Geomechanical Simulation to model creep deformation of salt formation

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SUMMARY

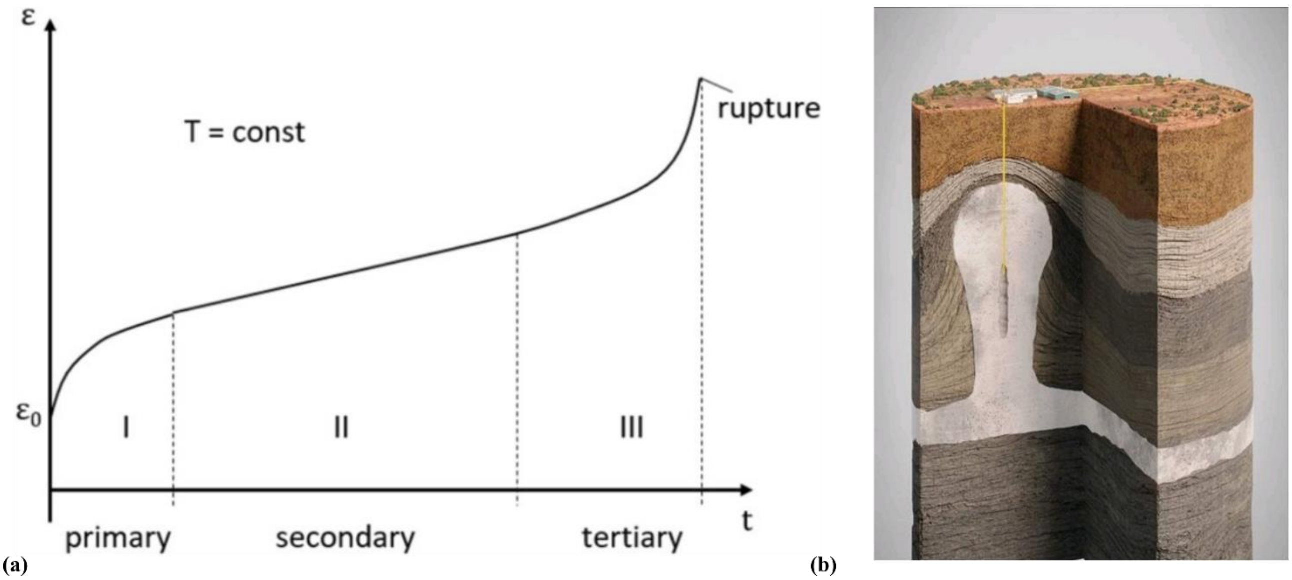
To combat the increasing demand of renewable energy, development of effectual system for energy storage is needed. Salt caverns serve as the feasible and efficient solution for hydrogen storage. Studying the complex structure and analysing deformation behaviour of these formations requires clear geological domain knowledge, suitable numerical technique and proper computational model when going to predict long-term deformation and associated stress state. In this work, a 2D finite element simulator code has been utilized to probe deformation characteristics of salt formation. Two cases: (i) creep under monotonic loading, and (ii) creep under cyclic loading are deployed to investigate the influence of non-linear primary creep and change in stress magnitudes under in situ conditions. Damage and creep constitutive laws like generalized Hooke's Law, total potential energy principle, infinitesimal deformation theory etc are utilized in the simulation engine assuming constant strain triangle elements. At suitable boundary conditions, the model captured axial deformation under uniaxial compression condition of the studied salt formation with the experimental data. A good match of compressive axial deformation is observed between experimental and numerical results. Finally, the model will be extended to understand permeability evolution under monotonic loading and possible relationship with volumetric change from gas transmission permeability measurement.

Key words: salt cavern, energy, subsurface storage, creep, deformation, simulation

INTRODUCTION

During the recent years, renewable energy sources such as wind and solar energy have become quite popular because of their low pollutant and greenhouse emissions. These sources produce electricity intermittently and are uncontrollable. To overcome this problem and meet the increasing demand of renewable energy, development of effective systems for green energy storage either in the form of compressed air or hydrogen is warranted. Rheology, low permeability, solubility in water and favourable thermal and mechanical properties are some of the unique features of rock salt formations. Because of these reasons rock salt is one of the prime alternatives for construction of underground caverns for storing green energy sources or radioactive wastage in large scale quantities (Khaledi et al., 2014). The construction of salt caverns mainly focusses on the salt diapirs or dome developed through a process known as diapirism. Salt domes are formed when thick bed of salt moves vertically upward into denser rocks due to the buoyancy forces over geological time (Figure 1). Caverns are artificially created using the solution-mining technique within the host rock.

When utilize for energy storage, salt cavern is exposed to a pressure difference from lithostatic and cavern's operational pressure. This causes deformation of the structure and surrounding medium. For the stability and safety of such structures, studying the microstructure and analysing the deformation behaviour of salt is very important. It requires clear geological domain knowledge, suitable numerical technique, and proper computational model to predict the long-term response of the host formation and associated in situ stress state. For modelling deformation behaviour, challenging part is salt's time dependent nonlinear deformation known as creep. It is a phenomenon in which solid material deform permanently with time when axial stress is applied to it. As shown in Figure 1, after applying an external load, the material consistently goes through three stages of creep. The first stage represents the initial loading if the material which leads to instantaneous recoverable elastic strain. The creep rate initially is relatively high which steadily decreases as the loading proceeds. This phase is primary creep and the phenomenon of decreasing creep rate at constant stress is called strain hardening (Twiss and Moores, 2006). At the second phase, the creep rate stabilizes at a constant value called steady (secondary or stationary) creep. It is the part of the experiment that presumably represents the long-term deformation processes that occur within the Earth. The third phase is tertiary creep accompanied with an accelerating strain rate and ultimately the sample's damage and failure. This is most common during high-stress and low-temperature experiments. A significant amount of creep occurs over short and long engineering time scale at temperatures in the range 20-200°C and at low stress of about 0.2MPa (Li and Urai, 2016).



(a) (b)

Figure 1. (a) Creep response of a material (left) showing three stages of creep with an initial elastic deformation of ϵ_0 under (b) example of geological structure of salt dome (taken from GA, 2022 LinkedIn page).

Several researchers reported geomechanical deformation of salt through numerical studies (Gunzburger and Cornet, 2007; Khaledi et al., 2014; Li and Urai, 2016). However, complex geometries were not considered in most of the work. Here we used an open-source finite element (FE) computational model (Makhmutov, 2020) to predict the evolution of stress and creep deformation in reservoir scale of a potential salt formation. The model is applicable for complex lithology and subsurface specific boundary conditions. First the governing equations of constitutive laws representing damage and creep are presented. Then monotonic and cyclic loading condition of a salt cavern are analysed. Finally, a comparison is made between the computed and experimental data.

METHODOLOGY

The computational model has been constructed based on some assumptions and constitutive relations which are (i) validation of generalized Hook's law (ii) infinitesimal deformation theory (iii) isotropic material (iv) no chemical reactions is taking place between inserted gas and salt rock (v) gas cannot inserted the media (vi) no heat transfer takes place and (vii) cavern is excavated instantly and loaded at time t = 0.

According to the elasticity theory, the force balance equation can be derived by minimization of potential energy principle which states that among all possible displacements and configurations of a conservative system that satisfies the equations of equilibrium, the correct state of the system is the one which minimizes the total potential energy (Makhmutov, 2020).

$$\delta \Pi = \delta (U + V) = 0 \quad (1)$$

where U is the internal strain energy and V is the potential energy given by

$$U = \frac{1}{2}\int_V \varepsilon^T \sigma \, dV \text{ and } V = -W = -\int u^T f \, dS - \int_V u^T f^b \, dV \quad (2)$$

Here, W is the work of the external forces, u is the displacement vector, f is the distributed force vector acting on part S of the surface and f^b is the body forces vector. Assuming infinitesimal deformation, total strain is represented by the sum of elastic, ε_{el} and inelastic, ε_{ie} strain i.e.

$$\varepsilon = \varepsilon_{el} + \varepsilon_{ie} \quad (3)$$

The inelastic strain is the overall effect of thermal, plastic, creep etc. In this work, modelling of the creep behaviour of rock salt is considered. Therefore,

$$\varepsilon = \varepsilon_{el} + \varepsilon_{cr} \quad (4)$$

The generalized Hooke's Law gives the relation between stress and strain tensors (assuming its validity) i.e.

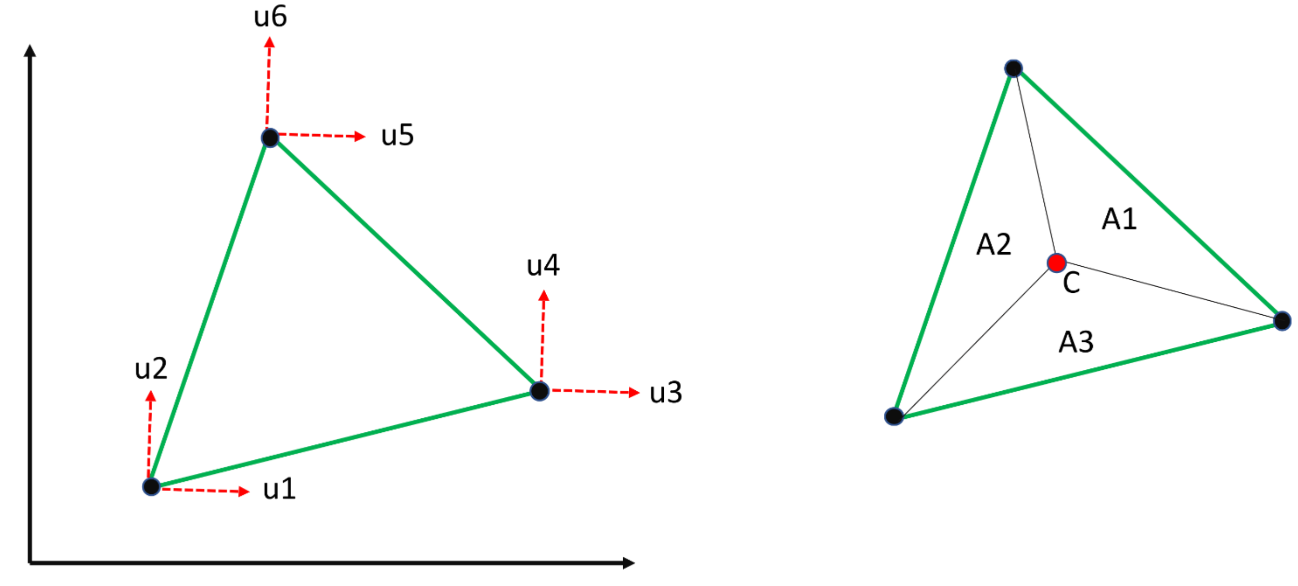
$$\sigma = C : \varepsilon_{el}$$

in which C is the 4th rank elasticity tensor. Then, for a 2D isotropic homogeneous material, the elasticity tensor can be expressed as

$$C_{ijkl} = \lambda \, \delta_{ij}\delta_{kl} + \delta_{il}\delta_{jk} \quad (5)$$

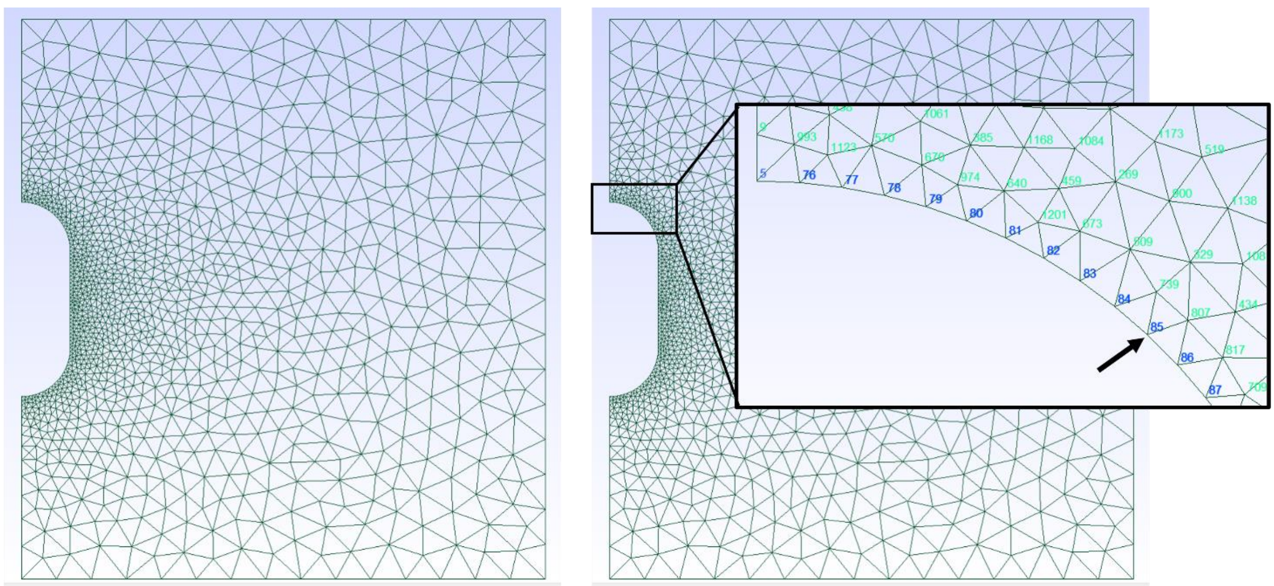
where μ and λ are the Lame's constants. Under the assumption of infinitesimal deformations, the strain tensor can be written in terms of the symmetric gradient operator, ∇^s as

$$\varepsilon = \nabla^s u \text{ where } \nabla^s = \frac{1}{2}(\nabla u + \nabla u^T) \tag{6}$$



(a) **(b)**

Figure 2. (a) Illustration of a 2D finite element with nodal displacements (b) Interior point interpolation.



(a) **(b)**

Figure 3. (a) Vertical cross section of salt cavern geometry and overlaid with mesh generated using Gmsh (b) Top of the salt cavern node position 85 is shown by arrow in the mesh.

Creep Formulation: To develop creep strain rate relation, it is assumed that the creep strain is a function of stress and temperature i.e.

$$\dot{\varepsilon}_{cr} = f_\sigma(\sigma_{eq}) f_T(T) \tag{7}$$

σ_{eq} is the equivalent stress and T being the temperature. The temperature dependency is given by the Arrhenius law as

$$f_T(T) = e^{-\frac{Q}{RT}} \tag{8}$$

where Q, R, and T are activation energy, universal gas constant, and temperature respectively.

Stress dependency is expressed by power law stress function (see equation 9) since it predicts better long-term deformation when fitting curve on experimental salt deformation data

$$f_\sigma(\sigma_{eq}) = a\,\sigma_{eq}{}^n \quad (9)$$

Thus, the creep strain rate is expressed as

$$\dot{\varepsilon}_{cr} = \frac{3}{2} e^{-\frac{Q}{RT}}\, a\, \sigma_{vM}{}^{n-1} s \quad (10)$$

where σ_{vM} is the von Mises equivalent stress, s is deviatoric part of the stress tensor, a and n are the material constants.

Damage is incorporated to study the propagation of microcracks ultimately leading to rupture in the tertiary stage of creep. Kachanov law is employed in the constitutive creep equation such that the strain rate not only depends upon the stress but also on the current Damage state D (Ramesh Kumar et al., 2021). Thus, the constitutive equation is given by

$$\dot{\varepsilon}_{cr} = \dot{\varepsilon}_{cr}(\sigma, D) \quad (11)$$

The damage state variable is expressed by evolution equation i.e.

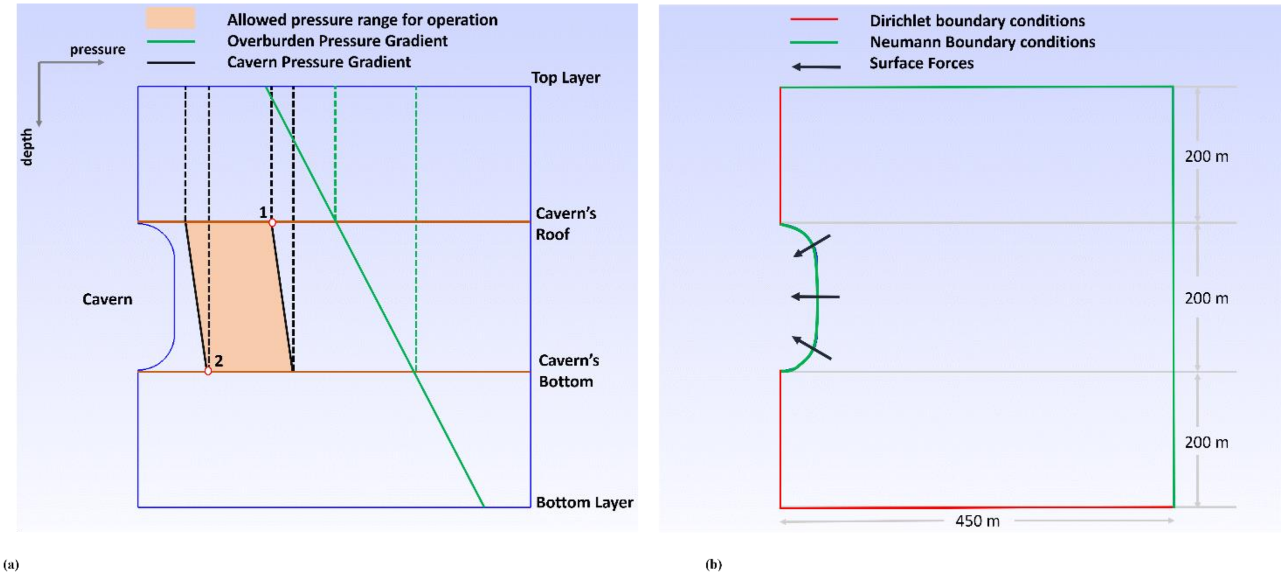


Figure 4. The pressure gradient and safe pressure range used for numerical simulation in the salt deformation numerical study (left) and applied boundary conditions (right) for both test cases. The depth of topmost salt layer from the surface is 600 m.

$$\dot{D} = \dot{D}(\sigma, D), \; D|_{t=0} = 0, \; D < D_* \quad (12)$$

Where D_* is the critical value of damage and damage evaluation rate is $\dot{D} = \frac{\sigma^r}{B\,(1-D)^r}$

Henceforth, the creep strain rate can be stated as

$$\dot{\varepsilon_{cr}} = a\left(\frac{\sigma}{1-D}\right)^n \quad (13)$$

Here variables a, B, n, and r in the above equations represent the material dependent constants.

If D = 0, this equation reduces to the well-known power-law constitutive equation (see below equation 14) i.e.

$$\dot{\varepsilon_{cr}} = a\,\sigma_d^n \quad (14)$$

in which σ_d is the dilatancy intensified stress written as

$$\sigma_d = \frac{\sigma}{1-D}$$

The equation of creep strain rate forms a well-posed system for nonlinear time-dependent deformation vector $u = (u, v)$ (here, u and v are the displacement in x and y directions respectively) of rock salt with elastic and inelastic deformation.

To solve this equation numerically, the system is discretised in space by using finite-element method which can be stated as

$$u \approx N u^h \quad (15)$$

where N the FE shape functions and u^h is the displacement vector at finite nodes corresponding to the mess resolution h. In this work, 2D triangular mesh is used to employ the finite element method (Figure 2). Numerical solutions are obtained for displacement at nodal locations of each element, whereas strains and stresses will be calculated for the entire element from the Gauss points. Therefore, these elements are also called Constant Strain Triangle (CST) elements. The geometry and the mesh generated using an open-source software Gmsh (Geuzaine and Remacle, 2009; Gunzburger and Cornet, 2007) for a 2D salt cavern is shown in Figure 3.

RESULTS AND DISCUSSIONS

To establishing a realistic field loading condition, the cavern's fluid and overburden pressure are chosen such that the fluid pressure lies in the range of 20-80% of the overburden value. Thus, the pressure difference between cavern's fluid pressure and overburden pressure will be minimum at the roof of cavern during injection (Point 1 in Figure 4) while it will be maximum at the bottom of cavern during production (point marked as 2 in Figure 4). Using the minimum and maximum cavern pressure and corresponding pressure difference, the equivalent surface forces (black arrow on cavern) acting on cavern's walls are calculated. In this case hydrogen gas density is selected to compute acting forces in the cavern's wall. These forces are converted to equivalent nodal forces that will be used in the numerical model as input. Dirichlet boundary condition was imposed at the bottom and face of the cavern. To observe any subsidence or any deformation, Neumann boundary condition was imposed on the top and the far end face of the defined salt cavern geometry (Figure 4). In Table-1, the properties of the material used for classical creep constitutive numerical simulation is listed. The developed simulator is exposed to test different features simultaneously including sensitivity of material constants and complex geological structures.

Parameter	**Value**
Rock Salt density [kg/m^3]	2250
Depth of the top of the salt layer [m]	600
Creep constant a [Pa^n]	8.1e-28
Creep exponent n	3.5
Temperature [K]	298
Creep activation energy Q [J/mol]	51600
Time step size [days]	1.5
Rock salt Poisson Ratio	0.3
Rock salt Youngs Modulus [GPa]	44e9
Scale	1

Table 1 Input parameters used to run numerical simulation reported in this study.

In the first case, the creep strain rate relation (see equation 9) is solved for a nonlinear elastic deformation under monotonic constant load with respect to time. For this, a constant fluid pressure of 20% of overburden pressure with respect to time is imposed on the caverns for 160 days. The evolution of displacement (u_x and u_y) and strain (ε_{xx}, ε_{yy}) obtained at multiple points of cavern (5– near cavern roof, 85 – side wall of the cavern near of the roof, 106 - cavern wall near of the floor, 6/7/128 – centre of the domain as shown by centre arrow in Figure 4) are depicted in the Figure 5. Highest strain rate is observed at roof of the cavern while intermediate for side wall near to roof and floor and minimal at mid-plane of the domain. Very low displacement rates of the order of 10^{-2} and strain rates of the order 10^{-5} are observed at points close to the mid-plane of the domain (Figure 5).

In the second case, cyclic loading conditions are employed by assuming the cavern's fluid pressure to be a function of time. When excess renewable energy is produced, it is converted to green gas and stored in the subsurface. Depending upon the supply and demand of the energy, the gas is injected and produced from the cavern which results in the cyclic loading. A discrete step function is used that varies between the maximum (with P_{max} = 80%) and minimum (with P_{min} = 20%) pressure applied during cyclic loading depending upon the overburden pressure. Figure 6 displayed the variation of horizontal and vertical displacements with time for several nodal points on the cavern's wall under cyclic loading. The high peak value represents the instantaneous elastic response of the rock salt material after which a creep development for short period is indicated by a line whose slope gives the magnitude of creep strain rate. The higher the load, the steeper the creep strain line and higher the creep rate.

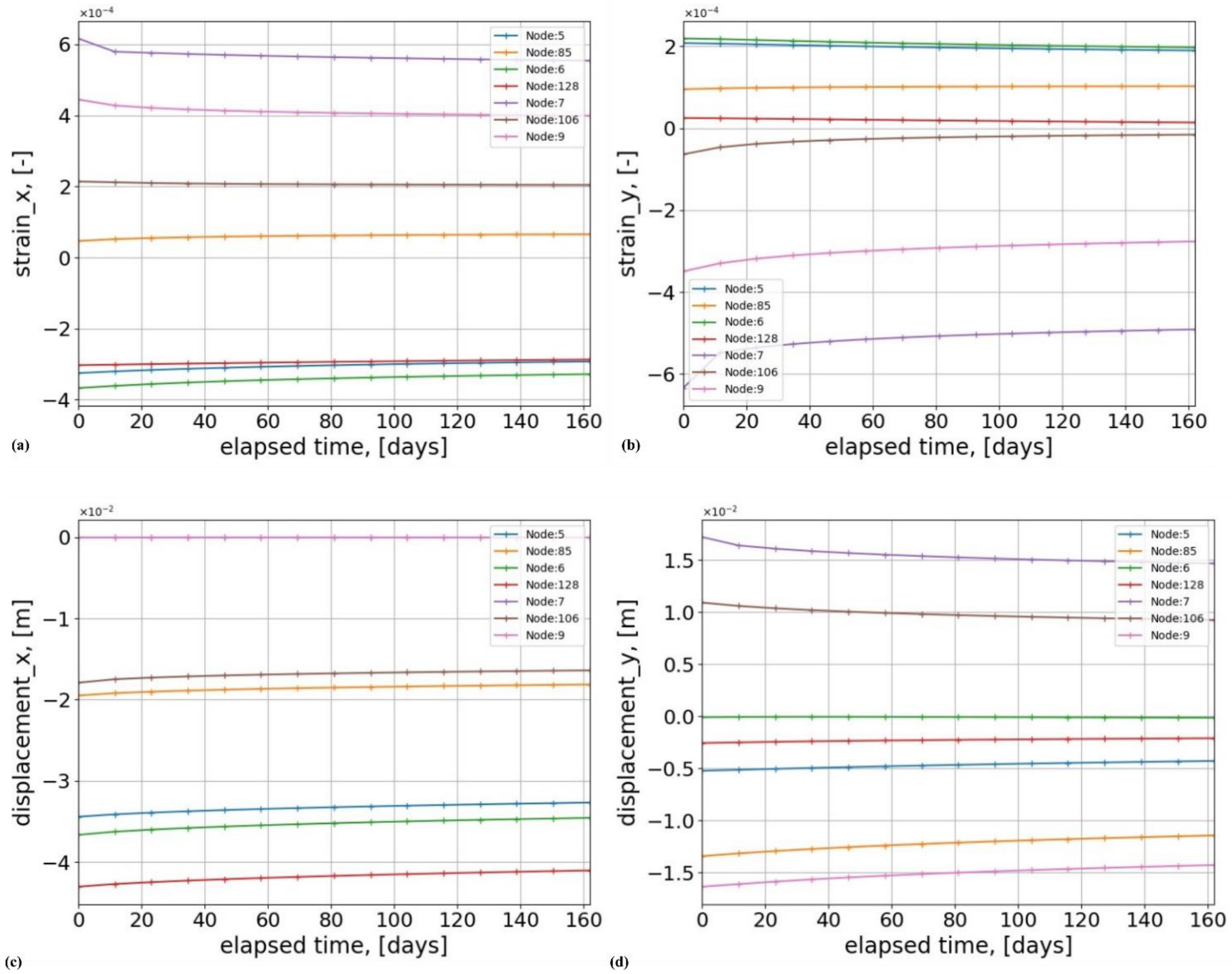


Figure 5. Creep under monotonic loading: (a, b) strain rate along radial and axial direction respectively and (c, d) horizontal and vertical displacement evolution with time respectively.

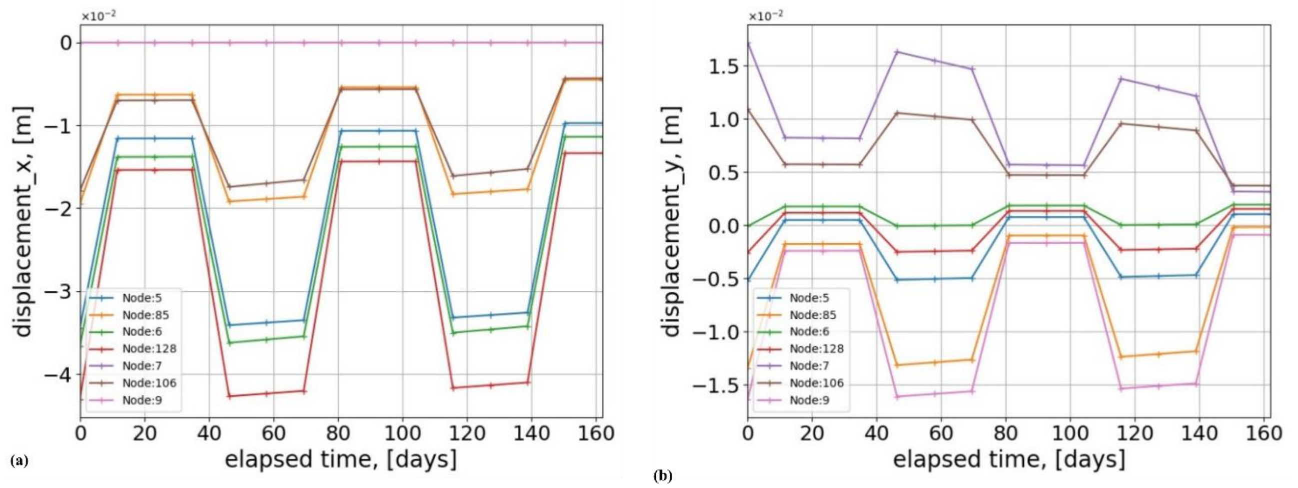


Figure 6. Creep under cyclic loading: (a) horizontal (u_x) and (b) vertical displacement (u_y) evolution with time.

Finally, the model is validated with experimental dataset from a uniaxial compression test conducted on a rock salt under 20 MPa axial loading condition. The axial deformation u_z in Figure & showed a reasonable match with the numerical simulation predicted profile. In addition, we are working on to validate the model's performance under axi-symmetric monotonic loading condition of salt with laboratory data which has been recorded for shorter duration of time. Further, numerically derived volume change will be linked with indirect gas transmission permeability test data.

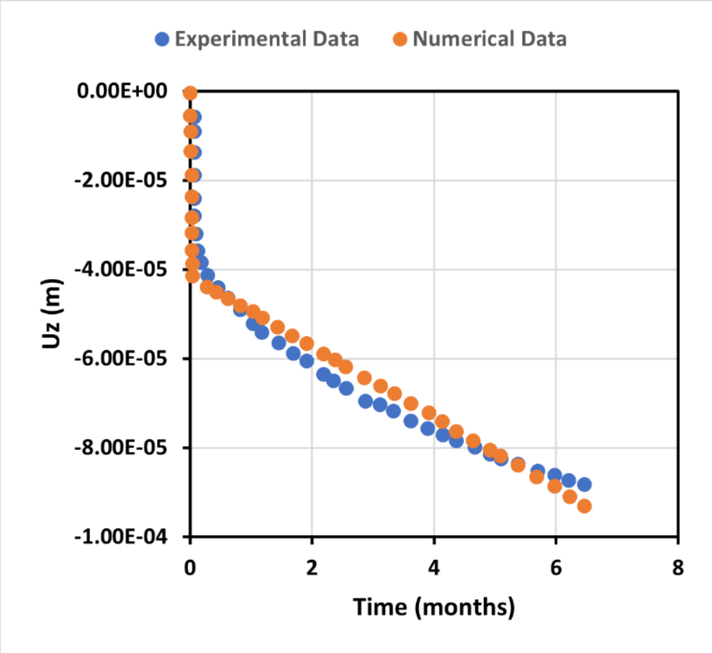


Figure 7 Comparison of axial displacement u_z evolution with time of rock salt from numerical simulation and laboratory data under uniaxial compression.

CONCLUSIONS

In this work, a geomechanical simulation model using a 2D finite element simulator is presented for understanding creep deformation of subsurface salt caverns employed for green energy storage. It is depicted in monotonic and cyclic loading test cases that creep is a very slow phenomenon which is insignificant for a short time scale. For longer year of operations, the effect of creep strain on the deformation of salt rock is become evident. Further work is ongoing to link permeability of the salt formation with creep deformation characteristics obtained from the current simulator.

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