Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

TIME-DEPENDENT BEHAVIOUR OF UNDERGROUND OPENINGS IN ROCK SALT

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Abstract. In rock engineering, the creep behaviour is critical for the structure's long-term stability and failure prediction. The creep is an important mechanism to consider when designing projects with extremely long lifespans, such as nuclear waste repositories. Therefore, in the present study, numerical investigations are carried out for the rock masses which exhibit creep. The creep behaviour of rocks is investigated by considering the viscoelastic constitutive law in the finite-element-based numerical tool. The cylindrical-shaped cavern in rock salt is investigated in this study concerning overburden depth, aspect ratio, and time. The results obtained from the investigations show inward displacement at the cavern crown and cavern wall. The uplift displacement of the heel is also observed in the analysis. The study showed that the increase in cavern's aspect ratio and overburden depth increase the cavern's wall, crown, and bottom displacement, which results in the reduction of the cavern dimensions with time. The findings suggest that unlined cavern displacement may be accurately predicted by using a power-law creep model.

Keywords: ABAQUS CAE, Creep, Overburden depth, Power-law, Unlined cavern

1 Introduction

Understanding rock's time-dependent behaviour can be quite useful in many aspects of rock engineering. The hard rocks such as gabbro and granite, exhibit low time-dependent strain, whereas soft rocks such as salt, potash, trona, coal, and alabaster project substantially higher instantaneous deformation [1]. The long-term stability of the rock mass depends upon the time-dependent nature of the rocks. This time-dependent phenomenon can be creep, swelling, consolidation, stress relaxation, and dilatancy. The creep plays an important role in designing projects with extremely long lifespans or projects built in rocks like rock salt [2]. The rock salt is ideal for the construction of a deep geological repository because of its unique ability to heal itself, indestructibility, low permeability, and availability [3-6].

Creep is one of the major mechanical characteristics of rock which affects long-term rock mass engineering stability. The creep of rock refers to the phenomena in which rock deformation increases over time when subjected to constant stress over a longer duration [7]. The classic creep curve has four components: an immediate deformation, a component of deformation decreasing with time termed "transient creep," a constant rate deformation or "steady-state creep", and an increasing rate deformation that leads to rupture called "tertiary creep" [8-11].

Creep in the material is determined by experimental, analytical, and numerical methods. Experimental methods include triaxial creep tests, creep testing machines, Brazilian test, and uniaxial compression tests [12]. In analytical methods, rheological models are adopted. These are used by combining various combinations of mechanical parts such as springs, dashpots, and sliders to account for the stiffness, viscosity, and strength of the in-situ rock. Numerical modelling is a fast-expanding discipline yet, the constitutive equations used to represent long-term rock rheology in nature are still questionable. Analysis of creep in underground structures has been simulated using various numerical software tools such as ABAQUS, ANSYS, LOCAS, FLAC3D, 3DEC, SAFEA, and others.

In the present study, axisymmetric FE analysis has been performed to simulate the long-term creep behaviour in the cavern using ABAQUS CAE. The rock mass is characterized by the viscoelastic power law creep model. The creep parameters such as stress component (*n*) and pre-factor (*A*) required for the analysis have been broadly studied in the past [13-18]. These viscoelastic properties were taken from the literature in the present analysis. The study aims at investigating the effect of overburden depth, time, and aspect ratio on the deformations at the crown, wall, and bottom of the cavern in rock salt.

2 Numerical Simulation

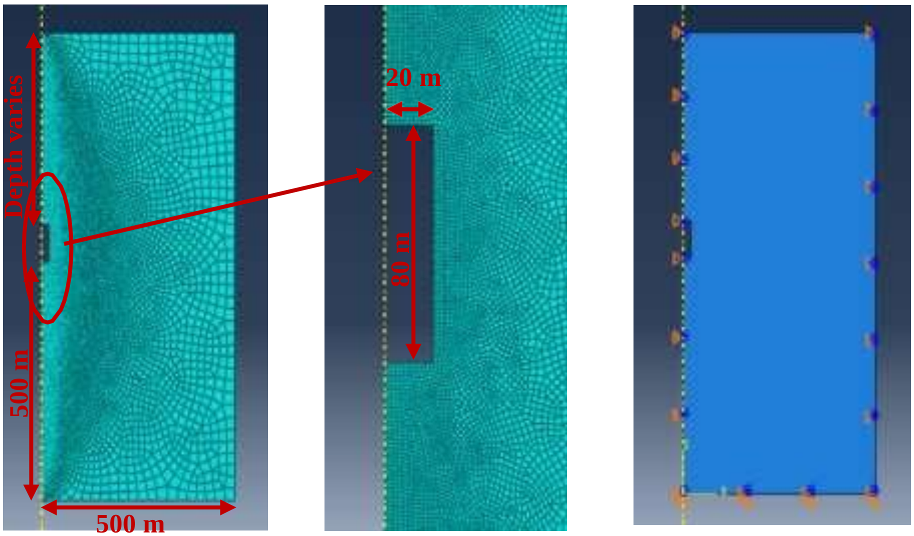
2.1 FE Model

The numerical modelling of cylindrical caverns represents four cases of varying aspect ratios of height to diameter i.e., 40 m x 40 m, 80 m x 40 m, 120 m x 40 m, and 160 m x 40 m. Moreover, each cavern's overburden depth varies from 200 m, 400 m, 600 m, 800 m, and 1000 m. The geometry of the cylindrical cavern model is shown in Fig. 1(a). The model boundaries are 2.5 times the height of the cavern. The mechanical and creep properties of rock salt used in the analysis are presented in Table 1.

Table 1. Parameters for salt cavern analysis [19]

Parameters	Rock salt
Density – ρ (Kg/m^3)	2200
Young's Modulus – E (GPa)	16.2
Poisson's ratio - v	0.3
Creep coefficient – A (Pa^{-n}s^{-1})	8.1 x 10^{-18}
Exponent - n	1.41
UCS (MPa)	14

A typical axisymmetric model with its boundary condition using Abaqus FEA is shown in Fig. 1(a). The finite element mesh is defined by 16000 and 45000 eight-nodded quadrilateral elements of *CAX8R*. Where *CAX8* stands for a quadratic axisymmetric element with 8 nodes and *R* represents reduced integration type. The area immediately surrounded by the cavern is very finely meshed to accurately represent the anticipated deformations, as shown in Fig 1(b).



(a) (b) (c)

Fig.1. Finite Element Model description (a) typical geometry with mesh (b) mesh around the cavern (c) boundary conditions of the geometry

The bottom boundary is constrained in all directions both the sides are constrained in the X direction, and the surface is free to move (refer to Fig. 1(c)). Mesh sensitivity analysis has been performed for element sizes of 20 m, 10 m, 8 m, 6 m, 4 m, 2 m, and 1 m respectively. The optimum results are obtained by considering 2 m and 1 m element sizes, therefore a 2 m element size is adopted for the analysis.

2.2 Modelling the creep behaviour

A non-linear viscoelastic power-law creep model is used in the present analysis. The power-law model accurately predicted the creep in rocks [20-22]. The stress-dependency of the creep rate as a function of stress component (*n)* and pre-factor (*A)* is represented as;

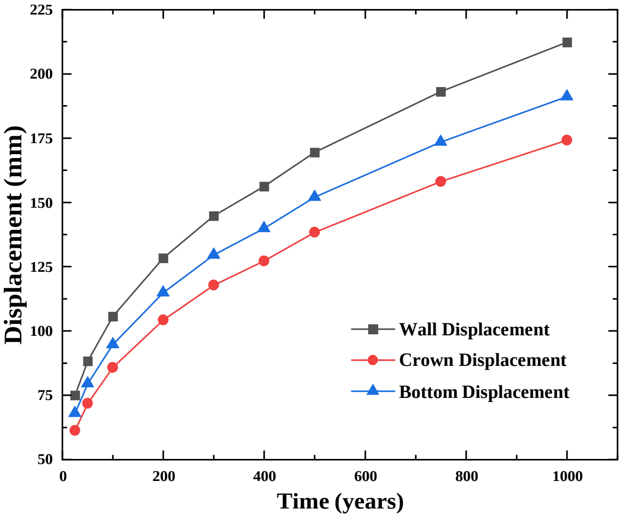
$$\dot{\varepsilon} = A\sigma^n \qquad (1)$$

where, $\dot{\varepsilon}$ = creep strain, σ = equivalent deviatoric stress, A and n are material constants derived from the log-log plot of stationary strain rate versus stress.

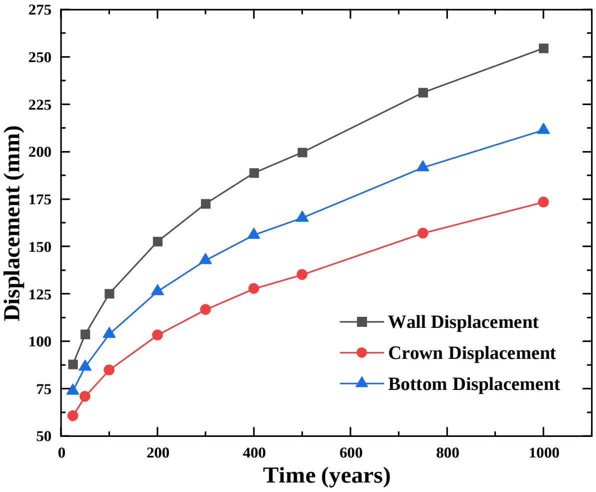
3 Parametric Study and Discussions

3.1 Effect of Time on Deformations

The present investigation is focused on the nuclear waste repository, therefore the deformations at the cylindrical cavern's wall, crown, and bottom are examined for the time duration of 25 to 1000 years. The obtained results are shown in Fig. 2 for the aspect ratios 2 and 4 i.e., 80 m x 40 m and 160 m x 40 m. It is observed from the figure that the displacement increases nonlinearly with time. It is noted that the rate of increase in deformation decreases with time due to the creep effect. It is also found that the wall displacement is maximum and crown displacement is minimum irrespective of aspect ratio. The deformation measured at the cavern wall is 212 mm and 254 mm for aspect ratios of 2 and 4 after 1000 years. Similarly, the deformation of the crown at these aspect ratios is 174 mm and 173 mm respectively. Whereas, the uplift at the bottom is 191 mm and 211 mm respectively. The graph shows that the crown displacement is the same for both aspect ratios.



(a)

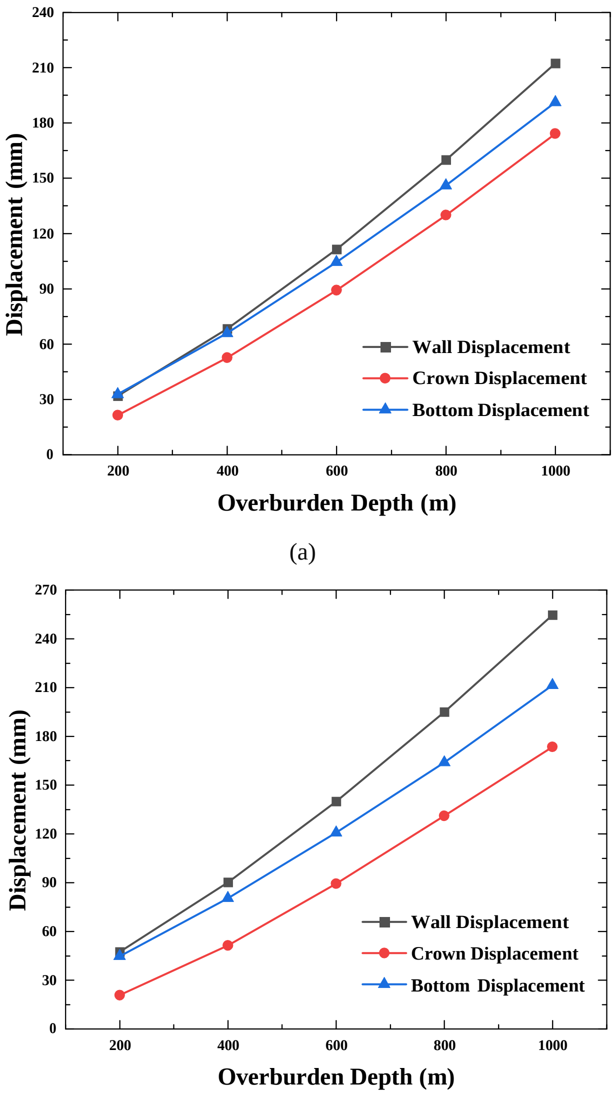


(b)

Fig.2. Variation of cavern deformation with time for (a) h/d = 2 and (b) h/d = 4

3.2 Effect of overburden depth

Understanding the effect of overburden depth on the overall cavern response and the extent of damage is of primary importance. Overburden depth has the maximum impact on the rock’s mechanical characteristics compared to any other parameters. Fig. 3 show the cavern's bottom, crown, and wall displacement after 1000 years for aspect ratios of 2 and 4. The closure rates in shallow caverns are much slower than in deep caverns. It is observed that the deformation of the cavern increases significantly with an increase in overburden depth.



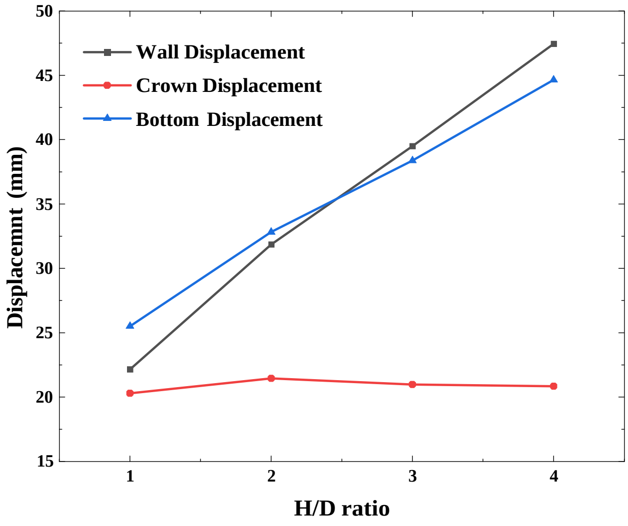
(a)

(b)

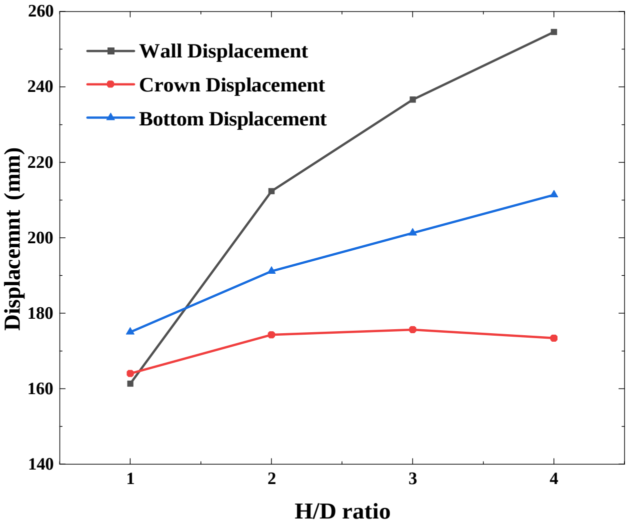
Fig.3. Variation of cavern deformation with overburden depth for (a) h/d = 2 and (b) h/d = 4

3.3 Effect of aspect ratio

Fig. 4 shows the variation of displacement with aspect ratios for a cylindrical cavern located at 200 m and 1000 m below the ground surface after 1000 years. A linear increase in bottom displacement and surge in wall displacement are noticed for the aspect ratio of more than 2. It is also found that the crown deformation is not affected by aspect ratio for the ratio greater than 2.



(a)

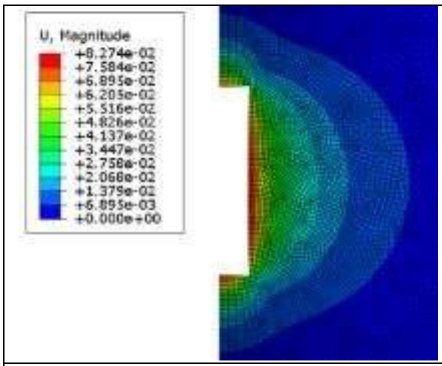


(b)

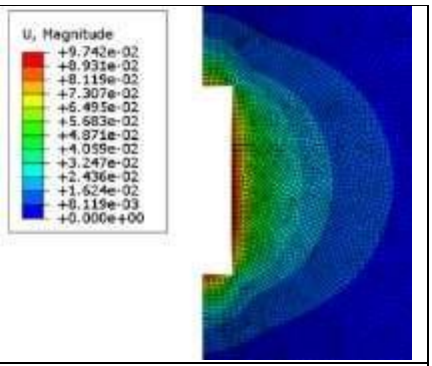
Fig.4. Variation of cavern deformation with aspect ratio for (a) Overburden Depth = 200 m and (b) Overburden Depth = 1000 m

3.4 Contour Plots

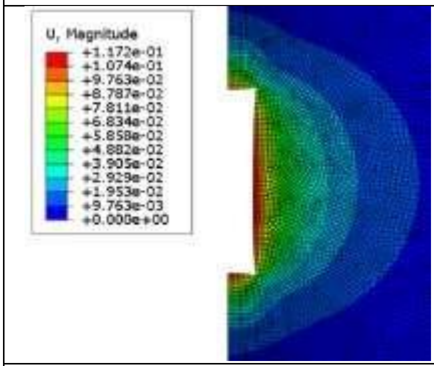
Fig. 5 shows the displacement contours for a cavern constructed in rock salt from 25 to 1000 years of period. It is observed that the squeezing of the cavern is increased with the life of the structure. It leads to shrinkage in the volume of the cavern. The maximum deformation observed at the wall is 82.74 mm for 25 years and increased to 236.8 mm at the end of 1000 years. The rate of displacement is higher in the initial years of the cavern lifetime. But as the lifetime of the structure increases the rate of displacement reduces.



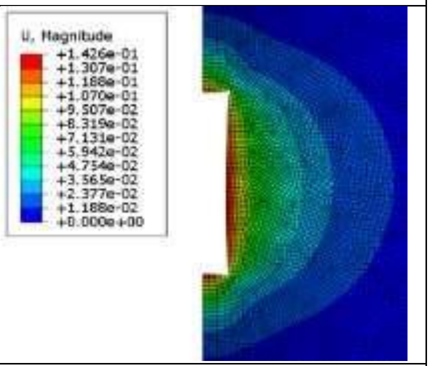
25 years



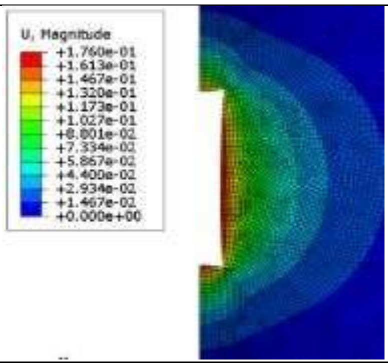
50 years



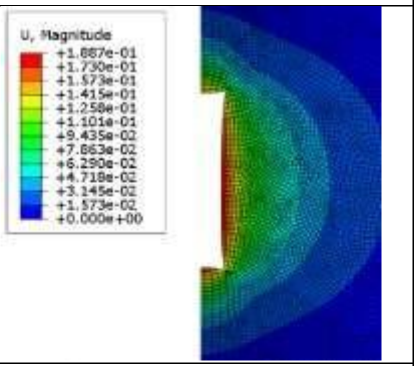
100 years



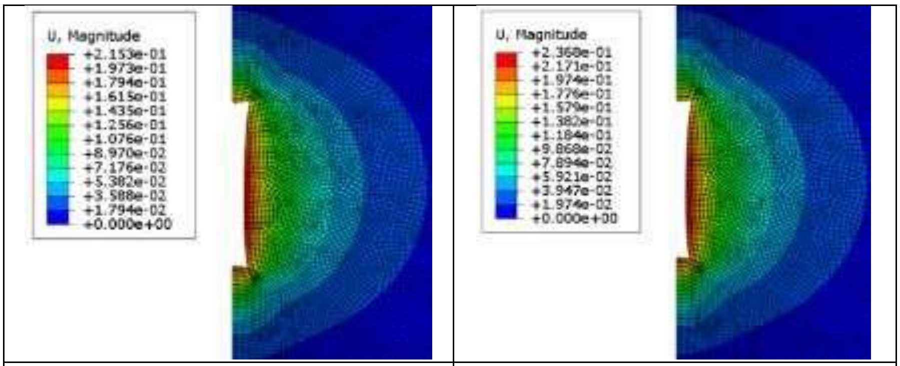
200 years



400 years



500 years



750 years

1000 years

Fig.5. Deformation contours of the cylindrical cavern in rock salt with varying lifetime

4. Conclusions

The major conclusions drawn from the present study are:

- Creep behaviour in the rock salt cavern is investigated by performing the axisymmetric finite element analysis in ABAQUS CAE.
- The creep displacements observed in the caverns at different locations (crown, bottom, and wall) increase linearly as the overburden depth increases. It is due to the applied geostatic stresses and surrounding confining pressure.
- The steady-state creep rate increases with an increase in geostatic stress (due to overburden depth) and is approximated by a creep power-law function.
- As the size (aspect ratio) of the cavern increases (at constant overburden depth), the observed bottom displacement increases linearly and wall displacements are higher as compared to the bottom. No change is observed in the crown displacements
- It is observed that creep displacements obtained in rock salt are at a higher rate in the initial years of cavern lifetime. But the rate of magnitude decreases as the lifetime of the structure increases.

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