SOLUTION MINING RESEARCH INSTITUTE
679 Plank Road
Clifton Park, NY 12065, USA

Telephone: +1 518-579-6587
www.solutionmining.org

Technical Conference Paper

Assessment of Cavern Stability:

Cavern Clusters vs Single Cavern

Benoit Brouard & Vassily Zakharov, Brouard Consulting, Paris, France

Pierre Bérest, Ecole Polytechnique, Palaiseau, France

SMRI Spring 2021 Virtual Technical Conference
19-22 APRIL 2021

Solution Mining Research Institute Spring 2021 Virtual Technical Conference

19-22 APRIL 2021

ASSESSMENT OF CAVERN STABILITY: CAVERN CLUSTERS VS SINGLE CAVERN

Benoit Brouard and Vassily Zakharov

Brouard Consulting, Paris, France

Pierre Bérest

Ecole Polytechnique, Palaiseau, France

Abstract

A lot of work has been dedicated to the mechanical behavior of a single salt cavern. Cavern clusters raise a more difficult problem, as 3-D numerical computations are required. The behavior of the salt pillar between neighboring caverns is an important issue in this context. The elastic theory predicts that the vertical load on the pillar is significantly larger when the distance between neighboring caverns is smaller. In some cases, the pillars cannot bear the load excess generated by a high extraction ratio, as proved by several examples of mine collapses (Minkley et al., 1996). When the mechanical behavior of the rock mass is viscoplastic, a significant part of the load excess is transferred to the abutment; i.e., outside the footprint of the cavern cluster (Bérest et al., 2008). The state of stresses in the pillars is less critical than in the elastic case. However, creep closure and subsidence rates often are faster than in single caverns. Through numerical computations, the paper will discuss the mechanical stability of a cluster of caverns. Several aspects are considered as vertical-stress distribution, creep-closure rate, and possible onset of dilation.

Key words: Cavern Design, Computer Modeling, Rock Mechanics

1. Introduction

Salt mechanical behavior exhibits several paradoxical features. One example of this is the ability of salt, in some geometrical configurations, to transfer high deviatoric stresses from heavily loaded areas to areas where deviatoric stresses are smaller, a phenomenon which cannot exist, for instance, when rock behavior is elastic. This is true in a cavern: deviatoric stresses at cavern wall are larger immediately after the mining phase than they will be later after the cavern has been kept idle at constant pressure for a While. The same is observed in a room and pillar mine (Bérest et al., 2008), where the load by individual pillars tend to decrease with time before reaching a stationary value. In this paper, it is show that a somewhat comparable analysis can be made in the case of a cavern cluster. Usual criteria such that dilation criterion or creep closure rate are less relevant than on the case of a single cavern and a new approach, still to be defined, must be used.

2. Simple cluster model

Let's consider a cluster of 4 caverns as shown in Figures 1 to 4. Caverns are considered cylindrical and vertical at an average depth of $Z_c = 1000$ m (3280 ft). The volume of each cavern is approximately 500,000 m^3 (3.14 MMbbls). The model is composed of a homogeneous overburden layer and a $H_s = 620$ m (2034 ft) thick salt layer. The top of salt if located at an $H_0 = 880\ \mathrm{m}$ (2887 ft) depth. Other dimensions of the model are given in Table 1.

Extraction ratio

The extraction ratio is defined in Figure 4.

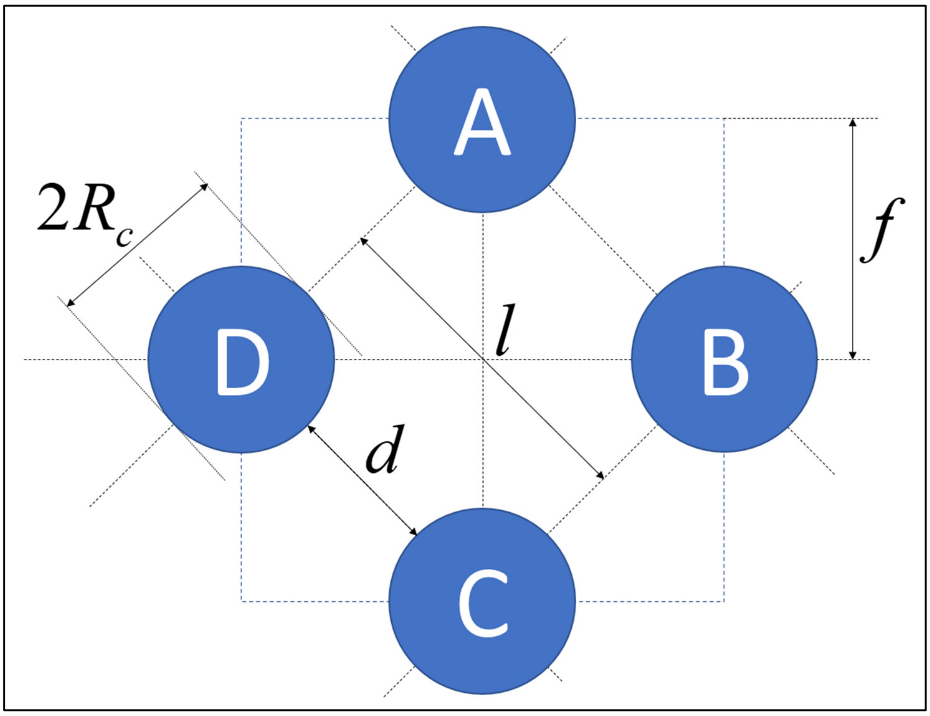


Figure 1. Model overview in the vicinity of caverns (case extraction ratio = 0.2).

Table 1. Caverns and model dimensions.

Dimension	Value (metric)	Value (imperial)
$L = L_x = L_y$	4000 m	13,124 ft
H	1500 m	4921 ft
H_o	880 m	2887 ft
Z_c	1000 m	3281 ft
R_c	35 m	115 ft
$H_c = 4 \times R_c$	140 m	459 ft
$r_c = R_c/3$	11.7 m	38.4 ft
$h_c = R_c \times 10/3$	116.7 m	383 ft

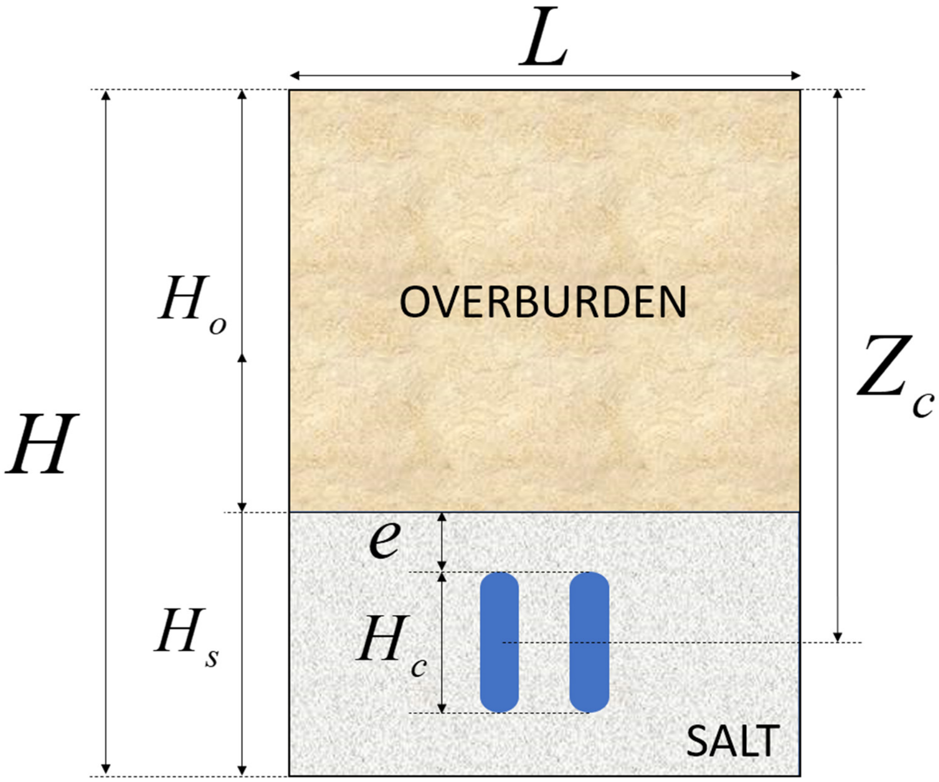


Figure 2. Model side view.

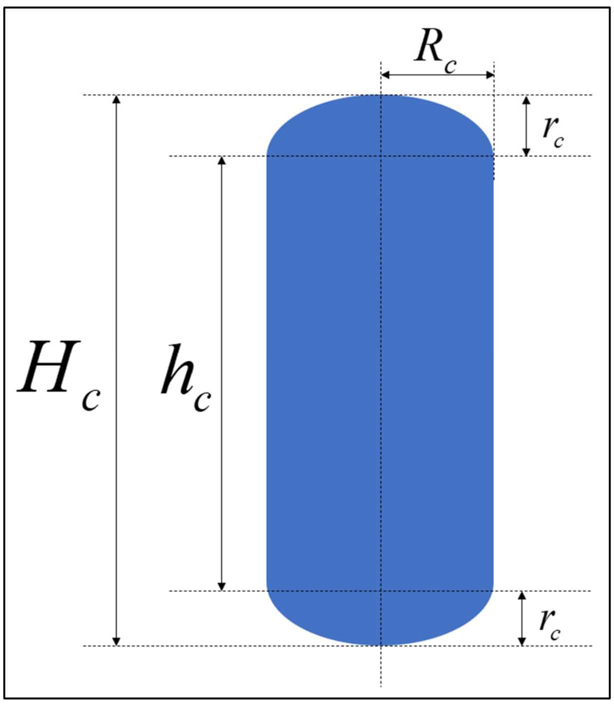


Figure 3. Considered caverns shape.

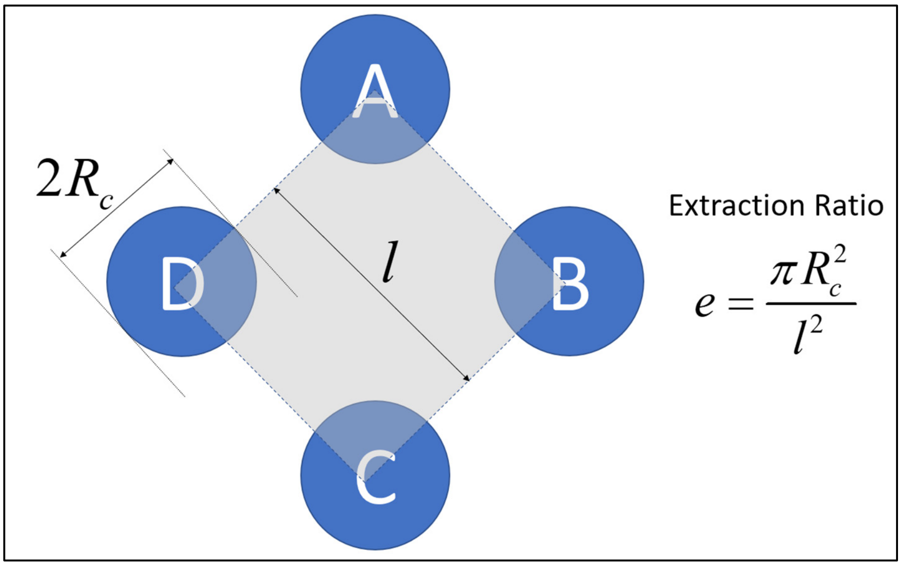


Figure 4. Definition of the extraction ratio (case extraction ratio = 0.2).

4. Computation cases

The considered computation cases for a simple cluster composed of 4 caverns are given in Table 2. In cases A, B and C rock salt mechanical behavior is considered as elastic; in cases #1 to #9, it is elasto-visco-plastic; i.e., creepy. Three extraction ratios are considered: $e = 20\%$, 40% and 60%. In the last case, the minimal distance between caverns is only $d = 10$ m (33 ft).

It is assumed that the four caverns of the cluster are mined simultaneously. Three mining durations are considered: 2 years, 5 years and 7.5 years.

Table 2. Considered configurations for a simple cluster of 4 caverns.

Case	Dimensions (m)		Extraction ratio			Mining Duration (years)			Elasticity	Creep
	l	*d*	20%	40%	60%	2	5	7.5		
A	140	70	×						×	
#1	140	70	×			×				×
#2	140	70	×				×			×
#3	140	70	×					×		×
B	98	28		×					×	
#4	98	28		×		×				×
#5	98	28		×			×			×
#6	98	28		×				×		×
C	80	10			×				×	
#7	80	10			×	×				×
#8	80	10			×		×			×
#9	80	10			×			×		×

5. Mechanical parameters

The overburden layer is assumed to be elastic. The Norton-Hoff creep law is assumed for rock salt, it states that the creep rate is a non-linear function of the deviatoric stress σ as follows:

$$\dot{\varepsilon} = A \exp\left(-Q/RT\right)\sigma^{n} \quad (1.1)$$

The considered parameters for elasticity and creep are given in Table 3.

Table 3. Considered mechanical properties.

Rock	Density	Elastic parameters		Viscoplastic parameters		
		E (GPa)	ν	A (MPa^{-1}-yr)	n	Q/R (K)
Salt	2200	25	0.25	0.64	3.1	4100
Overburden	2200	15	0.25			

Thermoelasticity of rock salt is not considered in the following computations for simplification purpose.

6. Thermal parameters

The brine temperature in the caverns is assumed to slowly decrease during the mining period. The brine temperature is assumed to be 35 °C (95 °F) for a 2-year long mining duration, 30 °C (86 °F) for a 5-year long mining duration, and 25 °C (77 °F) for a 7.5-year long mining duration. Rock-salt natural temperature at cavern mid-depth (1000 m) is assumed to be 39 °C (102 °F).

7. Numerical model

The LOCAS 3D software developed by Brouard Consulting (Brouard et al., 2018, 2020) is used for the numerical computations. LOCAS is a large software suite that has been developed continuously for 20+ years, especially for the purpose of analyzing salt caverns behavior. LOCAS is able to couple cavern thermodynamics and rock-salt complex geomechanics properly. This is of upmost importance for problems such as gas-storage management, caverns stability analysis, subsidence calculation, or cavern-abandonment. LOCAS provides a very user-friendly interface, usable by non-experts, which allows input of field data and calculations parameters, and also a very powerful finite-element core for stability analysis of caverns in the short or long term. LOCAS has been designed for all type of salt caverns: for brine production, liquid storage or gas storage -including all type of gases.

Figure 5 shows the mesh designed for cases A and #1 to 3 (extraction ratio = 20%), the horizontal size of the meshed area is 4 km × 4 km (13,124 × 13,124 ft). The minimum distance between caverns A and B for the same extraction ratio is shown in Figure 6.

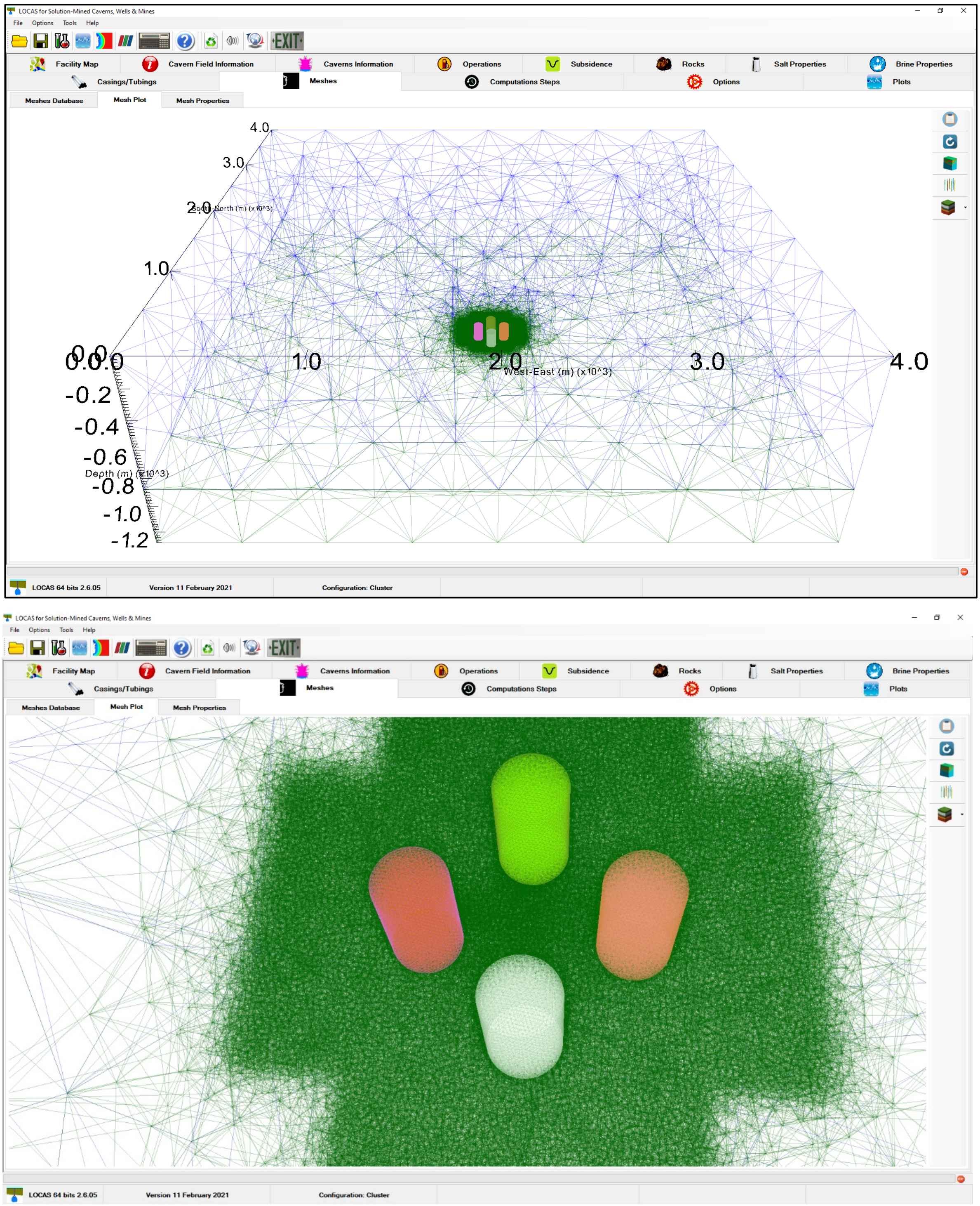


Figure 5. Example of 3D mesh as displayed in LOCAS software (case extraction ratio = 0.2).

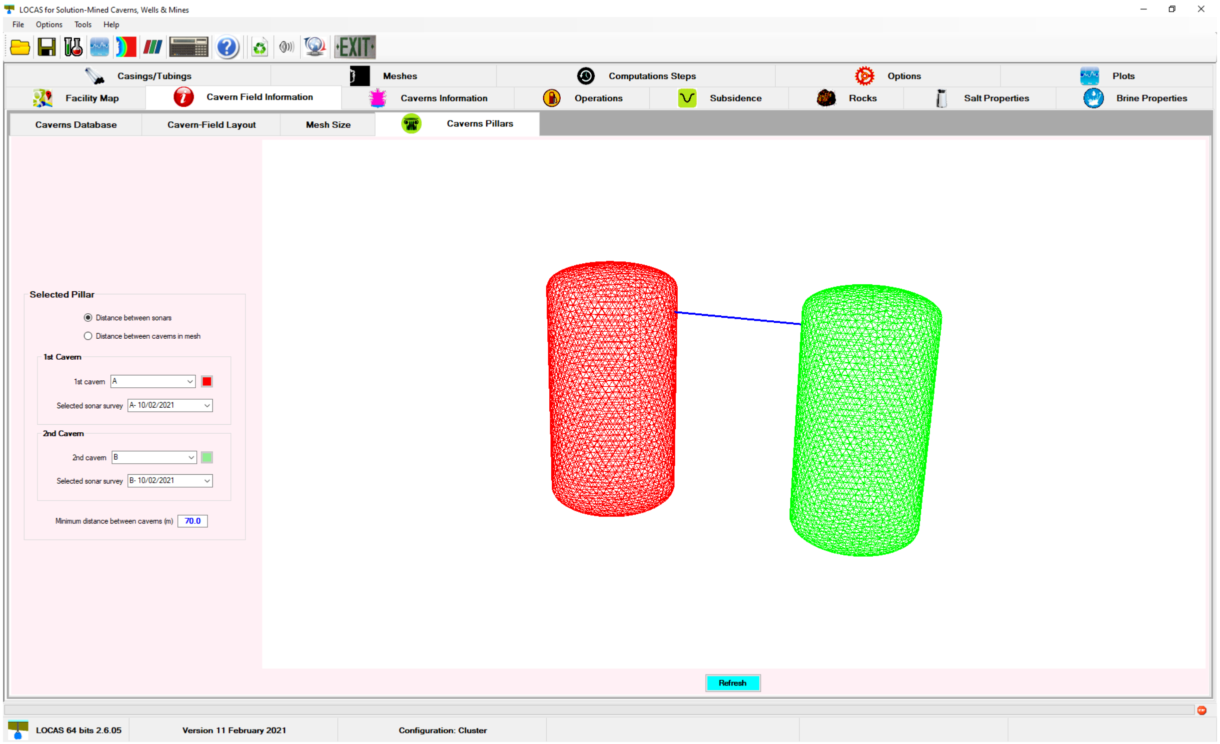


Figure 6. Minimum distance between caverns is 70 m (230 ft) in the case of an 0.2 extraction ratio.

8. Vertical stress in the middle of the pillar

The objective of this Section is to compare the behavior of an elastic (time independent) rock mass and a viscoplastic rock mass in which a cluster is mined.

Effect of extraction ratio, mining duration and time are detailed in the following figures. Distribution of vertical stress σ_{zz} along a vertical line in the center of the cluster (Point 0 in Figure 7) is plotted for all computation cases (see Table 2) in Figure 8 to Figure 10. The effects of extraction ratio, mining duration and time are discussed. When rock mass behavior is elastic (cases A, B, C) its elastic modulus is assumed to be the same (25 GPa, see Table 3).

On Figure 8, distribution of the vertical stress as a function of depth 20 years after mining started is represented. The dash line is the virgin vertical stress $\sigma_{zz}^{0}(z)$, which is 27 MPa (3915 psi) at a 1250-m depth (4100 ft) and 22 MPa (3200 psi) at cavern mean depth (1000 m or 3280 ft). On each of the three pictures, the elastic case (black line) is represented together with three viscoplastic cases which differ by the duration of the initial solution-mining phase (2, 5 and 7.5 years, respectively). From left to right, three extraction ratios (as defined on Figure 4) are considered: $e = 20\%$, 40% and 60%, respectively.

In the elastic case, as expected, the pillar is overstressed (the vertical load is larger than it was in the virgin state, $\sigma_{zz} > \sigma_{zz}^{0}$) and this is all the truer when the extraction ratio is larger. However, the classical tributary area formula, $\sigma_{zz} \approx \sigma_{zz}^{0} / (1-e)$ does not apply as, opposite to the case of a large room and pillar mine (in which horizontal dimensions are much larger than mine depth), a large part of the vertical load can be transferred to the abutment. In the elastic case, stability of the pillar can be discussed through a comparison between the actual vertical stress and rock strength.

In the viscoplastic case, the pillar at the center of the cluster is understressed and this is still truer when mining was completed earlier; i.e., when more time was left for stress redistribution in the rock mass. A large part of the vertical load above the cluster is transferred to the abutment. In fact, opposite to the elastic case, the larger the extraction ratio, the less compressive are vertical stresses in the pillar.

Effect of mining duration on the vertical stress distribution 20 years after the start of mining is shown in Figure 9.

In the case of a mining in 7.5 years, Figure 10 compares the vertical stress distribution as a function of time 9, 13.8 and 20 years after mining is completed. Similar figures are obtained when a shorter mining duration is considered. Shortly after the end of mining the vertical-stress distribution is close to the elastic one; later on, the load on the pillar is smaller and smaller. This effect is more pronounced when the extraction ratio is smaller. This Figure 10 illustrates the slow redistribution of stresses in the rock mass and, in particular, the progressive unloading of the central pillar which bears a smaller and smaller part of the load above the cluster (i.e., the overburden weight).

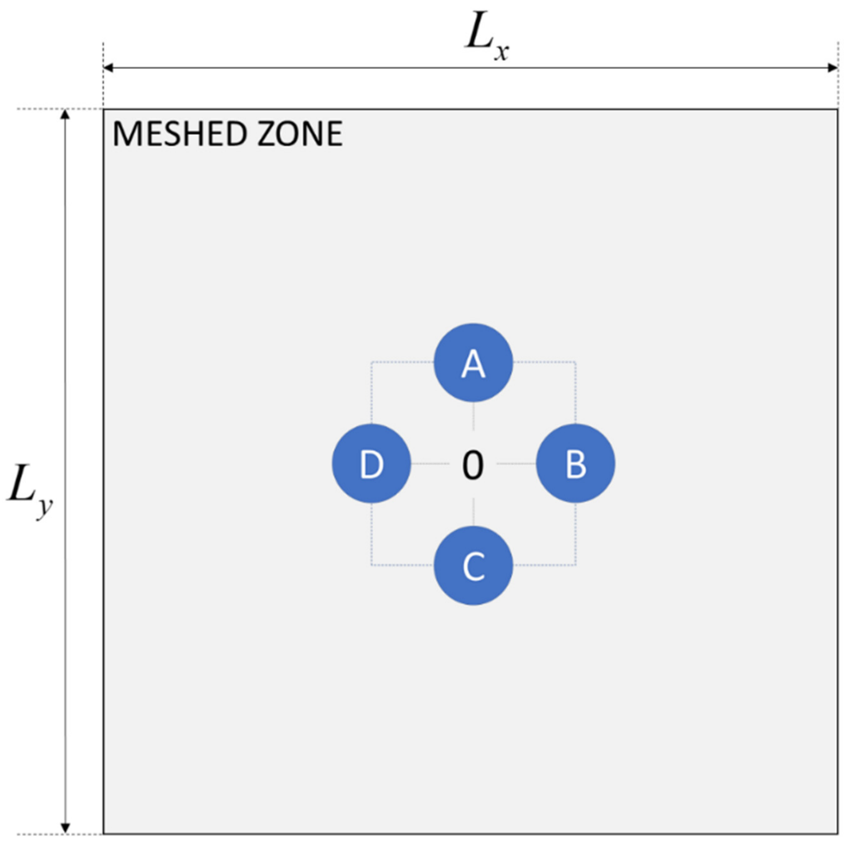
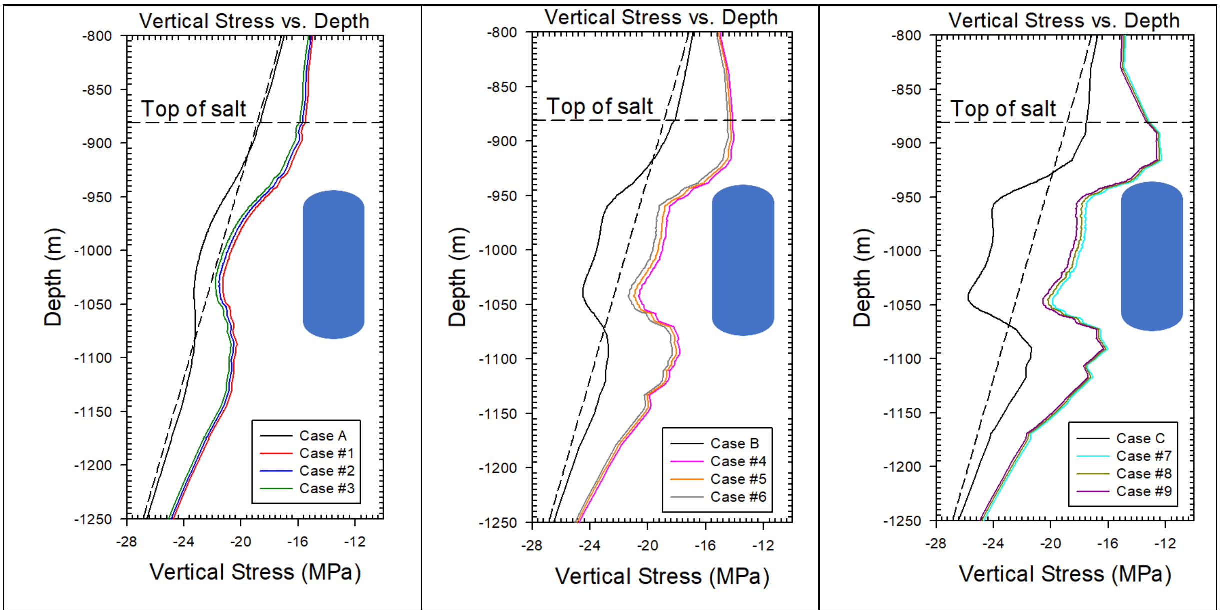
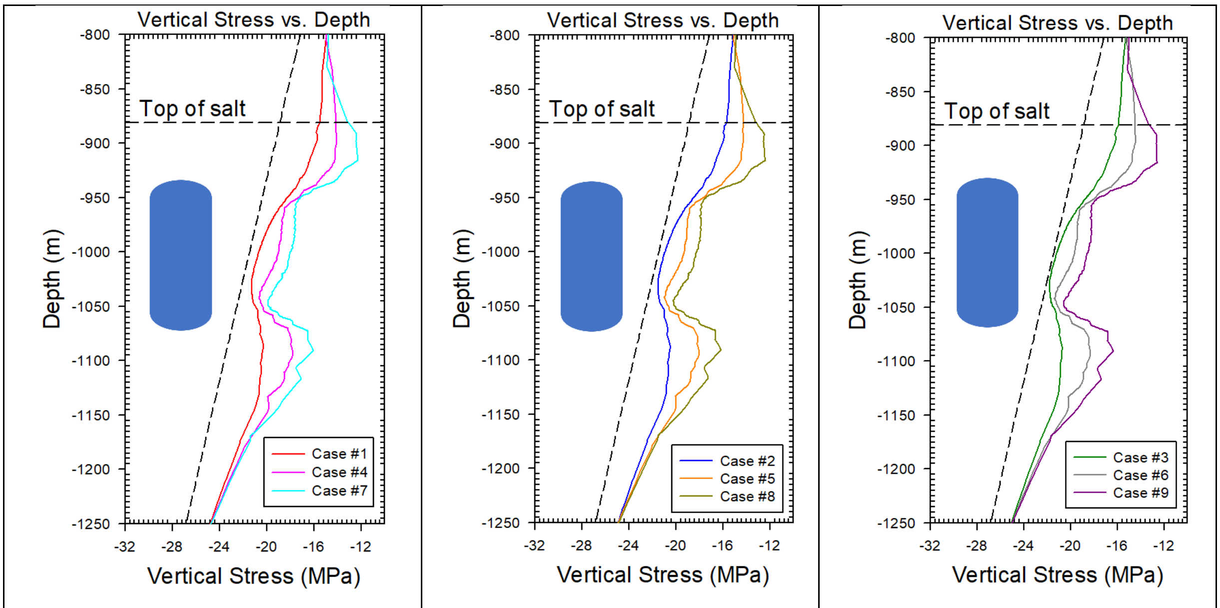


Figure 7. Model overview at mesh size.



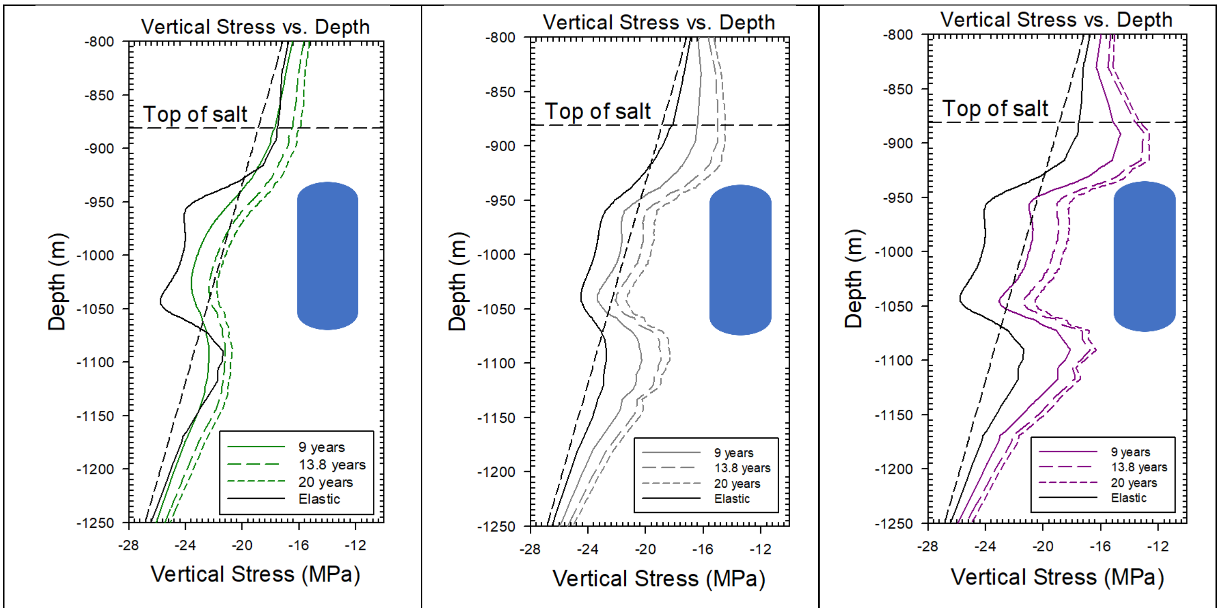
Extraction ratio = 0.2	Extraction ratio = 0.4	Extraction ratio = 0.6

Figure 8. Vertical distribution of vertical stress σ_{zz} in the center of the cluster 20 years after the start of mining, variation of the extraction ratio.



Mining in 2 years	Mining in 5 years	Mining in 7.5 years

Figure 9. Vertical distribution of vertical stress σ_{zz} in the center of the cluster 20 years after the start of mining, variation of the mining duration.



Case #3	Case #6	Case #9
Extraction ratio = 0.2	Extraction ratio = 0.4	Extraction ratio = 0.6

Figure 10. Evolution since start of mining of vertical distribution of vertical stress σ_{zz} in the center of the cluster, case of a mining in 7.5 years.

The same idea is represented in Figure 11 in which iso-contours of the vertical stress in the mid-depth (1000 m or 3280 ft) horizontal plane are represented. Two years after the end of leaching (Year 4) the central pillar is overloaded (the vertical stress is larger than the virgin stress). Sixteen years later, a large part of this overstress has been transferred outside the footprint of the cluster.

Note that, the vertical stress is especially low at the cavern wall.

In Figure 12, the extraction ratio is larger ($e =$ 40% instead of 20%) and the transfer of the vertical load to the abutment is still faster.

This notion is confirmed in Figure 13 (extraction ratio is 60%).

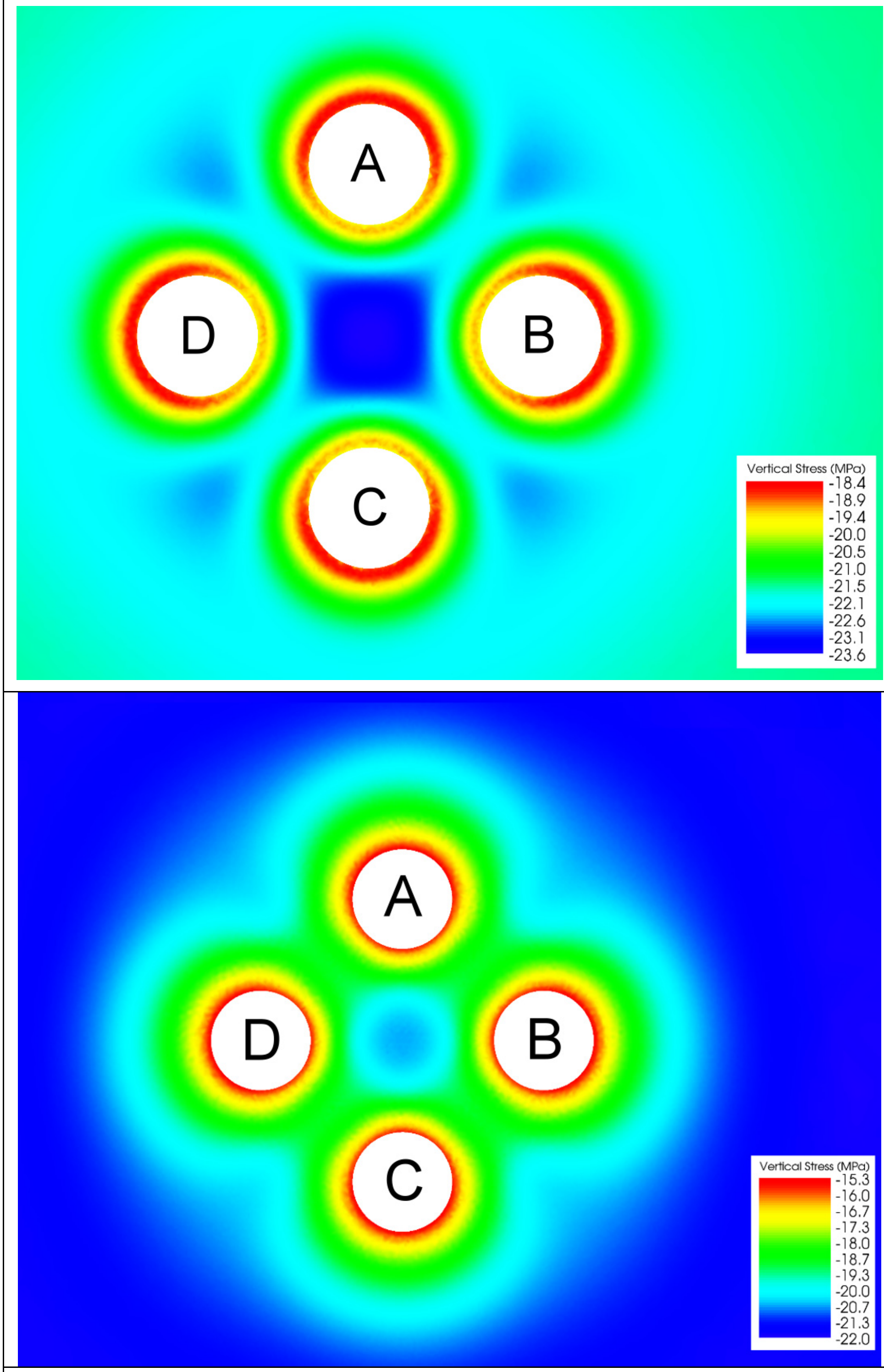


Figure 11. Case #1 – e = 20% – Vertical stress σ_{zz} contours at cavern mid-depth 4 years (top) and 20 years (bottom) after the start of mining.

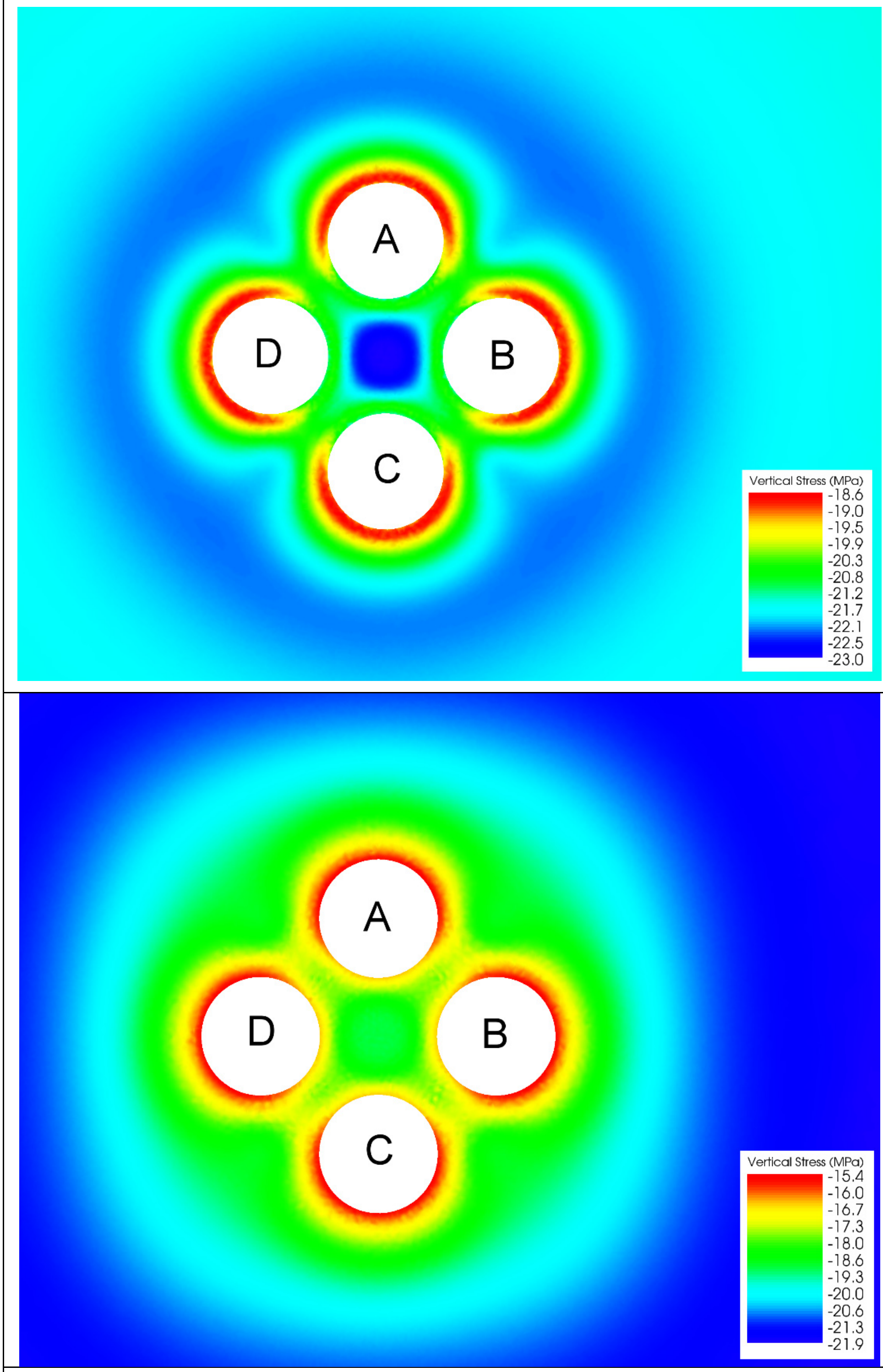


Figure 12. Case #4 – e = 40% – Vertical stress σ_{zz} contours at cavern mid-depth 4 years (top) and 20 years (bottom) after the start of mining.

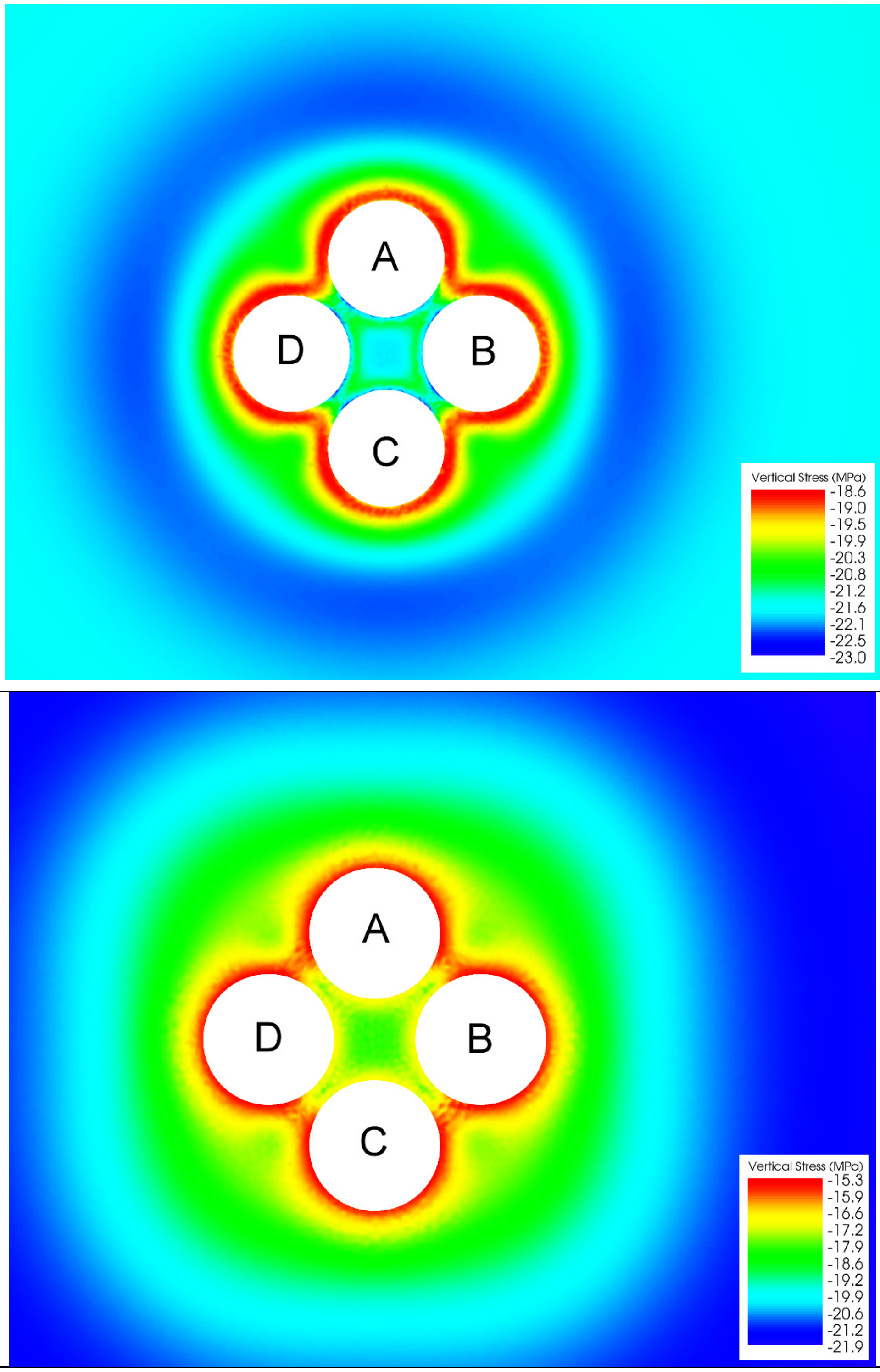
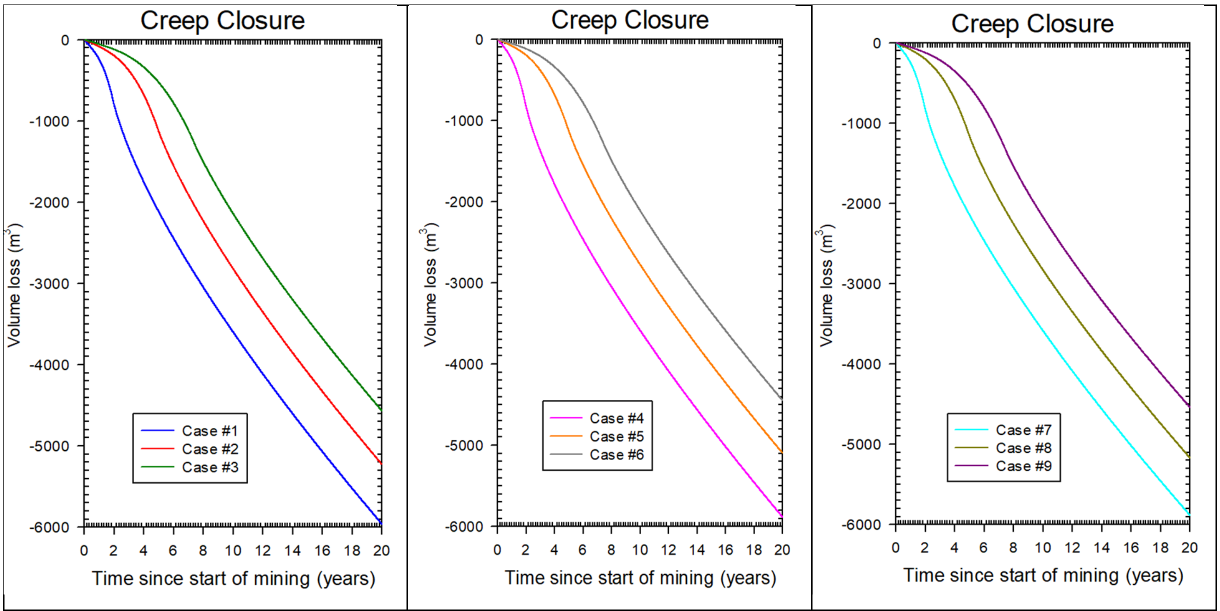


Figure 13. Case #7 – e = 60% – Vertical stress σ_{zz} contours at cavern mid-depth 4 years (top) and 20 years (bottom) after the start of mining.

9. Creep Closure

Figure 14 shows that creep closure after 20 years does not depend much on the extraction ratio in the case of a simple cluster composed of 4 caverns.



Extraction ratio = 0.2	Extraction ratio = 0.4	Extraction ratio = 0.6

Figure 14. Evolution of creep closure.

10. Onset of salt dilation

An irreversible increase in salt volume can occur under certain compressive stress states. This volume increase is due to micro-fracturing in the salt, a phenomenon called dilation. Salt dilation must be avoided, as it may cause an increase in salt permeability and a reduction in salt strength. The RESPEC/DeVries or RD dilation criterion (DeVries et al., 2003), was considered for this study:

$$\sqrt{J_2}_{\,dil} = \frac{D_1\left(\dfrac{I_1}{sign(I_1)\sigma_0}\right)^{\bar{m}} + T_0}{\left(\sqrt{3}\cos\psi - D_2\sin\psi\right)} \tag{2}$$

where $I_1 < 0$ is equal to three times the mean stress ($I_1 = 3\sigma_m$), and J_2 are the first and second invariants of the stress tensor. Salt parameters D_1, D_2, and m can be determined from laboratory tests. The lode angle (ψ) describes the relation between the principal stresses, and ranges between –30° and +30°. Dimensional constant σ_0 is equal to 1 MPa (145 psi), T_0 is the unconfined tensile strength, and $\bar{m}$, D_1, and D_2 are parameters that must be determined for each salt formation. The RD criterion can predict both linear and nonlinear relations for the dilation boundary in the $\sqrt{J_2}$ and I_1 stress spaces.

For all the considered dilation criteria, the **factor of safety** (FOS) is defined as

$$FOS = \sqrt{J_2}_{dil} / \sqrt{J_2} \qquad (3)$$

where $\sqrt{J_2}$ is the computed deviatoric stress, and $\sqrt{J_2}_{dil}$ is the value of the dilatant deviatoric stress. Dilation may develop when FOS < 1.

For the following computations, Moss Bluff salt parameters were selected (see Table 4 from Brouard Consulting & Respec, 2013). Dilation criterion in the space of stress invariants is shown in Figure 15.

Table 4. RESPEC/DeVries dilation criterion parameter values for Moss Bluff salt.

Parameter	US Units		SI Units	
	Value	Units	Value	Units
D_1	59.6	psi	0.411	MPa
D_2	0.664	–	0.664	–
$\overline{T}_0$	196	psi	1.351	MPa
m	0.85	–	0.85	–
σ_0	145	psi	1.000	MPa

Figure 16 to Figure 18 show vertical contours of dilation FOS for Case #1, Case #5 and Case #9 respectively. No dilation appears in the pillar or somewhere at cavern wall. The FOS tends to increase with time after the end of mining, so no onset of dilation is expected on the long term.

Horizontal stress in the pillar is in the order of magnitude of cavern pressure, or halmostatic pressure (12 MPa); vertical stress is smaller than geostatic pressure (22 MPa). Figure 15 shows that for this mean stress, $I_1/3 \approx (12+12+22)/3 \approx 15.3$ MPa, the onset of dilation is unlikely when Moss Bluff set of parameters is considered.

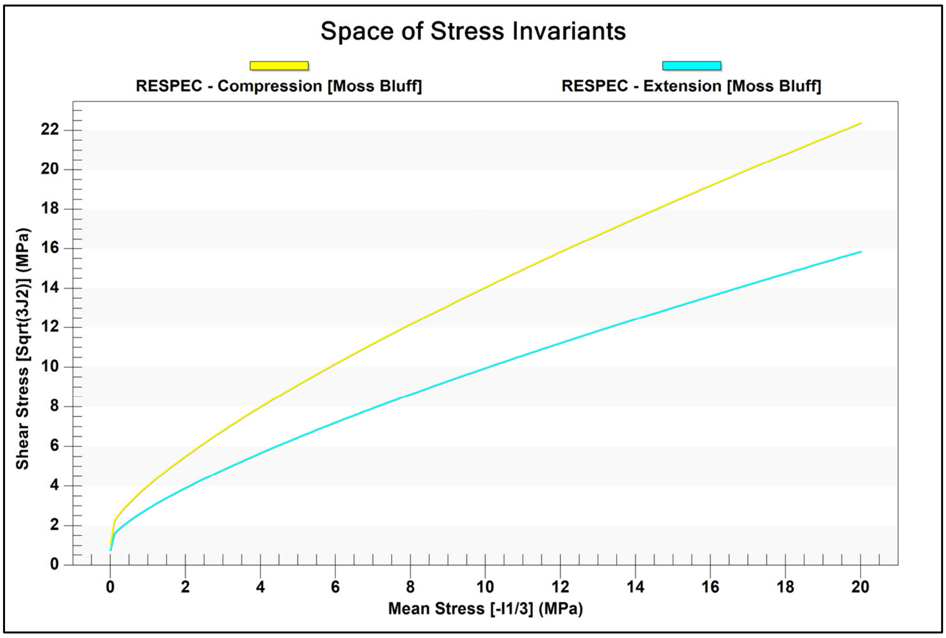


Figure 15. Space of stress invariants, Moss Bluff set of parameters for RD criterion.

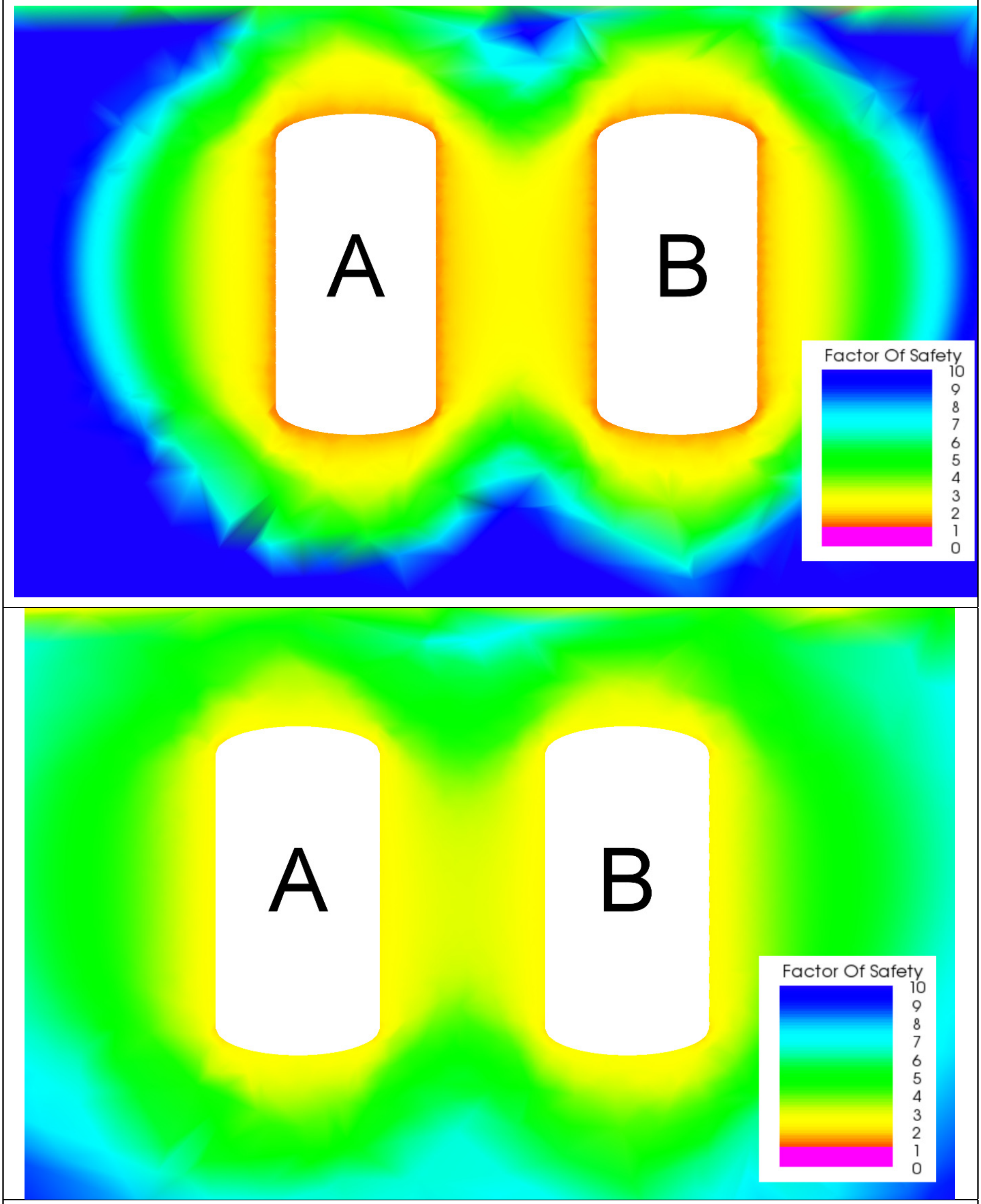


Figure 16. Case #1 – Dilation FOS contours 4 years (top) and 20 years (bottom) after the start of mining.

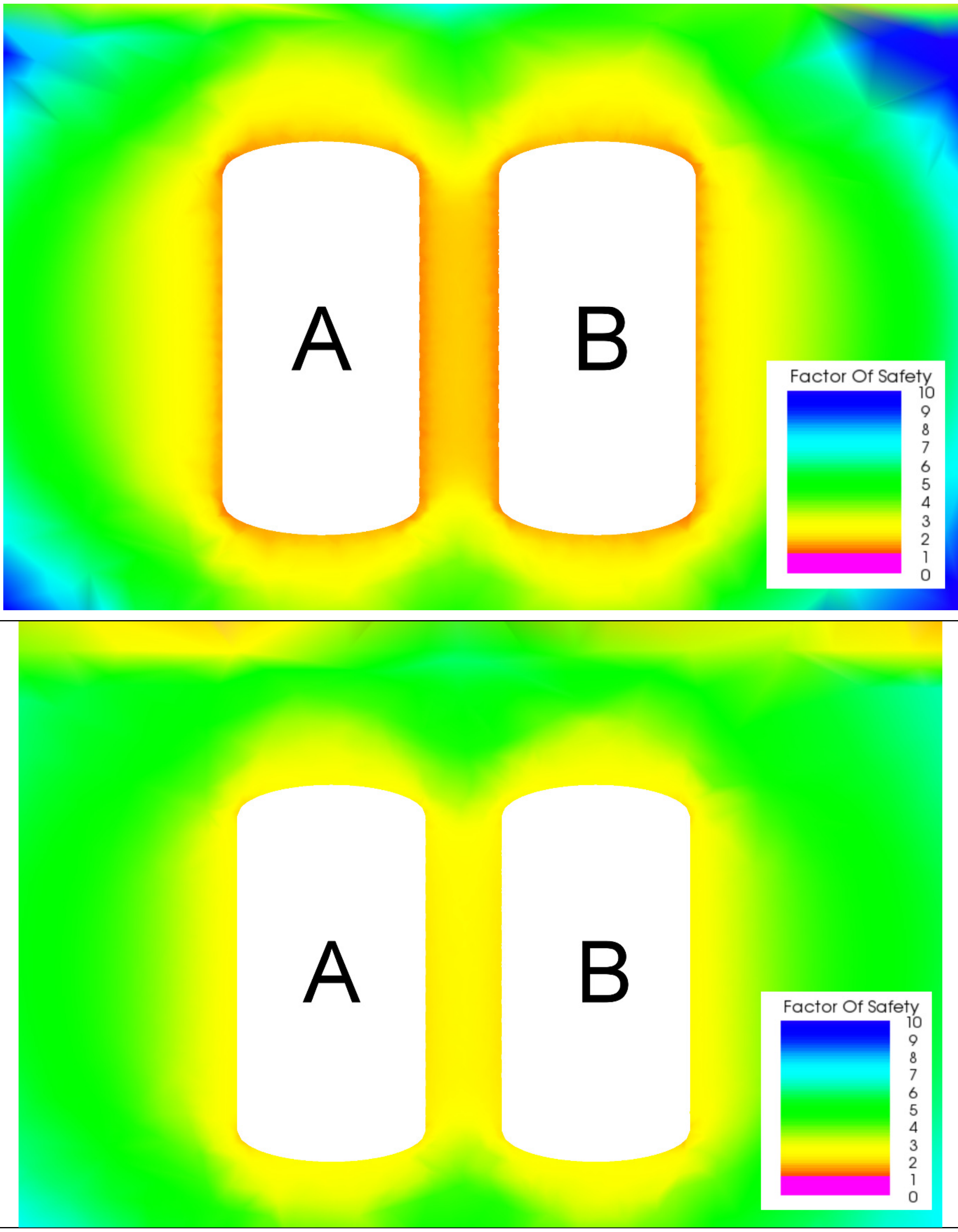


Figure 17. Case #5 – Dilation FOS contours 6.5 years (top) and 20 years (bottom) after the start of mining.

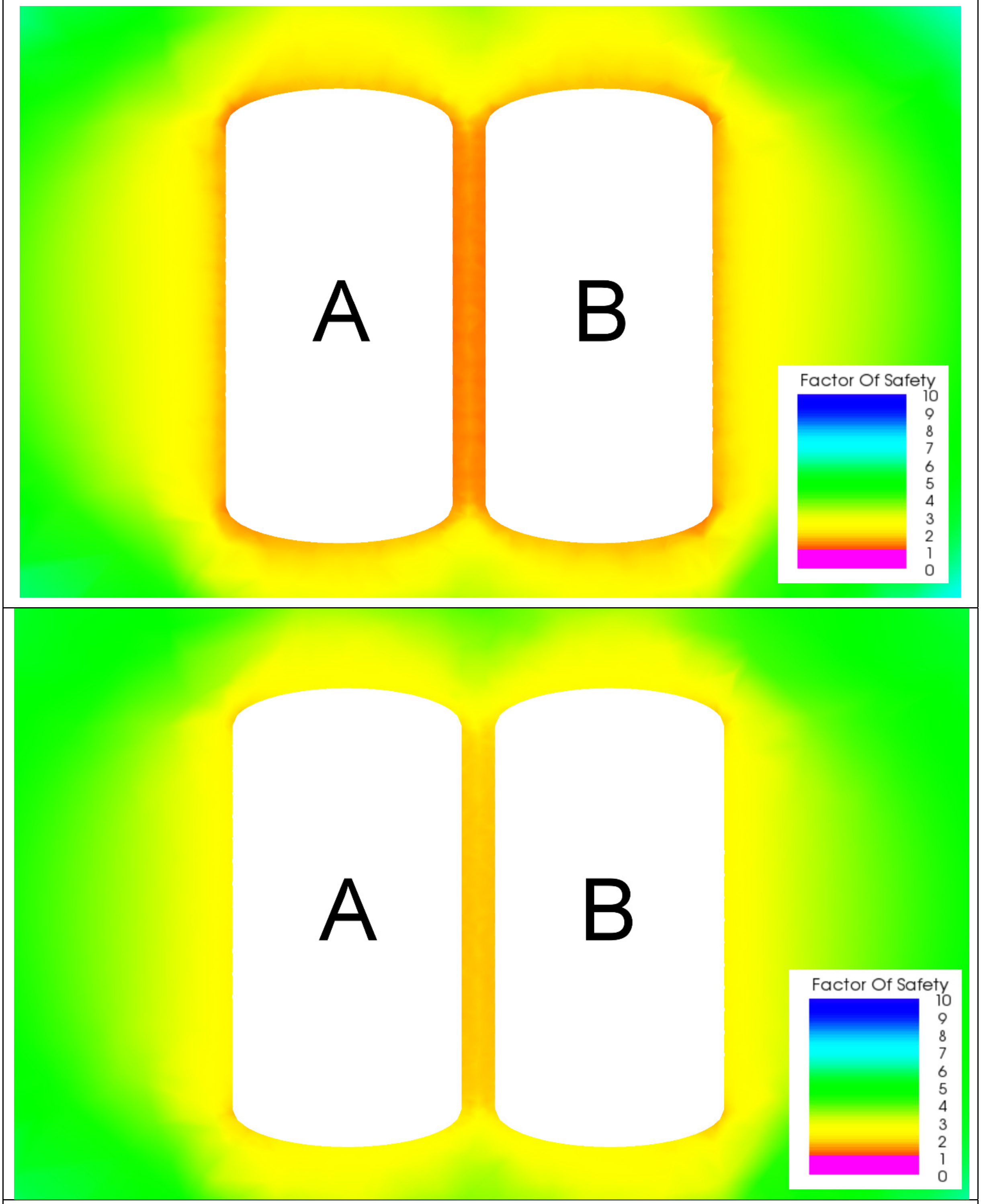


Figure 18. Case #9 – Dilation FOS contours 8.8 years (top) and 20 years (bottom) after the start of mining.

11. Cluster composed of 9 caverns

In the following a cluster composed of 9 caverns is considered (Figure 19).

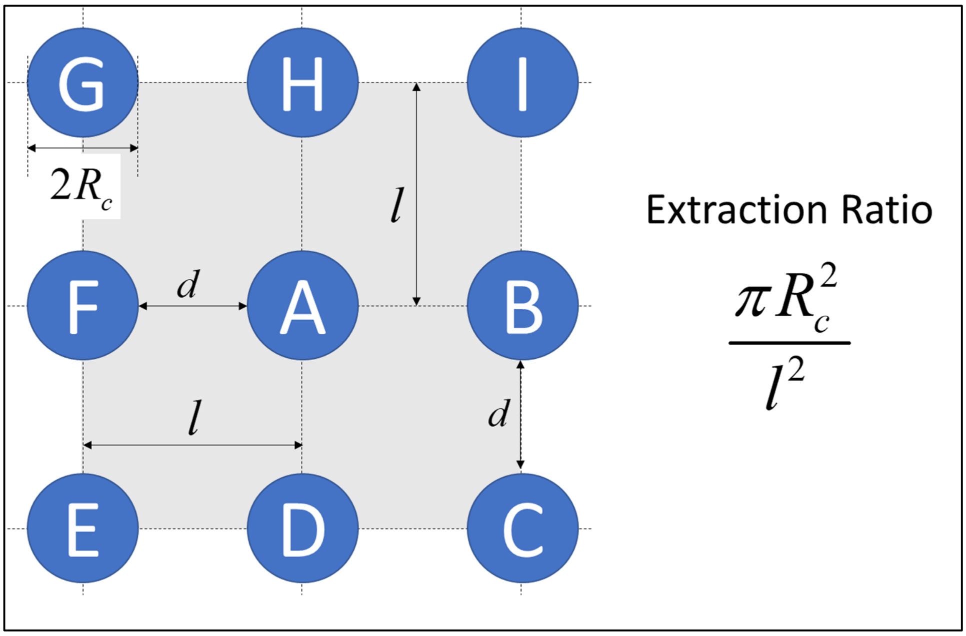


Figure 19. Cluster configuration with 9 caverns.

Table 5. Considered configurations for a cluster of 9 caverns.

Case	Dimensions (m)		Extraction ratio			Elasticity	Creep
	l	d	20%	40%	60%		
A'	140	70	×			×	
B'	98	28		×		×	
C'	80	10			×	×	
#1'	140	70	×				×
#4'	98	28		×			×
#7'	80	10			×		×

Figure 20. Case 1' – Horizontal cross section of vertical-stress contours 20 years after the start of mining.

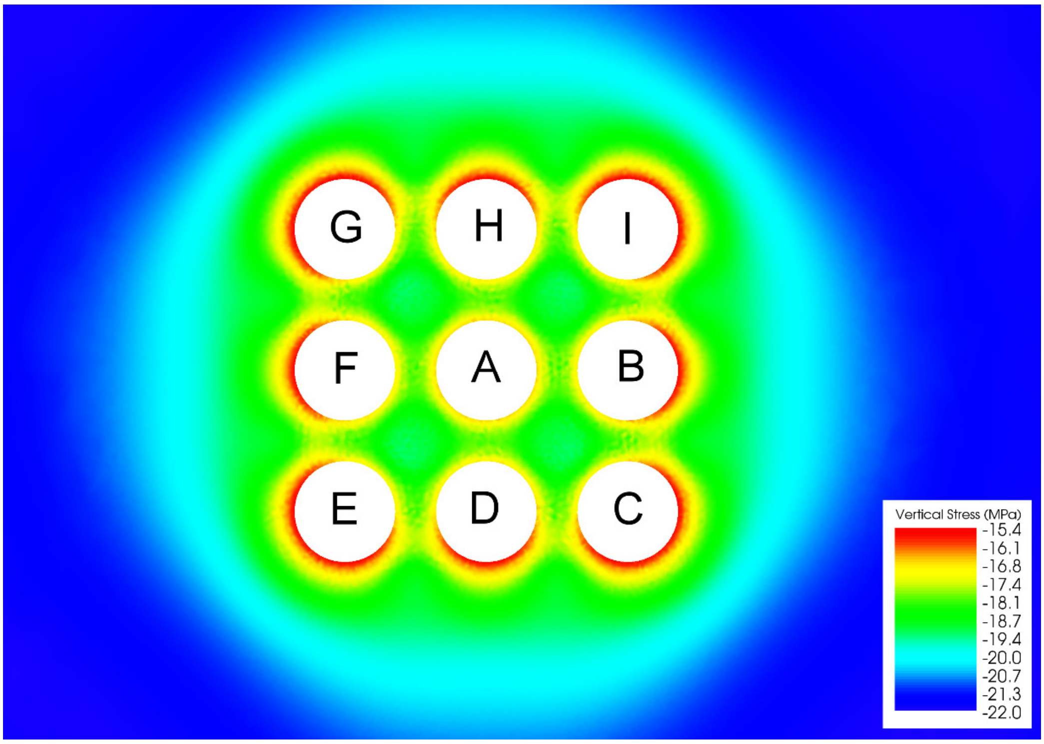


Figure 21. Case 4' – Horizontal cross section of vertical-stress contours 20 years after the start of mining.

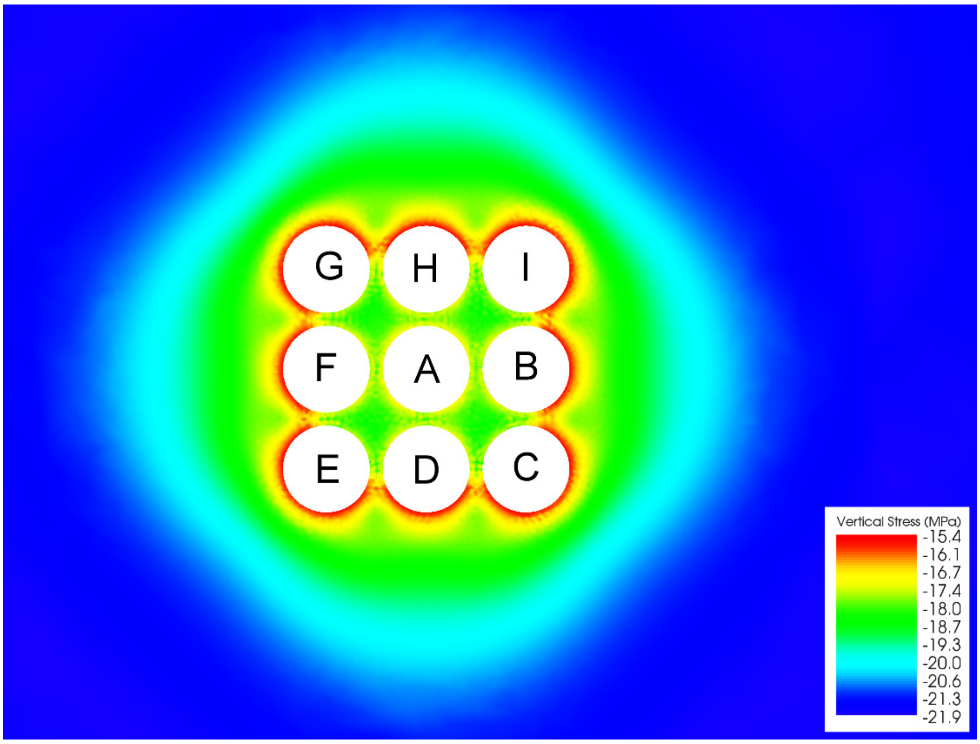


Figure 22. Case 7' – Horizontal cross section of vertical-stress contours 20 years after the start of mining.

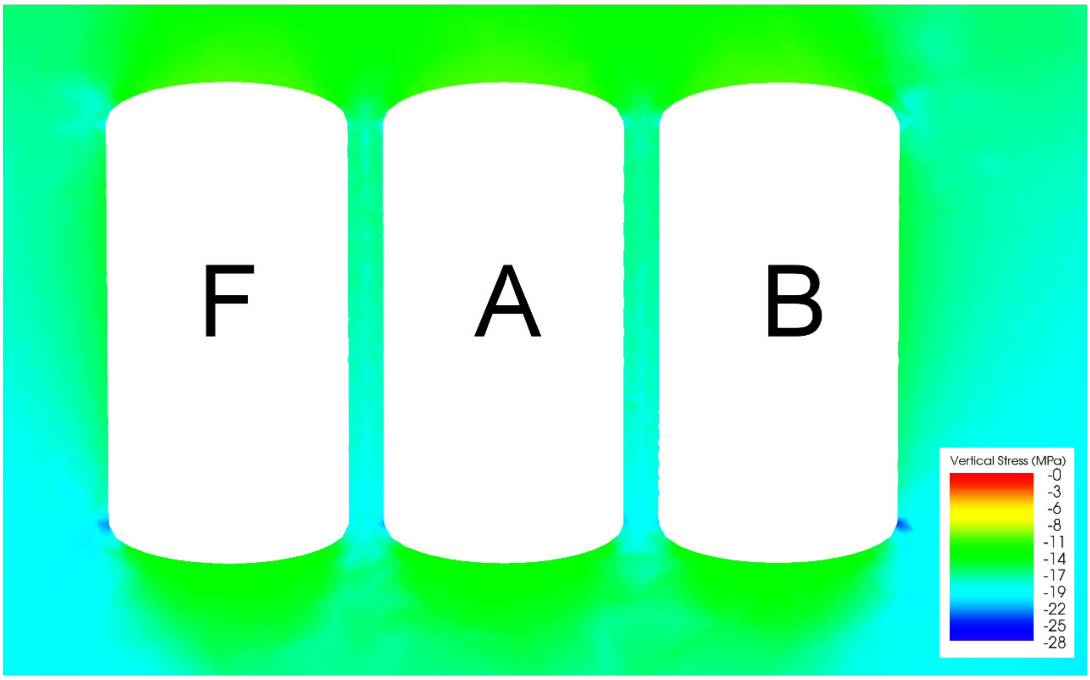


Figure 23. Case 7' – Vertical cross section of vertical-stress contours 20 years after the start of mining.

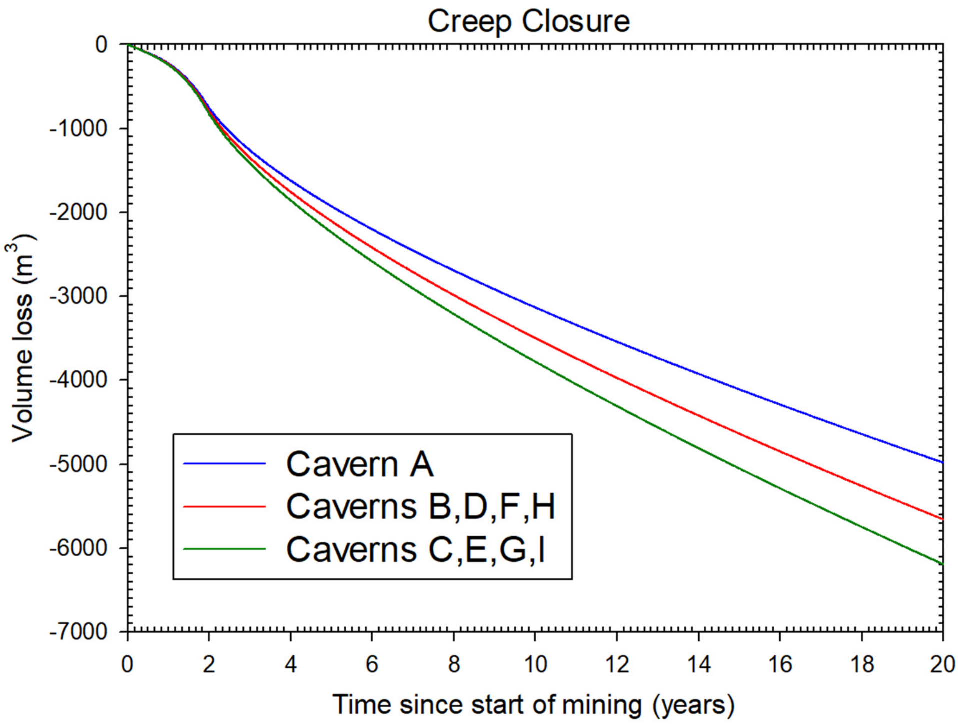


Figure 24. Case 4' – e = 40% – Evolution of creep closure.

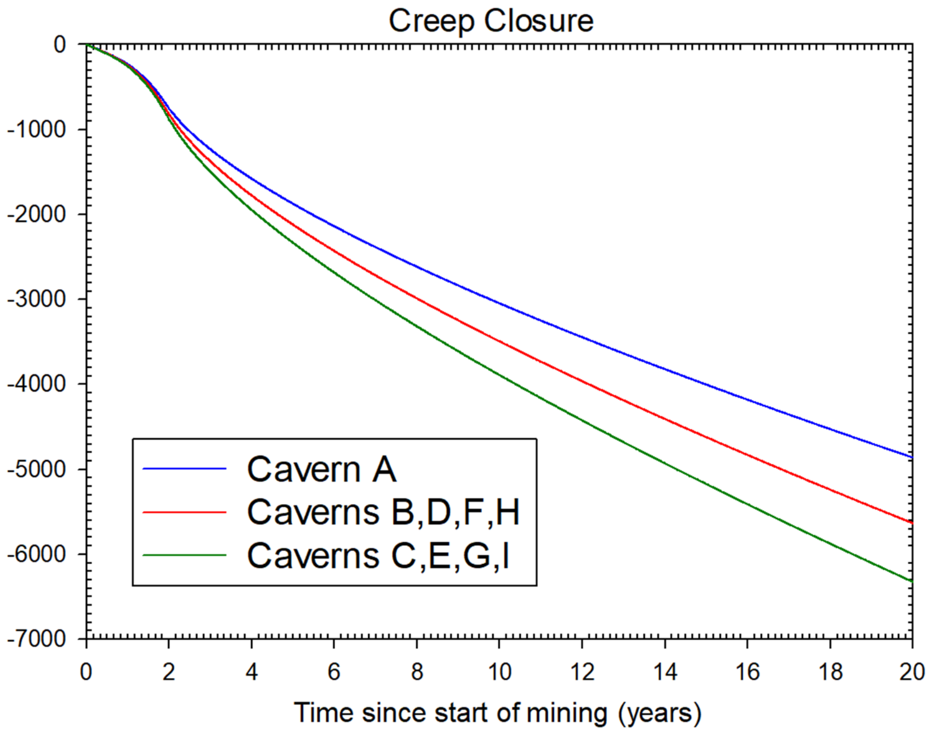


Figure 25. Case 7' – e = 60% – Evolution of creep closure.

Conclusions

The behavior of the salt pillar between 4 neighboring caverns was discussed. Several extraction ratios were considered (20%, 40% and 60%). Opposite to the case of an elastic rock mass, in the case of a visco-plastic rock mass (a salt formation), a few years after the end of mining, the vertical stress in the pillar is smaller than the virgin stress. This effect is more pronounced still when the extraction ratio is larger. Clearly, the standard analysis (in terms of comparison between the vertical stress and the rock strength) is of no use in this context. The same can be said of the dilation criterion: the horizontal stress is not very different from brine pressure in the caverns and the vertical stress is smaller than the virgin stress, resulting in a factor of safety larger than 1 (this might prove incorrect when the cavern is deeper). Unexpectedly, cavern closure rate is independent of the extraction ratio. These results may seem counter-intuitive as the larger the extraction ratio, the “safer” is the cluster. In fact, these results show that the standard criteria (dilation criterion, volume loss rate) might be irrelevant in the case of a cluster. Such phenomena as buckling of too thin a pillar, or the effect of two slightly different pressures in the cavern, should be discussed to get a relevant appreciation of cluster stability.

References

Bérest P., Brouard B., Feuga B. Karimi-Jafari M. (2008). *The 1873 Collapse of the Saint-Maximilien Panel at the Varangéville Salt Mine*. Int. J. Rock Mech. Min. Sc., n°45, 1025-1043.

Brouard Consulting (France) & Respec (USA). *Analysis of Moss Bluff Cavern #1 Blow Out Data*. Report for The Solution Mining Research Institute, Topical Report RSI-2013-01, 187 pages, 2013.

Brouard B., Zakharov V., Frangi A., Cremonesi M (2018). *Introducing LOCAS 3D Application to the Geomechanical Modeling of an Oil-Storage Facility*. Proc. SMRI Fall Meeting, 24-25 September 2018, Belfast, Northern Ireland, 18 pages.

Brouard B., Zakharov V. and Frangi A. (2020). *Full geomechanical modeling and data management of a gas-storage facility using LOCAS 3D*. Proc. SMRI Virtual Conference.

DeVries K. L., Mellegard K. D. and Callahan G. D. (2003). *Laboratory Testing in Support of a Bedded Salt Failure Criterion*. Solution Mining Research Institute Fall Meeting, Chester, United Kingdom, October 5–8, pp. 90–113.

Minkley W, Menzel W. (1996). *Local Instability and System Instability of Room and Pillar Fields in Potash Mining*. In: Proceedings of the 3rd conference on the mechanical behavior of salt. Clausthal-Zellerfeld, Germany: Trans Tech Publishers, 1996. p.497-510.