

## INTEGRATED APPROACH FOR PROBABILITY OF FAILURE ANALYSIS IN SALT CAVERNS: API AND PREDICTIVE MODEL FRAMEWORK

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Rock salt is a viscoplastic material that cannot withstand deviatoric stresses, leading to creep deformation. This displaces the walls of salt caverns, causing cavern convergence and subsidence. Inelastic volumetric expansion can increase microcracks, resulting in displacement phenomena, posing risks to the population and environment. A predictive model using the POD-RBF metamodel was developed to address these challenges. This model combines Proper Orthogonal Decomposition (POD) and Radial Basis Functions (RBF) to create Reduced Order Models (ROM) from high-dimensional data. An axisymmetric model was built to represent the cavern geometry, considering five evaluation points on the cavern wall. The geomechanical model includes shale, halite, and overburden. Abaqus software was used for simulations, modeling halite's creep behavior over 50 years using the Munson-Dawson model. The metamodel was trained using 200 parameter sets and validated with 20 additional simulations, achieving an  $R^2$  value of 0.9972 and an NRMSD of 0.0547. An API was implemented to automate parameter updates, reducing computational costs significantly. Reliability-based approaches analyzed uncertainties, with probability of failure assessed using the Monte Carlo method.

*Keywords:* Geotechnical engineering, Rock mechanics, Salt rock, Reliability analysis, Finite element method, Creep strain, Dilatancy, Internal pressure, Munson-Dawson Model

### 1. Risks in salt caverns

Rock salt is a viscoplastic material that does not resist deviatoric stresses, and whatever the condition of deviatoric stresses imposed, there is creep deformation (Thoraval et al., 2015). The displacements of the salt cavern's walls due to the rock salt's creep can cause the cavern to converge. This halokinetic movement displaces the strata close to the salt layer and causes subsidence. In addition to creep, when the salt rock reaches inelastic volumetric expansion, microcracks increase causing displacement (Firme et al., 2019). Both mechanisms can move the ground surface and pose risks to the population and the environment.

In this study, we use a predictive model, regarding reliability-based approaches through the metamodel that combines Proper Orthogonal Decomposition (POD) with Radial Basis Functions (RBF) to evaluate the behavior of rock salt caverns over 50 years. We implemented the POD-RBF using Abaqus software, Python language scripting, and Matlab software. The cavern geometry considered the shale, halite, and overburden characterized by pressure of 19.03 MPa. Multimechanisms deformation model and Mohr-Coulomb elastoplastic model represent the behaviour of halite and shale. The POD-RBF metamodel creates Reduced Order Models (ROM) from high-dimensional data. POD reduces the dataset into orthogonal modes, retaining most of the system's energy and significantly reducing the number of variables. RBFs interpolate the POD mode coefficients for new parameters, enabling predictions for unseen conditions. Finally, we considered different scenarios to evaluate the evolution of the materials' behaviour over time.

### 2. Application Programming Interface and Predictive model

The POD-RBF metamodel create Reduced Order Models from high-dimensional data (Buljak 2012). This method is widely used to solve complex parametric problems, such as nonlinear simulations. POD is an order reduction technique that decomposes a dataset into orthogonal modes, allowing the data to be represented on a reduced basis. This is done while retaining most of the system's energy, decreasing the number of variables needed to describe the system. RBFs are used to interpolate the coefficients of the POD modes for new parameters. Thus, it is possible to build a model that may predict the system's behaviour for parameters not included in the original snapshots.

To develop the POD-RBF metamodel, 200 sets of parameters were generated using the optimized Latin hypercube sampling technique. Analysed parameter are presented in Table 1. Also, a finite element simulation was performed for each set of parameters. Then, output value matrices for these simulations were generated to construct the metamodel. The accuracy level of the metamodel was examined using 20 additional finite element simulations, where the finite element model results were compared with the metamodel results. Two error measures were considered:  $R^2$  and the normalized root mean square deviation (NRMSD), yielding an  $R^2$  value of 0.9972 and an NRMSD value of 0.0547. To enable these 200 simulations mentioned in the previous item, we implement an Application Programming Interface (API) to automate the parameter updates for each new simulation. Figure 1 shows the eight main steps performed for this automation, which utilized Abaqus software, the Python platform, and Matlab software.

Regarding the computational cost, the metamodel solves 10,000 simulations in 2 hours and 37 minutes. By comparison, and using the same computer to perform the simulations, it is estimated that the finite element model would take about 30 days to perform such simulations.

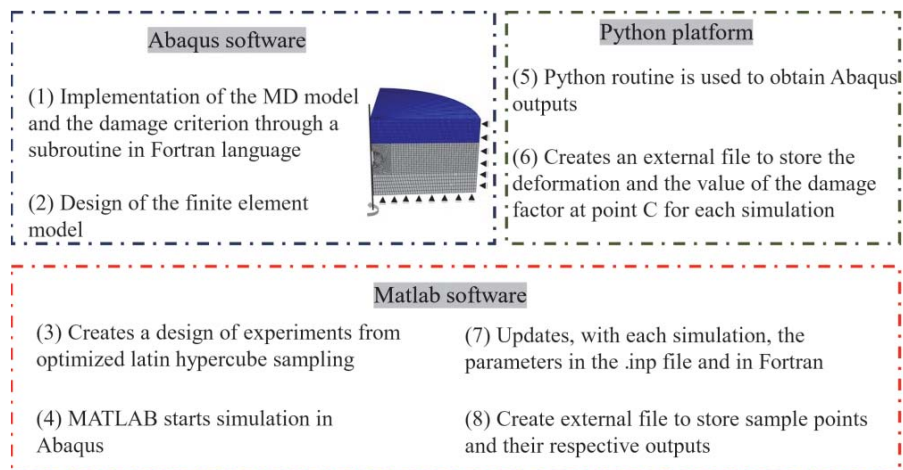


Fig. 1. Main steps in automating numerical simulations used to train the metamodelo

### 3. Structural description and numerical modeling

We built an axisymmetric model to represent the cavern geometry. The geomechanical model considers two materials: shale (blue) and halite (gray) (Figure 1). We also applied a pressure of 19,03 MPa to characterize the overburden. The mine has a height of 96 m and an approximate radius of 55 m.

Abaqus software simulated the materials' behavior. We discretize the geometry using C4X4R (4-node, bilinear axisymmetric quadrilateral with reduced integration). We use a three-step analysis to simulate the halite's creep behavior. In the first step, Abaqus calculates the geostatic stress, and the mine's excavation is instantaneous by removing the material. In the second step, Abaqus calculates the instantaneous elastic behavior of the material. Moreover, the third step simulates the viscoelastoplastic halite behavior using the Munson-Dawson (MD) Model over 50 years.

We used the elastoplastic model proposed by Mohr-Coulomb to model the shale's behavior. The elastic modulus, Poisson's ratio, friction angle, cohesion, and specific weight of shale receive the values of 18,97 GPa, 0.15, 22°, 4.8 MPa, and 24.00, respectively (Costa et al., 2015). Halite was modeled using a subroutine Creep from Abaqus to implement the MD model and simulate its behavior over time. There are several constitutive models used to model salt rocks. We selected the model proposed by Munson and Dowson (1979) due to its ability to represent primary and secondary creep. This model used three mechanisms to determine the secondary creep: dislocation climb, undefined mechanism, and dislocation glide. In addition, we considered the temperature rate of geotechnical materials (Costa et al 2012). The temperature increases with the salt layer depth. Costa et al (2012) suggested the values of 10°C/km and 30°C/km for saline material and sedimentary rocks that constitute the overburden, respectively.

We constrained the horizontal displacement on the right side of the model. This restriction represents the continuity of the layer and allows vertical displacement. The model's bottom edge had its vertical displacements constrained.

Cristescu (1993) observed the compression-dilatancy behavior in geomaterials, which is important for the stability of salt mines. Initially, halite exhibits ductile compressive behavior, healing fissures. When the inelastic volumetric expansion occurs, microfissures increase, leading to spalling. In this research, we used the formulation proposed by Ratigan et al. (1991), which is applied to Brazilian halite. This behaviour was determined from triaxial tests conducted on the Waste Isolation Pilot Plant (WIPP) formation and the Avery Island dome.

#### 4. Uncertainties associated with the probabilistic framework

Reliability-based approaches systematically and more completely analyze complex uncertainties compared to deterministic analyses alone. Statistical distributions and statistical parameters perform the analysis of these complex uncertainties. Here, we consider the mean and the coefficient of variation. Table 1 presents the parameters considered in the uncertainty analysis performed in this study. The uncertainty levels are represented by the pessimistic, neutral and optimistic scenarios in order to assess the influence of the uncertainty level on the value of the probability of failure.

Table 1. Probability distributions and coefficients of variation of the analysed parameters

Parameter	Description	Unit	Mean value	Distribution	Coefficient of variation (%)		
					Pessimistic	Neutral	Optimistic
	Young modulus	GPa		Normal	15	10	5
	Poisson's ratio	(-)		Normal	15	10	5
	Limit factor for primary creep	(-)		Lognormal	90	60	30
	Structural factor of salt related to undefined mechanism	()		Lognormal	150	100	50
	Young modulus of overburden	GPa		Normal	15	10	5
	Poisson's ratio of overburden	(-)		Normal	15	10	5
	Internal pressure	MPa		Normal	15	10	5

\* Coefficient of variation adopted from Fossum et al (1996);

\*\* Coefficient of variation adopted from Fossum and Friedrich (2007);

\*\*\* Based on safety internal pressure values for mine closure suggested by Bérest et al. (2020).

#### 5. Probability of failure

We solved probability of failure using the Monte Carlo method. Therefore, we determine the failure probability by the ratio between the number of sets that did not reach the performance criterion and the total number of evaluations. We considered two criteria for simulating the performance of the salt rock. The first criterion is the creep, which considers the cavern volume loss. We defined the largest shrinkage volume as 10% of the initial cavern volume throughout the analysis (50 years) (Yuan et al., 2021). The second criterion is dilatancy, which is a rise in the permeability of the rock due to damage. We used the Ratingan's criterion (Van Sambeek et al., 1993).

The first limit state function considers the maximum limit of strain equal to 10% at the wall of the salt cavern (Point C). Thus, we have

$$(1)$$

The second limit state function considers the maximum limit of dilatancy for the occurrence of microcracks in the salt rock. That is the difference between the damage factor (evaluated at the wall of cavern – Point C) and its limit value. This value was taken to be equal to 0,8 for starting to generate the microcracks, when  $D$  is greater than 1 the material is already in the dilatant zone. Thus, we define as

$$(2)$$

Therefore, for each configuration considered, a definition of a function of failure that considers both criteria is necessary. In this way, we identify the lesser value between the functions of failure as  $f$ . Finally, we verify if  $f$  was taken equal to or lesser than 0. These cases indicate failure.

According to the coefficients of variation considered (Table 1), there are 3 simulation scenarios: pessimistic, neutral, and optimistic. For each scenario, 40,000 simulations were performed. Figure 2 (a) shows the probability of failure for each scenario according to the number of simulations. It is possible to notice the stabilization of the probability of failure value for 40,000 simulations. One can observe that this number of simulations is sufficient. There was no failure considering the first limit state function (optimistic scenario). Figure 2 (b) shows the cumulative distribution function (CDF) of the damage factor for the different scenarios.

Table 2 presents the probabilities of failure and the respective reliability indices ( $\beta$ ) for the three uncertainty scenarios considering 40,000 sets of random parameters for each scenario. Civil engineering applications, which involve the safety of people, consider reliability indices between 3 and 4 as satisfactory. In mining, values lower than these are accepted. Therefore, to determine whether the values are acceptable or not, the location of the mine must be verified, as well as whether there are industries or residences nearby, which could potentially lead to loss of life, for example. However, it is not the objective of this research to determine whether the values obtained are acceptable or not.

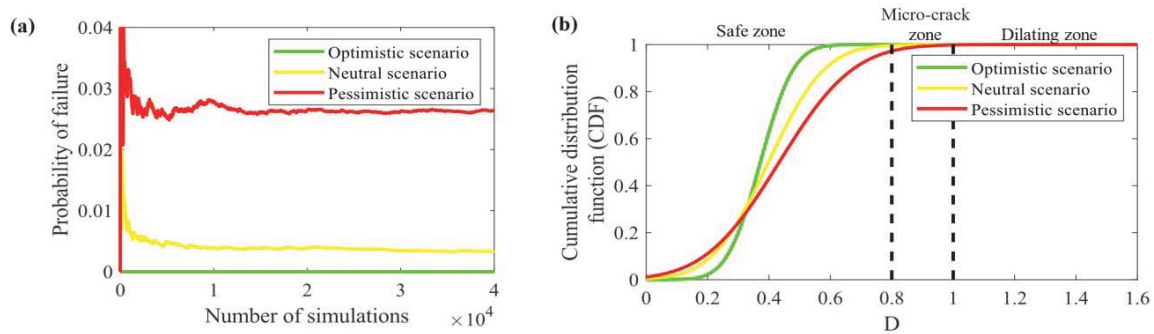


Fig. 2. Analysis scenarios, being. (a) probability of failure according to the number of simulations and (b) cumulative distribution function (CDF) of the damage factor for the scenarios.

Table 2. Probability of failure and reliability indices of the scenarios.

Scenario	Probability of failure	Reliability index
Optimistic	Lower than 0.000025	
Neutral	0.0034	2.71
Pessimistic	0.0264	1.93

## 6. Conclusions

This study highlights the risks associated with salt caverns due to creep deformation and inelastic volumetric expansion of rock salt. POD-RBF metamodel is effective in predicting system behavior reducing computational costs significantly. Numerical modelling using Abaqus and API enabled a probability of failure analysis, encompassing non-linear behaviour and multiple input parameters. Uncertainty analysis shows that the value of the reliability index can be drastically affected according to the level of uncertainty. In cases where it is desired to reduce uncertainty, additional geotechnical investigations and laboratory tests can be carried out. The proposed approach provides a robust tool for risk management in salt caverns, contributing to public safety and environmental protection.

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