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Two-dimensional thermomechanical creep analysis of solution-mined cavern convergence – Regina cavern n°5 – Phase 2.

Nina Rosa dos S. Silveira. Author1, Leonardo J. do N. Guimarães. Author2, Inaldo J. M. da Silva. Author3.

[1]*Dept. of Civil Engineering, University of Pernambuco*
Avenue Prof. Moraes Rego, 1235 – University City, 50670-901, Pernambuco/Recife, Brazil
nina.rosa@ufpe.br
[2]*Dept. of Civil Engineering, University of Pernambuco*
Avenue Prof. Moraes Rego, 1235 – University City, 50670-901, Pernambuco/Recife, Brazil
leonardo.guimaraes@ufpe.br
[3]*Dept. of Civil Engineering, Federal Institute of Pernambuco*
Avenue Prof. Luiz Freire, 500 – University City, 50740-645, Pernambuco/Recife, Brazil
inaldo.jose@recife.ifpe.edu.br

Abstract. This study aims to evaluate the convergence of the second phase of a cave, obtained by dissolution in a bedded salt, under the effect of different temperatures applied in its cavity. The shape of the cave was obtained from sonar surveys at Regina Cave No.5 in 1983 by TransGas Ltd. The creep model used is based on an empirical formulation that considers the stationary phase of creep, this model is known as the double mechanism creep law or also called the Norton simplified model, presenting good results when the analysis involve long periods. Numerical geomechanical simulations, with a maximum time of 30 years, were performed with CODE-BRIGHT (Coupled DEformation BRIne Gas and Heat Transport) finite element code to the evaluation of rock stability and deformation, showing excellent results in this type of numerical simulation scenario.

Keywords: Creep, Salt Rock, Long-term creep, Convergence.

1 Introduction

The problem of storage has been leveraged with the discoveries of oil and natural gas in the subsea layers of the post and pre-salt. They bring with them a forecast of extraction of large volumes and shipments of crude oil and gas, requiring mega deposits. However, it must be made clear that there is still no adequate solution to carry out this storage. The traditional method, done in open-air steel tanks, is expensive and dangerous. On the other hand, methods of using depleted gas or oil reservoirs have been studied, but without conclusive results. As for caves in salt deposits by dissolution, for example, they need to be studied and understood regarding their thermo-mechanical behavior when used for gas storage. In Brazil, pioneering works, such as those by Goraieb, Iyomasa and Appi [1], presents possibilities for storing natural gas in Brazilian geological structures. But only recent works, such as those by Vassalo, Roehl, Costa, Amaral and Poiate [2] and Costa, Amaral, Poiate, Roehl and Gattass [3] are discussed, in a technical/economical way, but still incipient, the strategic use of underground space for gas storage in caves opened by the dissolution of saline rocks.

Regina No. 5 from TransGas Ltd. is located in the south of the city of Regina, capital of the province of Saskatchewan in Canada, where the cave began to be excavated in April 1983 and completed in December 1984, Crossley [4]. This cave was selected to be the object of this study because during its construction and operation several tests were carried out, generating a large amount of monitoring information on its structure over time. Figure 1 shows the stages of construction of the cave over time, where the geometry can be observed in its five phases of construction, by the dissolution method.

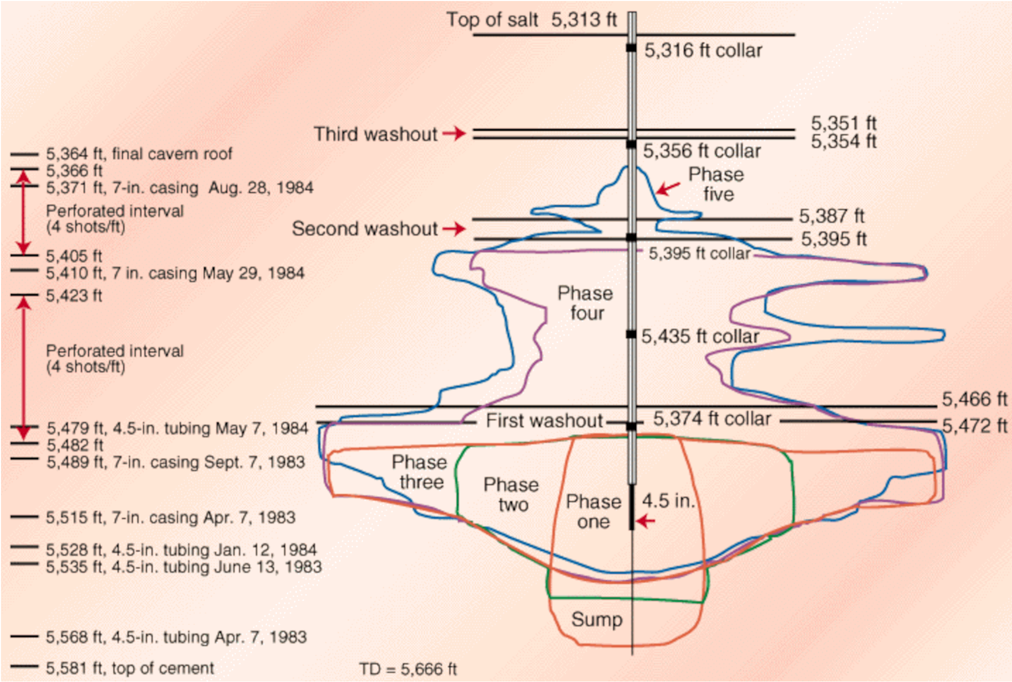

Figure 1. Development stages of Regina No. 5, Crossley [4].

2 Geo-mechanical modeling

In this section, the equations of the constitutive creep model applied in the numerical simulation will be presented and its variables will be detailed. The salt rock behavior is analyzed according to the elasto/viscoelastic behavior, adopting the Double Mechanism creep law. Uniaxial strain rate due to creep is:

$$\dot{\varepsilon}_{sc} = \dot{\varepsilon}_d \left(\frac{\sigma_d}{\sigma_{do}} \right)^n \tag{1}$$

Where $\dot{\varepsilon}_{sc}$ is the strain rate due to creep at the steady-state condition, $\dot{\varepsilon}_d$ is the strain rate due to creep at the steady-state condition corrected depending on temperature, σ_d is the applied deviatoric stress of von Mises (MPa), σ_{do} is the reference deviatoric stress of von Mises (MPa), the exponent n depends on the level of deviatoric stress of von Mises which the salt rock considering eq. (2).

$$n = \begin{Bmatrix} n_1, if \ \ \sigma_d \le \sigma_{do} \\ n_2, if \ \ \sigma_d > \sigma_{do} \end{Bmatrix} \tag{2}$$

The strain rate $\dot{\varepsilon}_d$ depending on temperature and can be calculated as:

$$\dot{\varepsilon}_d = \dot{\varepsilon}_{sco} \exp\left(\frac{Q}{R(T_0 + 273{,}15)} - \frac{Q}{R(T + 273{,}15)} \right) \tag{3}$$

Where $\dot{\varepsilon}_{sco}$ is the reference strain rate due to creep at the steady-state condition, Q is the activation energy (kcal/mol), R is the universal gas constant (kcal/mol/K), T is the rock temperature (°C); T_0 is the reference temperature (°C). The exponential term of the eq. (3) is known as the thermal activation factor and can be considered as a multiplicative factor of the reference strain rate, that is, a constant defined as a function of temperature. This term is also known as the Arrhenius Law according Mohriak, Szatman and Anjos [5].

The combination of equations 1 to 3 was implemented by Silva [6] in finite element code, CODE-BRIGHT (COupled DEformation BRIne Gas and Heat Transport) from the Laboratory of Computational Methods in Geomechanics - LMCG of the Federal University of Pernambuco - UFPE, resuming in Eq. 4 which defines the multiaxial strain state:

$$\dot{\boldsymbol{\varepsilon}}_{\mathbf{sc}}(\boldsymbol{\sigma}) = \frac{3}{2}\left[\dot{\varepsilon}_{sco}\; e^{\left(\frac{Q}{R\cdot T_0}-\frac{Q}{R\cdot T}\right)}\left(\frac{\sigma_d}{\sigma_{do}}\right)^n\right]\mathbf{M}\,\boldsymbol{\sigma}\,\frac{1}{\sigma_d} \tag{4}$$

Where $\dot{\boldsymbol{\varepsilon}}_{\mathbf{sc}}(\boldsymbol{\sigma})$ is the vector of strain rate due to creep at the steady-state condition (year^{-1}), $\mathbf{M}$ is the desviatoric operator, $\boldsymbol{\sigma}$ is the stress tensor (MPa).

The parameters $\dot{\varepsilon}_{sco}$, σ_{do}, n_1 and n_2 can be obtained through laboratory creep tests under controlled conditions of temperature and desviatoric stress, Mohriak, Szatman and Anjos [5].

3 Case study

The evaluated cave is located at a depth of 1680 meters. For simplification, the modeling of a part of the cave with dimensions of 400 x 300 meters was considered. In this sense, it was necessary to apply pressure to the top of 40.77MN/m2, to represent the upper layers.

The thermomechanical simulation was performed using implicit stress integration and for mesh discretization were used quadratic triangular elements with three numerical integration points. Totaling 15,512 elements and 31,147 nodes with a greater discretization in the cave contour.

Regarding the parameters of the thermal part of the simulation, the temperatures of 52°C at the top and 58°C at the bottom were imposed on the model, to create the temperature gradient in the rock mass and the average temperature values according to the depth were obtained in the work of Poiate, Costa and Falcão [8]. Six scenarios were analyzed where a temperature was applied inside the cave cavity, the temperatures adopted were 31°C, 38°C, 45°C, 61°C, 75°C and 86°C with temperatures of 38°C and 55°C the most commonly reached during the operation of the Regina cave n°5, Crossley [4]. The thermal conductivity of halite was estimated through the work of Robertson [9]. In fig. 2 it is possible to visualize the finite element model with mesh discretization, location of mechanical and thermal boundary conditions.

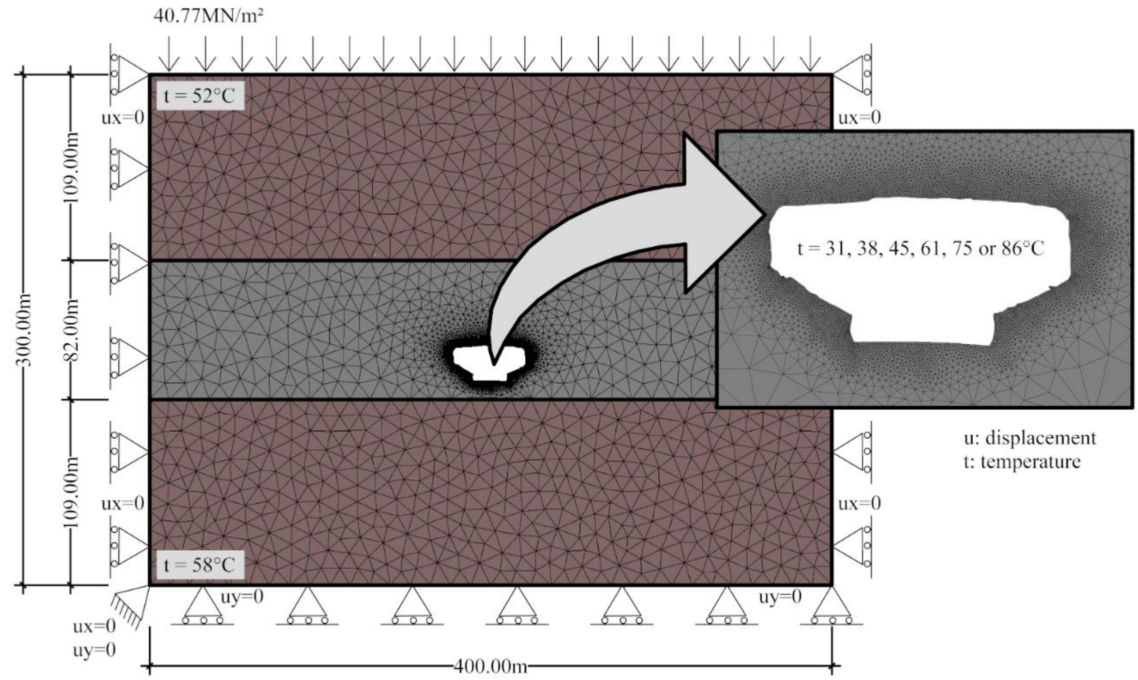

Figure 2. Finite element model with mechanic and thermal boundary conditions.

In tab.1 there are the elastic-plastic and creep parameters adopted for the analysis, with indications of each layer and respective materials of the geological profile. For the saline rocks, the double-mechanism-deformation model was applied, with a reference temperature of 43°C, Costa, Gonçalves and Amaral [7], and for the shale the classical elastoplastic Mohr-Coulomb model.

Table 1. Mechanical properties, Costa, Gonçalves and Amaral [7].

Layer	Material	E (MPa)	ν	c (MPa)	φ (°)	σ_{do} (MPa)	$\dot{\varepsilon}_{sco}$ (year)$^{-1}$	n_1	n_2
1	Shale	18,971	0.15	4.80	22				
2	Halite	20,403	0.36	3.00	40	10.00	0.0016	3.00	5.80
3	Shale	18,971	0.15	4.80	22				

The six scenarios were simulated with a final time of 30 years and at the end of the simulations it was observed that the cave closed well before that time, the cavity subjected to 86ºC took approximately 6 years to close while the one at 31ºC was approximately 14 years. In fig. 3, the cave convergence graph over time for the six simulations is presented, where the moment when the cave is completely closed can be observed.

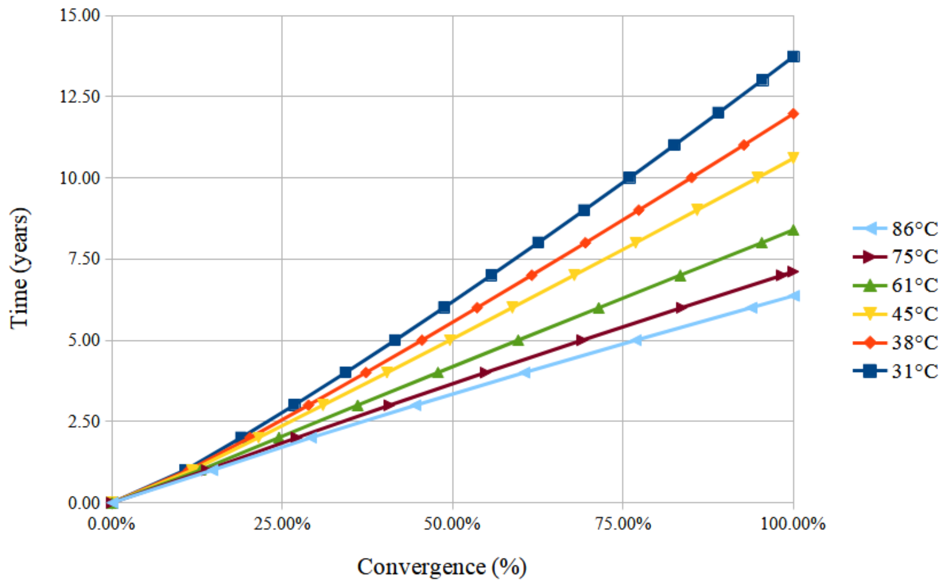

Figure 3. Convergence variation over time.

For comparison, the results of the simulations presented below will be for the time of 5 years where all the caves have not yet closed. The fig. 4 shows the temperature distribution of the six scenarios for the time of 5 years.

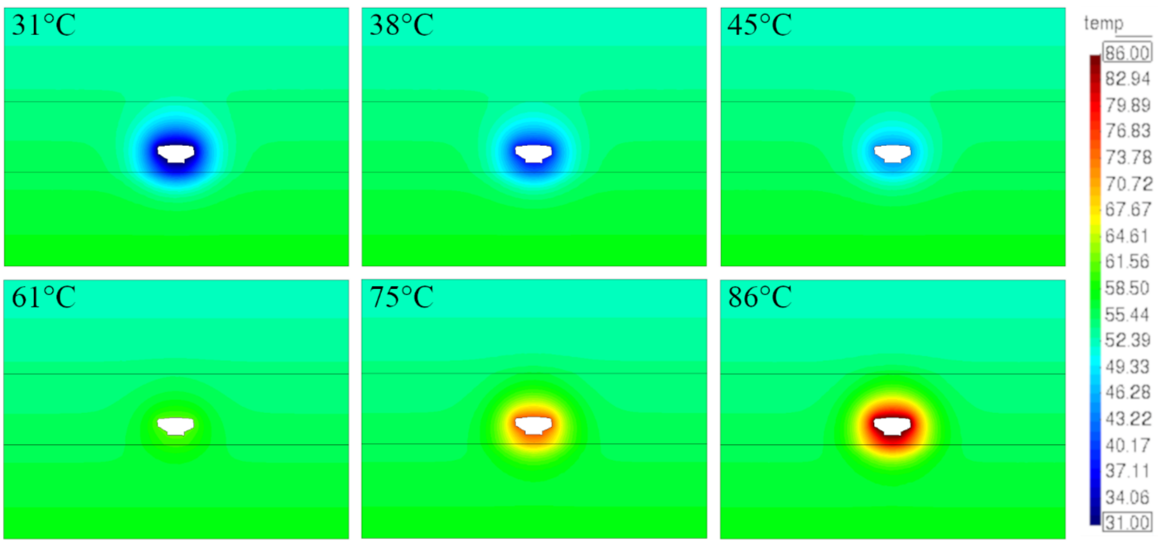

Fig. 4. Temperature distribution for the time of 5 years.

The distribution of shear stresses (represented by the second invariant of the desviatoric tensor, J) in the foundation is shown in fig. 5 where one can observe the disturbance caused by the excavation of the rock mass, the high level of shear in the shale layers and, in the surroundings of the cave, mainly in the corner regions. This is because the shale, in this case, is a non-viscous material interspersed with material that has a high creep strain rate. While in fig. 6, the applied deviatoric stress of von Mises can be observed with greater emphasis on the concentration of stresses in the corners of the cave.

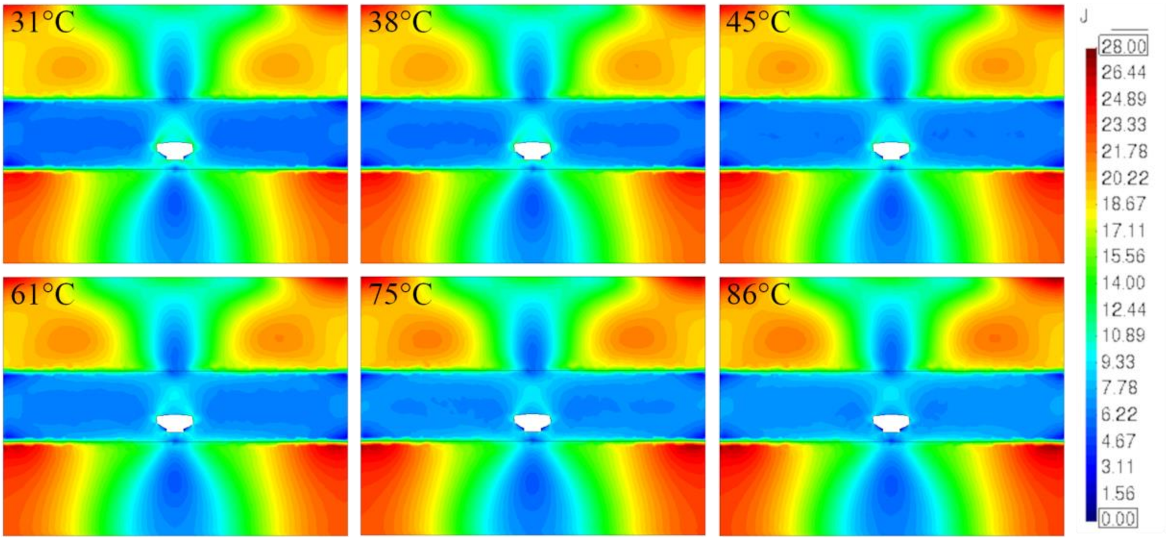

Fig. 5. Shear stresses for the time of 5 years.

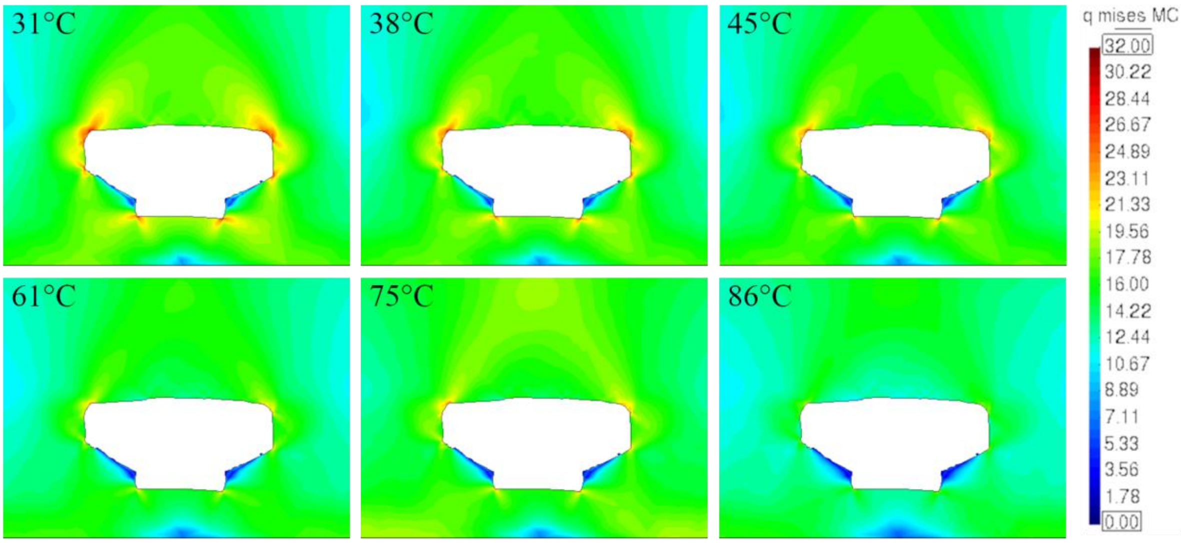

Fig. 6. Desviatoric stress of von Mises for the time of 5 years.

The fig. 7 shows the distribution of creep strains, and it can be seen that they propagate through the rock mass. With a concentration in the corners, corroborating with what was observed in the applied deviatoric stress of von Mises. While fig. 8 shows the shape of the cave for a period of 5 years using the representation of displacement vectors with a scale factor of x1. Where it can be observed that there is a significant loss in the final volume of the cave when it is subjected to high temperatures, reducing its usefulness.

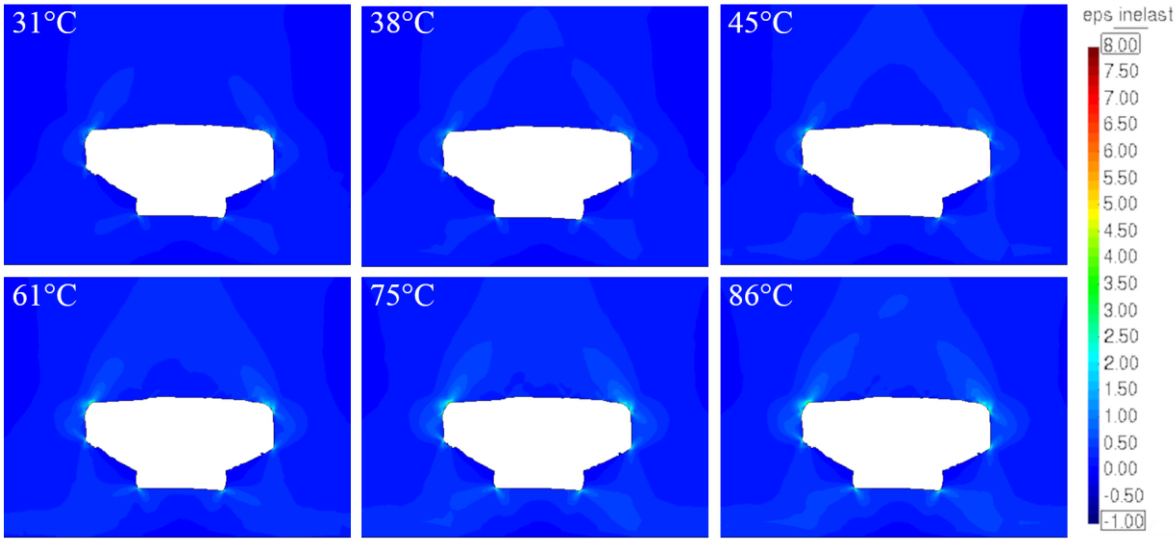

Fig. 7. Creep strain for time of 5 years.

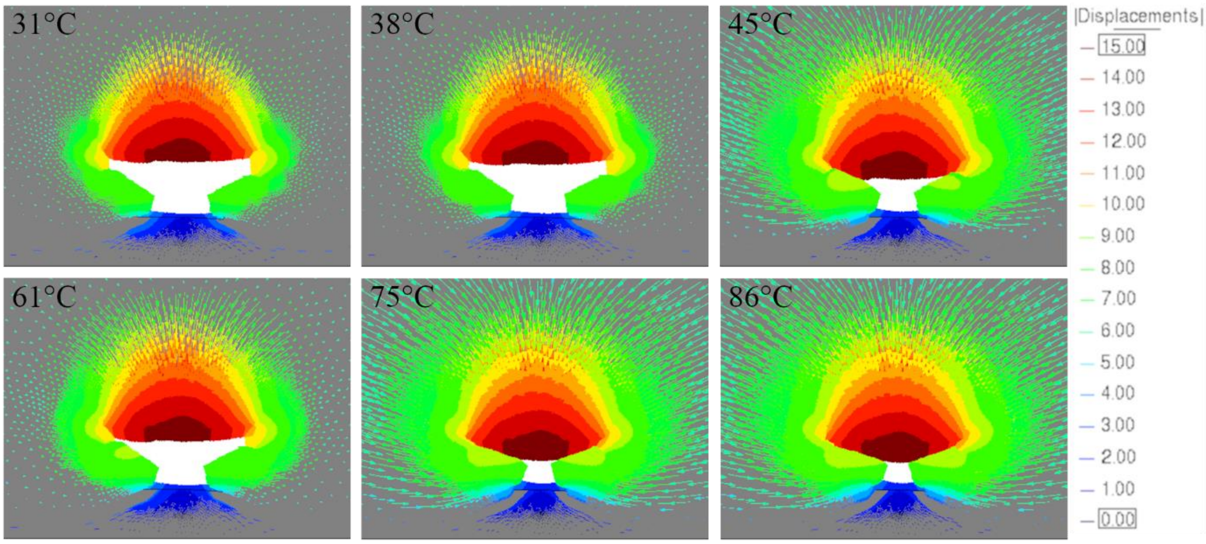

Fig. 8. Displacement vectors for time of 5 years.

4 Conclusions

Due to the shape of the cave, there was a greater concentration of stress in its corner regions, suggesting that there will be possible collapses within the cavity, which is in accordance with what actually occurred during its operation, Crossley [4].

The temperature of the material stored inside the cave directly influences its useful life as it accelerates its convergence, reducing its storage capacity. For temperatures above that of the rock mass, the degradation process intensifies, as shown in the graph in fig. 3 where there is a more intense increase in cave convergence rate over time between temperatures of 45ºC and 61ºC.

The finite element code CODE_BRIGHT was able to analyze thermomechanical problems using a creep model to represent the behavior of stability and deformation of cavities in saline rocks. It is worth emphasizing that the studies presented in this case of gas storage are preliminary, thus requiring more in-depth analyzes and comparisons with real data for a better validation of the applied methodology.

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