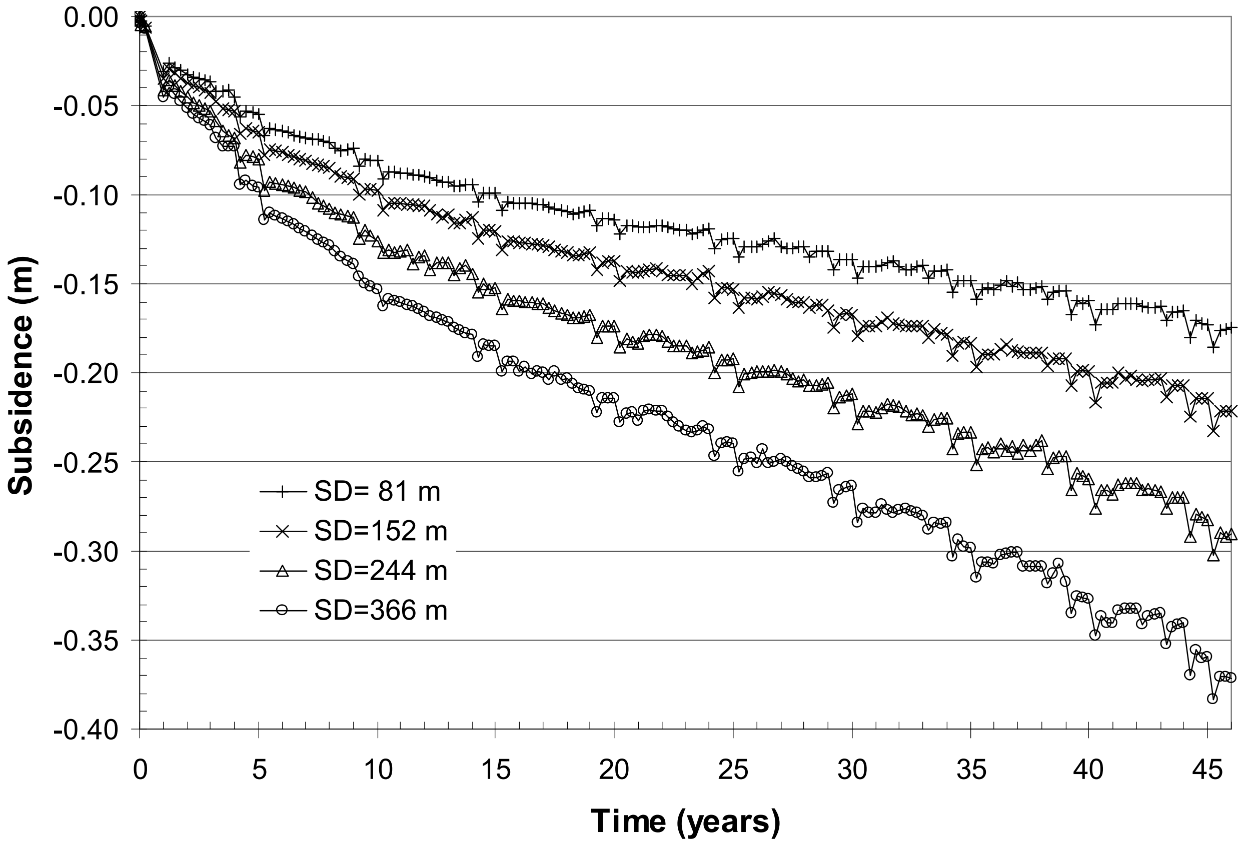
Subsidence vs. Distance from Central

- A larger SD yields a larger subsidence.

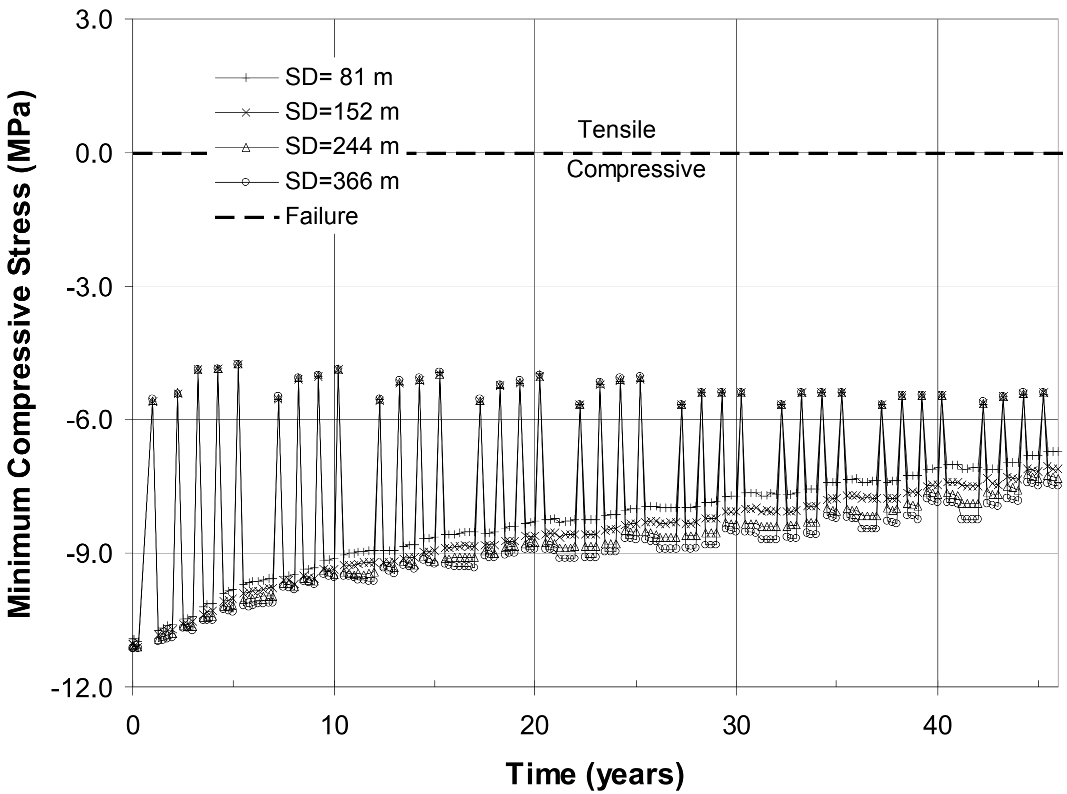


Subsidence vs. Time

- A larger SD also yields a larger subsidence with time

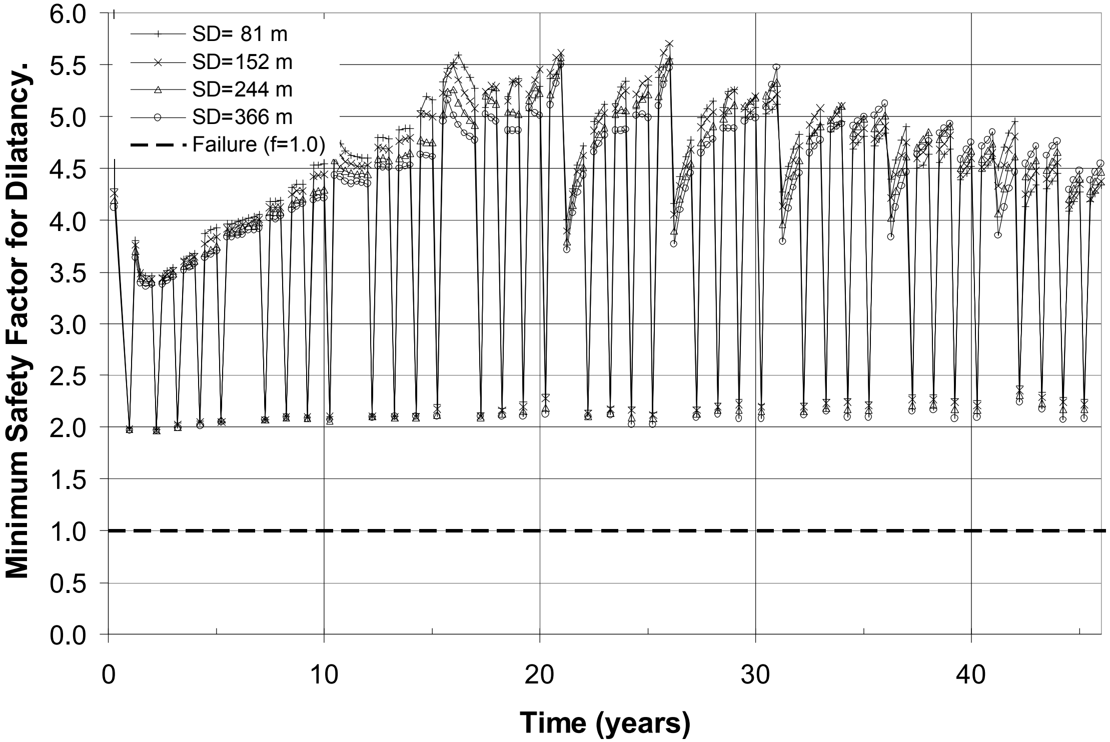


Minimum Compressive Stress



- **The minimum compressive stresses are approximately 5 MPa for all cases.**
- **The caverns are, therefore, stable against tensile failure for all SDs over time.**
- **This implies SD has little effect on the formation of tensile stresses.**
- **Shorter SDs yield smaller minimum compressive stresses when a workover is not in progress.**

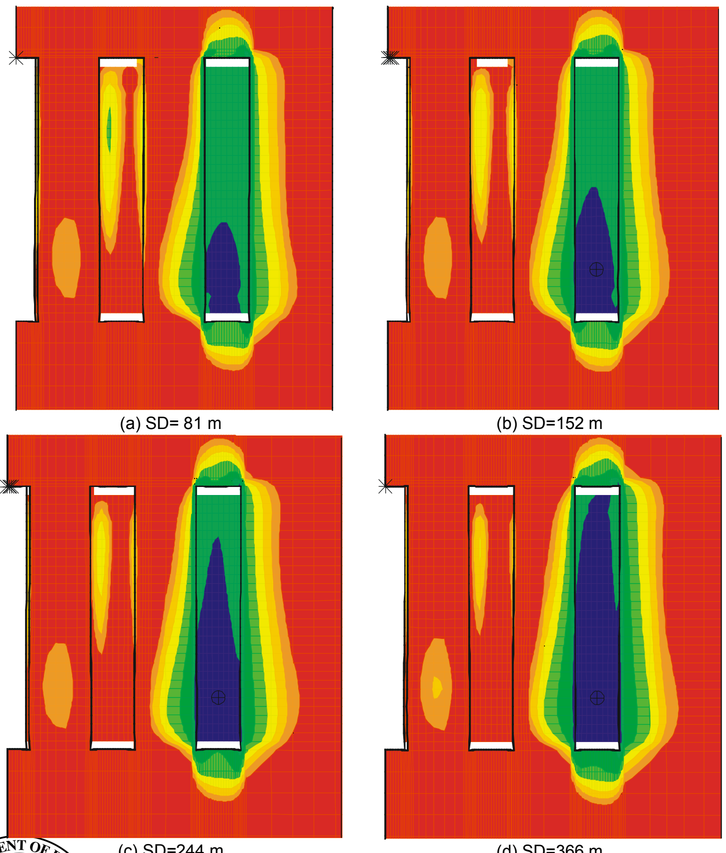
Minimum Safety Factor Histories against Dilatant Damage



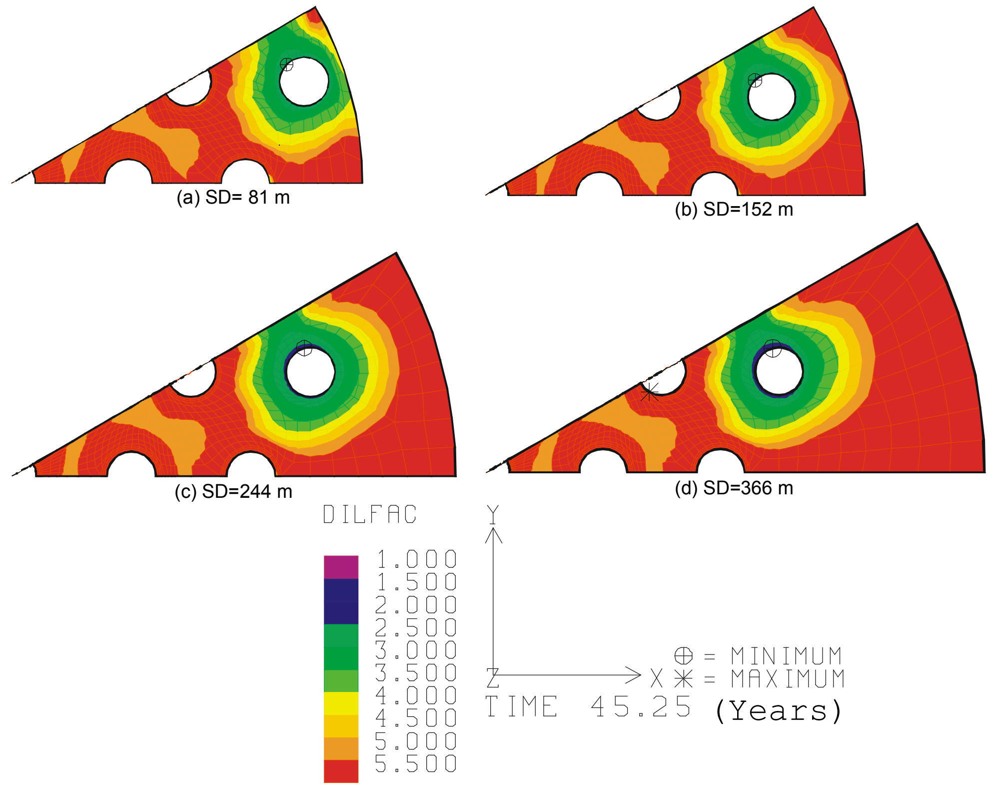
- The standoff distance does not have much influence on the dilatancy factor (DILFAC) from an overall point of view.
- A larger SD yields a lower safety factor during workover, while a larger SD yields a higher safety factor during normal operating conditions.
- The safety factor is greater than the failure criterion, 1.0. Thus, the caverns should be stable against dilatancy damage

Dilatant Safety Factor Contours during Workover of Each Cavern

Vertical section view



Plan view



Concluding Remarks

- Three dimensional FEM model for 31 caverns and five drawdowns with associated leaching was constructed
- The analyses includes a recently derived damage criterion obtained from testing of Big Hill salt cores.
- The smaller SD yields structurally weaker web between the outmost cavern and the edge of the dome.
- However, the SD has little effect on the formation of tensile stresses and the dilatancy in the salt around the caverns.
- From the structural stability of the modeled cavern array, it appears that many additional caverns can be added safely to the existing Big Hill facility.

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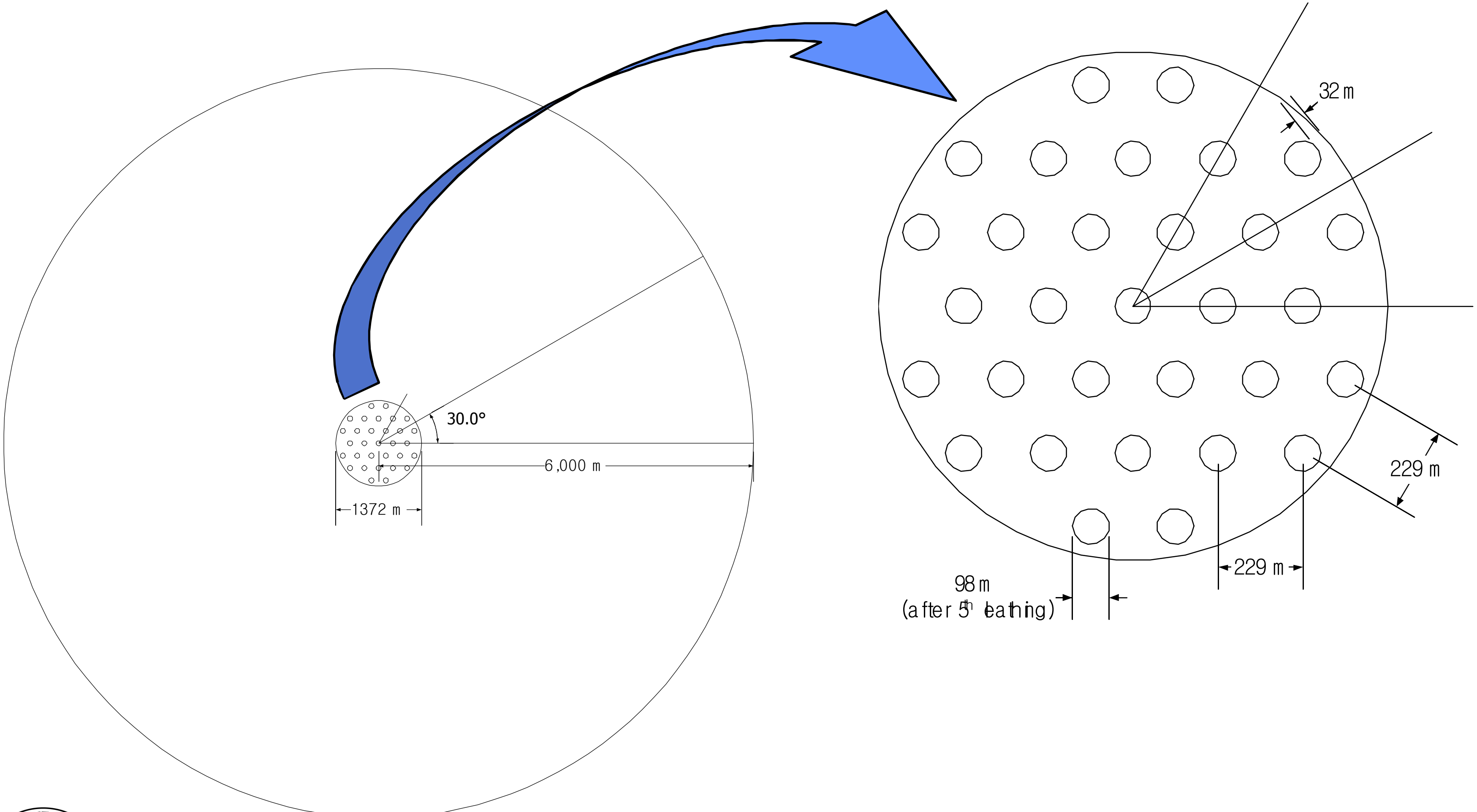
Far-field Boundary



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