CONFIDENTIAL MEMORANDUM

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January 26, 2024
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Date: January 26, 2024

Subject: Geomechanical Evaluation of Westlake Caverns PPG 6 & PPG 7 at the Sulphur Mines Salt Dome, Calcasieu Parish, Louisiana: Phase 2 Results

INTRODUCTION

This letter memorandum provides a summary discussion of the Phase 2 geomechanical modeling focused on the Westlake caverns PPG 6, Louisiana Serial Number (S.N.) 57788, and PPG 7, S.N. 67270, in the Sulphur Mines salt dome. RESPEC Company, LLC (RESPEC) is conducting a multiphase geomechanical study of the Westlake caverns, which began with a baseline geomechanical assessment of the caverns using typical modeling assumptions and methods [Nieland, 2023]. The Phase 1 baseline modeling provided insight into potential risks for cavern instability at hypothetical low-pressure conditions. The Phase 1 modeling also indicated that the salt web between PPG 7 and the dome flank may exhibit strength characteristics different from what was assumed in the geomechanical model based on RESPEC's testing of salt core recovered from Well PPG 22 [Arnold, 2015]. The Phase 1 modeling did not predict dilatant stress states in the salt near the PPG 7 cavern where historical sonar surveys indicate rock falls have occurred since approximately 2010. Subsequently, RESPEC completed Phase 2 of the study to estimate the in situ salt dilation strength in the salt web between PPG 7 and the dome flank based on the historical sonar surveys conducted in PPG 7. The in situ salt dilation strength was estimated in the web between PPG 7 and the dome flank for use in subsequent phases of the study. Additionally, RESPEC evaluated several hypothetical scenarios for a select subset of model parameters to assess the potential influence these model parameters may have on the model-predicted stresses in the salt web between PPG 7 and the dome flank for consideration in subsequent phases of the study. The following model parameters were evaluated in Phase 2 through the analysis of hypothetical conditions:

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- A weak layer of material between the salt stock and the adjacent nonsalt strata
- A competent caprock overlying the salt dome with a relatively high elastic stiffness
- An Edge Anomalous Zone (EAZ) along the dome flank with slower creeping salt
- A depleted reservoir next to the salt dome near PPG 7

The modeling scenarios discussed herein regarding the potential effects of several model parameters (listed above) are purely hypothetical and not representative of actual conditions at the Sulphur Mines salt dome. The real-world conditions, precise structure and characteristics of the salt dome boundary, the adjacent formations, and the likely extensive faulting along the dome flank are extremely complex and are not well defined or entirely undefined.

Numerical modeling was used to represent very simplified hypothetical conditions and scenarios for a select subset of the many parameters and inputs required to define the large-domain geomechanical model. The simplified representations of the various scenarios are considered useful for assessing the potential impact these parameters may or may not have on the model-predicted stresses in the salt surrounding the caverns. The results discussed herein do not constitute an exhaustive sensitivity study of the parameters evaluated and their possible range or interrelationships that may exist and could impact the study's conclusions.

The results of the hypothetical scenarios presented herein should not be considered representative of the actual conditions on the salt dome. The simplified hypothetical scenarios are not representative of any specific point in time with regard to the historical or future operation of the caverns within the salt dome or the production of hydrocarbons or other products on or around the salt dome.

BACKGROUND

The fluid pressure in a solution-mined cavern helps support the geologic loads that act on the rock surrounding and overlying the cavern. As the cavern pressure decreases, the loads that must be supported by the surrounding rock increase. If the loads exceed the rock strength, the rock will fail and lose strength. Unlike brittle rock types that fail suddenly, rock salt around a solution-mined cavern will typically begin to fail through microfracturing along the grain boundaries, a process referred to as dilation (or damage). If dilatant states of stress are maintained, the microfractures will increase and coalesce, which, in turn, reduces the strength of the salt, as illustrated in Figure 1. Salt damage is a progressive process that can lead to salt spalling from the roof and walls of the cavern and may lead to salt web failure or roof collapse.

The cavern and salt-web stability between adjacent caverns and between the caverns and the edge of salt (i.e., dome flank) is a function of web thickness, web height, and cavern fluid pressures. If the web thickness is small and the cavern pressure is too low, the shear stresses in the salt surrounding the caverns can exceed the strength of the salt. Shear stresses are always present in the salt surrounding solution-mined caverns that are unplugged because the internal fluid pressure is always less than the in situ stress in the surrounding salt stock. It is desirable to design and operate salt caverns in a manner that precludes the onset of salt dilation to maintain cavern stability.

GEOMECHANICAL MODEL OVERVIEW

The large-domain 3D geomechanical model of the Sulphur Mines Dome developed in Phase 1 was updated with a new salt contour map and caprock contour map provided by Lonquist & Co. LLC [Larcom, S., 2023]. The 3D model was also updated to include all available historical sonar surveys for the Westlake caverns PPG 6 and PPG 7, providing a conservative representation of the gross volumes of both caverns. Many other caverns in the salt dome were explicitly represented in the 3D geomechanical model, as shown in Figure 2. Westlake caverns PPG 18, PPG 21, PPG 22, and Boardwalk caverns BLM 3,BLM 4, and BLM 5 were excluded from the 3D model because they are sufficiently distant from the Westlake PPG 6 and PPG 7 caverns to not significantly influence the salt web between PPG 7 and the dome flank, shown in Figure 2.

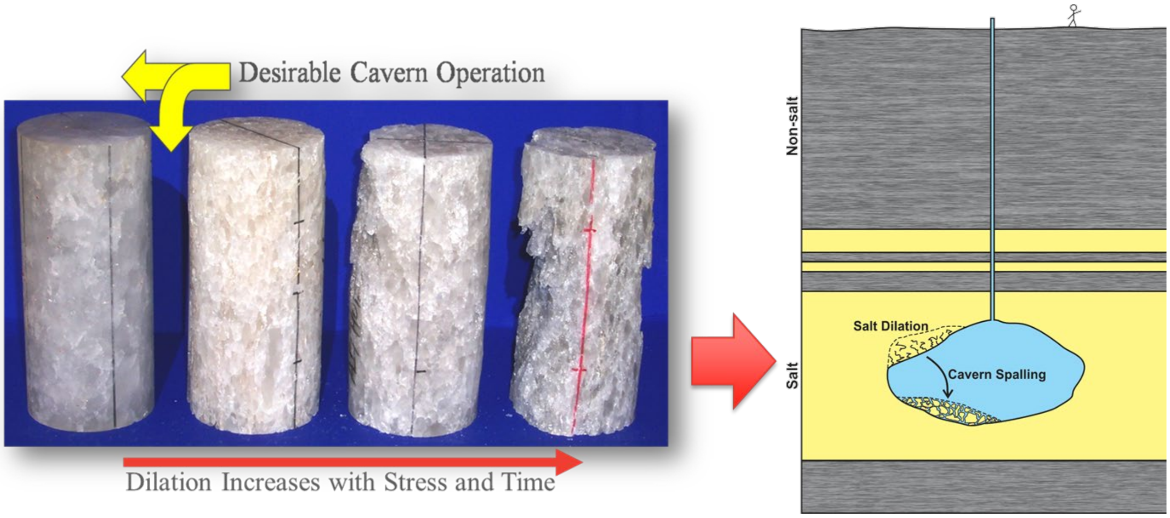

Figure 1. Example of Salt Dilation Illustrating How Dilation Will Increase With Stress and Time (Progression From Left to Right in the Right Image).

The caverns' historical development was approximated by sequentially excavating the caverns based on the well spud dates. The caverns' historical operating conditions were approximated in the model by conservatively representing all caverns as being brine-filled with minimal wellhead pressure. The cavern pressures in PPG 6 and PPG 7 were adjusted beginning in January 2021 to approximate the recent cavern pressure histories up to the present day more closely. Several caverns in the salt dome have already been plugged and abandoned, and these caverns were represented in the 3D model as plugged caverns after their approximate plugged and abandoned dates, i.e., the cavern pressures were gradually increased based on the model-predicted creep closure of the caverns.

SALT WEB IN SITU DILATION STRENGTH ESTIMATE

The historical sonar surveys in PPG 7 indicate that rock falls began to occur in the west-northwest area of the lower cavern lobe sometime between 2003–2011. The sonar surveys before 2011 were combined into a composite cavern geometry to conservatively represent the cavern shape and gross volume before 2011. The sonar surveys from 2011 through November 2023 were also combined into a composite cavern geometry to conservatively represent the change in the cavern shape and gross volume up to the present day, as illustrated in Figure 3.

The model-predicted stress states in the web between PPG 7 and the dome flank were post-analyzed to determine factor-of-safety (FS) values with respect to salt dilation using the RESPEC Dilation Criterion (RD Criterion) [DeVries et al., 2005]. The RD Criterion parameter values previously developed by Heiberger [2017] for the Sulphur Mines salt, based on RESPEC laboratory testing of salt specimens

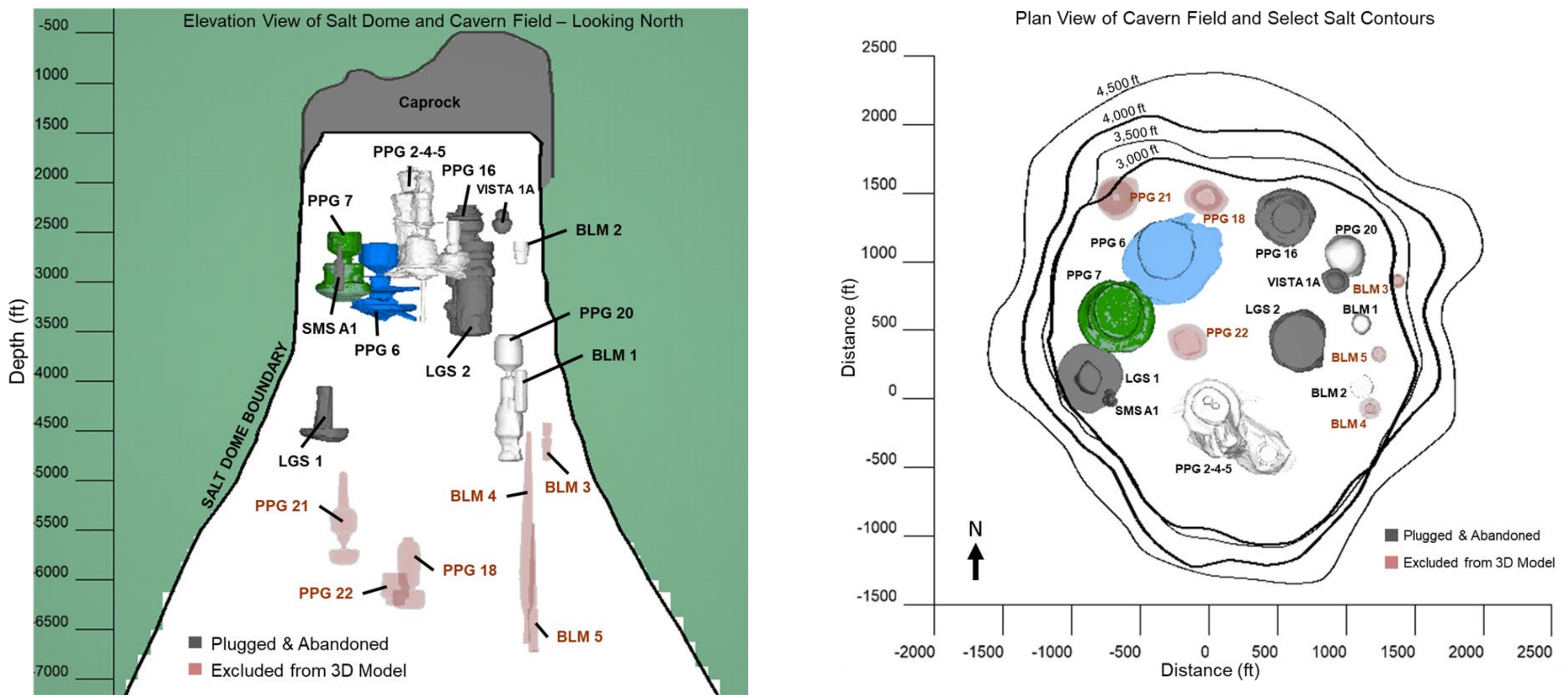

Figure 2. Elevation View (Left) and Plan View (Right) Schematic Illustrations of the Phase 2 Updated 3D Geomechanical Model.

recovered from Well PPG 22 [Arnold, 2015], were used to define the baseline salt dilation strength. The baseline salt dilation strength was reduced by a factor of 2.7 (i.e., an approximate 63 percent reduction) in the web between PPG 7 and the dome flank to predict the onset of salt dilation at the cavern surface along the west side of the cavern before excavating the rock fall region, as illustrated in Figure 4. The resulting model-predicted dilation FS values in the web between PPG 7 and the dome flank range from approximately 1.0 to 2.5 (i.e., before excavating the larger cavern volume in the model) with the cavern assumed to be brine-filled and minimal wellhead pressure. The model-predicted stress states in January 2024 (i.e., after excavating the larger, present-day cavern volume in the model), with the cavern brine-filled and approximately 90 pounds per square inch (psi) wellhead pressure, were post-analyzed using the estimated in situ dilation strength in the web and the original salt strength elsewhere. The modeling indicates that the dilation FS values are slightly improved compared to the pre-rockfall conditions, and the FS values in the web in January 2024 range between approximately 1.0 and 3.0. The dilation FS values improved slightly, partly because of the increased wellhead pressure and because salt creep tends to redistribute shear stress over time, resulting in higher dilation FS values near the cavern.

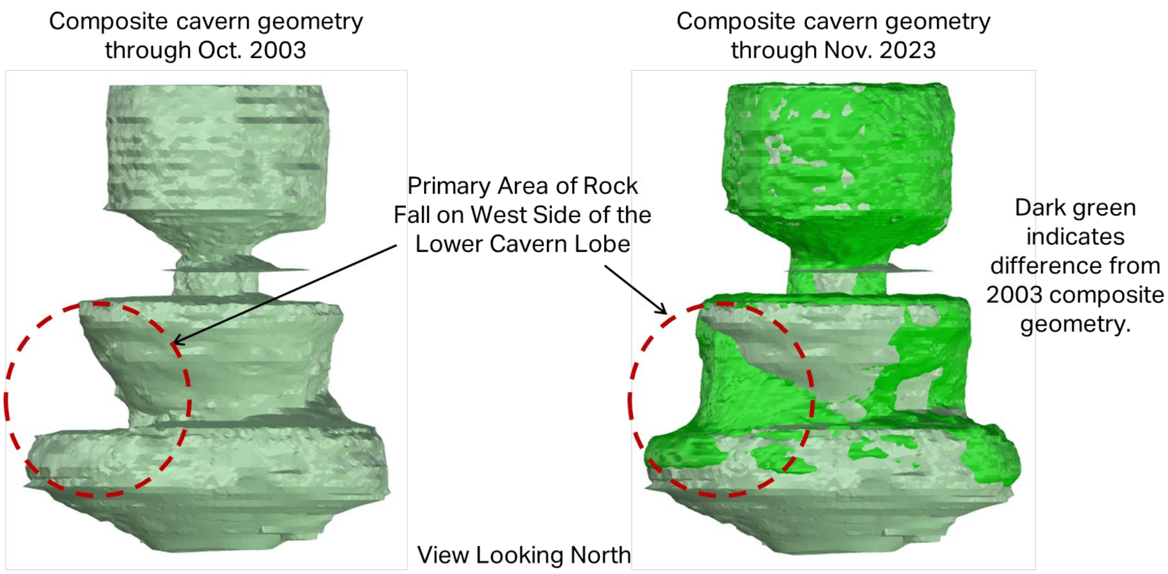

Figure 3. Illustration of the Composite Cavern Geometries for PPG 7 Showing the Area of Rock Fall on the West Side of the Lower Cavern Lobe.

WEAK LAYER AT THE DOME FLANK

In Phase 1 of the geomechanical study, the salt stock was assumed to be perfectly bonded to the adjacent nonsalt rock formations—a typical modeling approach for geomechanical assessments of caverns in salt domes. In Phase 2, a hypothetical scenario of a very weak layer between the salt stock and adjacent nonsalt formations was evaluated to assess the potential impact on the stresses in the salt web between PPG 7 and the dome flank. An iteration of the 3D model included a thin layer of material along the dome flank near PPG 7 that was assumed to be a cohesionless material with no tensile strength. The modeling indicates that a weak layer of material at the dome flank has a negligible effect on the model-predicted stress states in the salt web between PPG 7 and the dome flank, with no observable difference in the predicted dilation FS values.

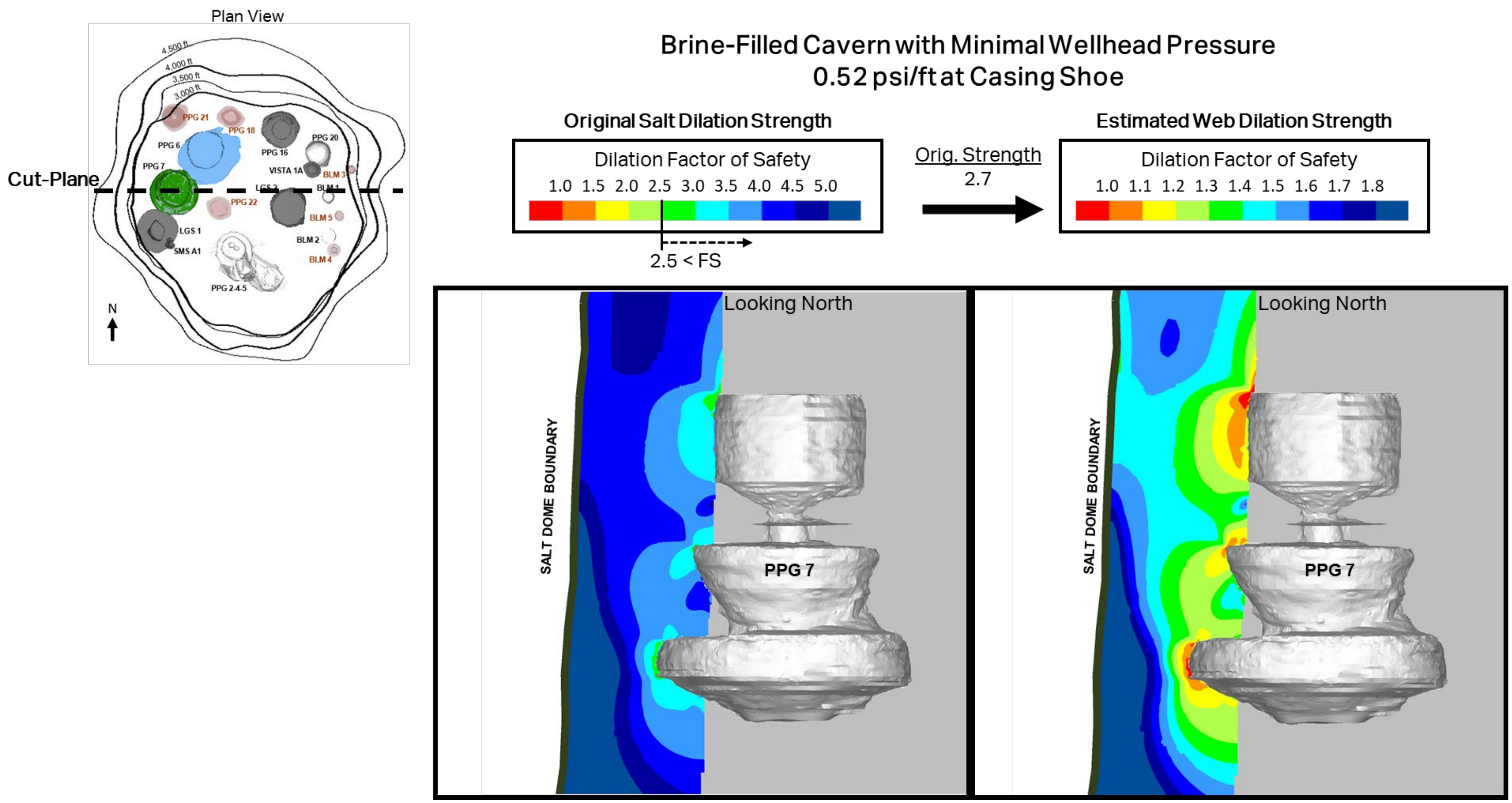

Figure 4. Contours of Salt Dilation Factors of Safety for the Original Salt Dilation Strength and the Estimated In Situ Salt Dilation Strength in the web Between PPG 7 and the Dome Flank.

STIFF CAPROCK OVERLYING THE SALT DOME

The caprock overlying the Sulphur Mines salt dome was assumed to have low mechanical stiffness and minimal strength because of the history of extensive sulphur mining in the caprock in the Phase 1 modeling. Typically caprocks overlying salt domes exhibit significant faulting resulting from the diapirism (i.e., uplift) during dome formation. The presence of a massive caprock with high stiffness overlying the salt dome has the potential to affect the predicted stresses near salt caverns within the dome because the caprock can bridge the overburden load across the dome, effectively reducing the overburden load seen by the caverns. Additionally, a competent caprock with high stiffness can absorb the shear stress that the salt creep will tend to redistribute away from the caverns.

To assess the hypothetical scenario of a stiff caprock overlying the Sulphur Mines Dome, an iteration of the 3D model was used. The caprock was assumed to have a stiffness of 8.7E+06 psi (60 GPa), which is typical of massive anhydrite caprock in the Gulf Coast. The modeling indicates that a hypothetically stiff caprock overlying the salt dome has a small effect on the model-predicted stresses near PPG 7. The hypothetically stiff caprock slightly improves the dilation FS values predicted around PPG 7 but is not significant enough to alter the conclusions of this study. Therefore, assuming the caprock has low stiffness provides a conservative assessment of the stability of the caverns PPG 6 and PPG 7.

EDGE ANOMALOUS ZONE WITH SLOWER CREEPING SALT

The steady-state creep deformation of the Sulphur Mines salt was modeled based on RESPEC's testing of salt core recovered from Well PPG 22 [Arnold, 2015]. The modeled steady-state creep rate of the Sulphur Mines salt is comparable to the steady-state creep rate of soft salt [Munson, 1998], which is considered a relatively faster-creeping salt, as illustrated in Figure 5. Also shown in Figure 5 is the steady-state creep rate of hard salt, which is considered a relatively slower creeping salt. In evaluating the potential effects of a hypothetical EAZ with slower creeping salt between PPG 7 and the dome flank, the salt in the EAZ was assumed to have a creep rate comparable to hard salt. The steady-state creep rate of hard salt is approximately one order of magnitude less than the Sulphur Mines salt, based on the PPG 22 salt core testing.

An iteration of the 3D model was used to assess the effects of a hypothetical EAZ, assuming 300 feet (ft) of salt from the dome boundary exhibits a steady-state creep rate similar to hard salt. The modeling indicates that a slower creep rate in the EAZ has an appreciable effect on the model-predicted stress in the salt web between PPG 7 and the dome flank, resulting in slightly lower dilation FS values in the salt web. The modeling indicates areas of dilating salt at the cavern surface along the west side of the cavern (i.e., within the 300-ft EAZ) and FS values less than 2.0 through the web between PPG 7 and the dome flank, assuming the estimated in situ dilation strength for the salt within the EAZ. This analysis assumes the salt in the web has a slower creep rate, but the creep rate of the salt in an EAZ could potentially be higher than soft salt (i.e, faster creep rate), which would generally improve the dilation FS values throughout the web.

DEPLETED RESERVOIR NEXT TO THE DOME FLANK

An iteration of the 3D model was used to evaluate the effects of a hypothetical depleted reservoir next to the salt dome. The complex geologic structure and faulting expected near the flank of the salt dome are not well defined and not represented in this analysis. A simplified representation of a hypothetical reduction in pore pressure within an adjacent reservoir was used in the 3D model to approximate the effect on the stress state in the salt web between PPG 7 and the dome flank.

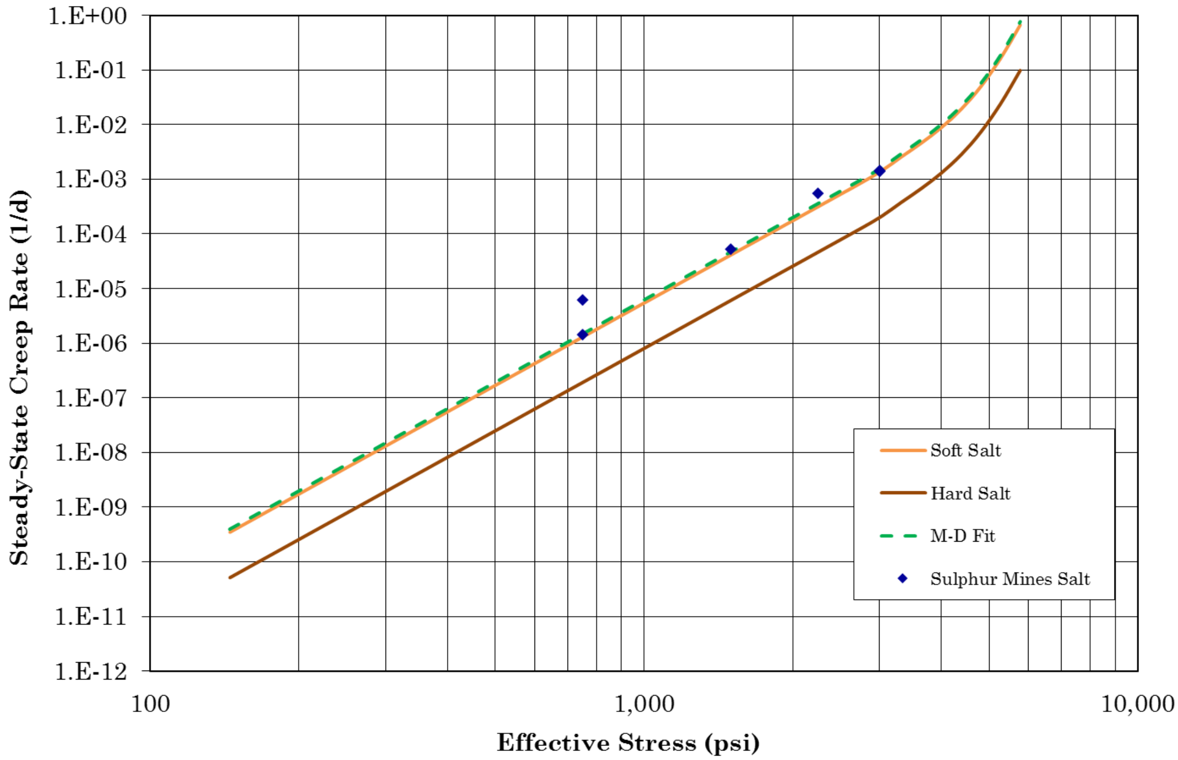

Figure 5. Steady-State Creep Model Fit to the Laboratory Tests of Salt Core From Well PPG 22 Compared to Soft Salt and Hard Salt.

The hypothetical reservoir was assumed to be located within the depth interval from 3,000 ft to 3,200 ft. The reservoir's lateral extent was assumed to extend approximately 2,000 ft to the west from the dome flank. The initial pore pressure in the reservoir was assumed to be approximately 0.70 psi/ft of depth at the top of the reservoir, and the pore pressure was assumed to reduce to approximately 0.465 psi/ft of depth. The pore pressure in the reservoir was assumed to remain constant at 0.465 psi/ft and not repressurized. The pressure reduction in the reservoir was conservatively assumed to occur very rapidly, and the elastic response of the host rock was considered for this analysis to provide a high-level assessment of the potential impacts on the salt web. The horizontal stresses within the reservoir were assumed to be reduced by approximately two-thirds of the pore pressure change [Zoback, 2007]. The 3D model was used to assess the impact of the reservoir pressure change on the stress state in the salt web and evaluate how the stress state in the web changed over time with salt creep deformation.

The analysis indicates that a rapid pressure change in a hypothetical reservoir next to the salt dome can have a significant effect on the stress state in the salt web between PPG 7 and the dome flank. The modeling also indicates that salt creep will redistribute the shear stress in the web to a state similar to the conditions before the pressure change after approximately 10–20 years. The modeling suggests that the magnitude of the pressure change and the rate of pressure change are significant factors in determining the magnitude of the impact on the salt web. Furthermore, the timing of the pressure change relative to the development of the cavern can also be a significant contributing factor. Gradual pressure changes in an adjacent reservoir are expected to have a lesser impact on the salt web, and years between reservoir depletion and cavern development are expected to reduce the potential impacts on the salt web.

SUMMARY AND CONCLUSIONS

The 3D geomechanical model of the Sulphur Mines salt dome was updated in Phase 2 to include updated salt and caprock contour maps and the available historical sonar surveys for PPG 6 and PPG 7. The 3D model was used to estimate the in situ dilation strength of the salt web between PPG 7 and the dome flank based on the historical sonar surveys from PPG 7. The salt web's estimated in situ dilation strength is approximately 37 percent of the original salt dilation strength based on approximating the rock falls indicated by the historical sonar surveys in the model. Considering the potential for heterogeneity of the lithology in the web between PPG 7 and the dome flank and the likelihood of structural features along the dome flank, the estimate of the in situ salt strength in the web is considered a reasonable approximation based on the available data.

Several modeling parameters were evaluated in Phase 2 to assess their potential impact on the stresses predicted near the Westlake caverns PPG 6 and PPG 7. The presence of a hypothetical weak layer of material between the salt stock and the adjacent nonsalt formations was found to have a negligible effect on the stress state in the salt web between PPG 7 and the dome flank. The modeling suggests that the stiffness of the caprock overlying the salt dome can have a small effect on the stresses predicted around the caverns. Assuming the caprock has a low stiffness results in slightly lower dilation FS values predicted near PPG 7, providing a more conservative assessment of the caverns' stability.

The presence of a hypothetical 300-ft EAZ with a steady-state creep rate approximately one order of magnitude slower than the creep rate determined from the laboratory tests of salt core from Well PPG 22 is predicted to decrease the dilation FS values in the salt web between PPG 7 and the dome flank. Alternatively, if the salt in the web between PPG 7 and the dome flank has a faster steady-state creep rate compared to the rest of the salt dome, the dilation FS values would generally increase for a given cavern pressure and dilation strength.

A simplified analysis of a hypothetical depleted reservoir next to the dome flank suggests that a rapid pore pressure drop from approximately 0.70 psi/ft to 0.465 psi/ft could significantly affect the salt web between PPG 7 and the dome flank. This analysis did not include the complex geologic structure next to the salt dome, which likely includes numerous radial faults from the diapirism of the dome. The magnitude of a pressure change, the rate of pressure change, and the timing of the reservoir depletion relative to the cavern development in the salt dome are likely strong contributing factors that can affect the reservoir's impact on the salt web.

Based on the Phase 2 modeling and analysis results, RESPEC recommends proceeding with Phase 3 of the geomechanical study, using the estimated in situ salt dilation strength for the web between PPG 7 and the dome flank to evaluate the salt web stability. RESPEC recommends that the modeling employ assumptions for a caprock with low stiffness and the absence of a weak layer of material between the salt stock and the adjacent nonsalt formations. RESPEC considers the creep testing of salt core recovered from Well PPG 22 constitutes the best available data to date for defining a creep model of the Sulphur Mines salt. In lieu of data to better estimate the salt creep behavior of the salt near the dome boundary, whether it is faster or slower compared to the current creep model, we recommend the original salt creep model be used in subsequent modeling efforts.

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