Assessment of the creep behavior of siltstone for the Snowy 2.0 hydropower station using multistage uniaxial and triaxial creep tests

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ABSTRACT: The creep behavior of the siltstone rock type formations at the site of the Snowy 2.0 hydropower station was studied through multistage uniaxial and triaxial creep tests. The tests were conducted for up to 4 months to assess the effect of creep on the siltstone and to evaluate the impact on the short-term parameters. Samples were collected from boreholes located 650-850 meters beneath the surface from the Ravine Beds Unit formation and found to be composed of siltstone with interbedded sandstone (70/30% average). The siltstone was characterized by medium strength, a stiff matrix, and low porosity. The results of the creep tests showed negligible secondary creep deformations after full development of the primary stage. Additionally, the effect of confining pressure on creep behavior and deformation amplitude was also investigated. These tests provide valuable information to better understand the behavior of the siltstone rock type and its impact on underground excavation.

Keywords: multistage triaxial creep test, multistage uniaxial creep test, siltstone, hydropower station, creep behavior.

1 INTRODUCTION

The time-dependent behavior of rocks in underground structures is a critical consideration for the planning and construction of underground projects. In order to fully understand the time-dependent behavior of these rocks, laboratory testing methods such as triaxial and uniaxial creep tests are essential. Both triaxial and uniaxial creep tests apply a constant axial stress to rock samples over a period of time. In the triaxial tests a constant axisymmetric confining pressure is maintained. This allows to compare the effect of confining pressure on creep behavior and deformation amplitude.

When a rock is subjected to a uniaxial constant stress for long periods and then taken to failure, its failure stress may be lower than that determined by short-term tests. This is caused by subcritical crack growth and chemical reactions between the rock and geofluids, such as water, which increase microcrack density and lead to failure. Non-brittle creep processes under confined loading, however, may also lead to strengthening over time. To understand the time-dependent behavior of rocks, rock creep tests are conducted over practical periods of time, ranging from weeks to months, which is significantly shorter than the expected design life of an underground excavation.

When a rock sample is subjected to a differential stress variation, there is first an instantaneous elastic strain. If the stress is maintained the sample then undergoes three main phases of time dependent deformation known as primary creep, secondary creep, and tertiary creep. Underground excavations in rocks may experience increases in deformation with delayed failure over their design life, particularly in Mudrocks such as shales and siltstones, which are difficult to study and often exhibit complex behavior (Fabre & Pellet 2006). Even though design parameters can be adjusted arbitrarily to cater for the time dependent characteristics of rocks, comprehensive analyses based on laboratory creep tests are preferable to well understand the time-softening of rocks to ensure long term stability of underground openings (Bieniawski 1970). This study presents the long-term creep behavior and its effect on the short-term parameters of the siltstone formation where the Snowy 2.0 caverns will be excavated. Snowy 2.0 is a major Pumped Storage Hydropower project in Australia that involves the creation of two large underground caverns with a total volume of 590000 m3 at a depth of about 720 m .

2 GEOLOGY OF THE EXTRACTION SITE AND MACROSCOPIC STRUCTURE OF THE TESTED SPECIMENS

The project area is located in the southeast of the Lachlan Orogen in NSW. The two caverns in question are located in the early Paleozoic Ravine Beds formation, which is made up of shale, slate, siltstone, conglomerate, and shallow marine shelf deposits. The high quality rock cores in Figure 1 shows the lithological layers at the elevation of the cavern. The rock mass appears to be massive, constituted by an alternance of interlaminated to interbedded 70% siltstone and 30% sandstone with RQD values at or close to 100%. The representative mineralogical composition of the rock is: Quartz (40%), Sericite (35%), Muscovite (3%), Biotite (1%), Chlorite (15%), Carbonate (5%), Veins (1%).

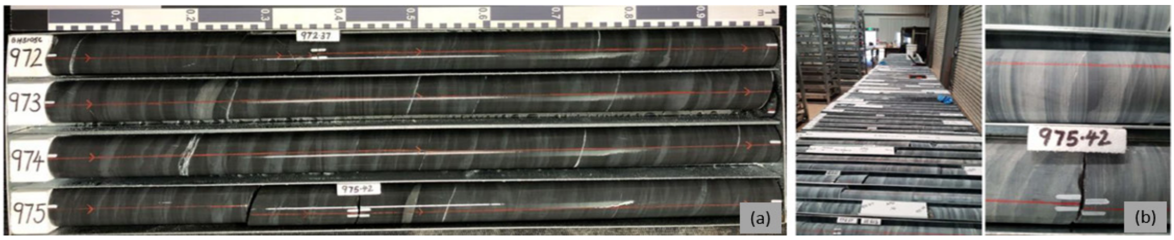

Figure 1. (a) Core box from 972 to 976 m depth; (b) Core box and detail with siltstone lamination/bedding visible. Mechanical induced discontinuities (as the ones due to handling) are identified with white marking.

3 TRIAXIAL CREEP TESTING EQUIPMENT AND SAMPLE PREPARATION

The long-term triaxial creep tests on rock samples were performed by the Institut für Gebirgsmechanik GmbH (IfG Leipzig) for laboratory tests in Germany. The laboratory prepared the rock samples for testing and determined their petrophysical properties. The time-dependent deformation was investigated using long term triaxial creep tests (TCC) and the maximum strength of the rock samples was determined using conventional triaxial compression tests (TC). The compressive creep deformation was explored in this study. Therefore, to characterize the siltstone behavior in stress state values that are present in the excavation boundaries, the experimental program was based on 71 UCS tests, 183 conventional triaxial tests, 15 uniaxial creep tests detailed in Abou Kheir et al. (2023), and 5 long term triaxial creep tests presented in Table 1.

3.1 Sample conservation conditions, preparation and testing procedure

The triaxial creep testing program was performed on 5 rock core specimens (D=40mm) that were wax-sealed after extraction and carefully transported the laboratory. They were gently cut to maintain a length to diameter ratio of 2 close to ISRM specifications (Ulusay 2015).

The fine-grained siltstone samples were extracted from a depth level between 711 m and 867 m. The triaxial creep tests were performed based on ASTM D7070-16,0 where a multistage stress loading approach was applied. As few creep tests were available in the literature for siltstone samples, the current testing procedure was a continuation of the uniaxial creep testing program.

The cylindrical samples were subjected to prolonged compression loading at constant temperature. Deformation measurements were carried out using three dial gauges around the samples, with accuracies of 0.001 mm. After a consolidation phase during 5 days under 5 MPa of hydrostatic stress conditions, keeping this confinement stress, 2 loading stages under differential stress conditions lasted 1 month each with differential stresses of 45 MPa and 75 MPa. At the end of the loading stage, a final unloading-stage back to hydrostatic conditions was performed during 5 days where the samples recovered their elastic deformations. To determine the short-term strength of the rock samples, the samples were removed from the creep test rigs but still installed in the triaxial cells and a conventional triaxial test was conduct.

Table 1. The list of samples used for triaxial creep tests and triaxial tests on samples from cavern depth.

Tests name	Extraction depth (m)	Lithology SLT/SST	Nb. of test stages	Test duration (days)	Failure stress [(1)] (MPa)
TCC1 & TC1	711.15	90%/10%	4	73	111
TCC2 & TC2	786.85	70%/30%	4	73	114
TCC3 & TC3	791.00	80%/20%	4	73	121
TCC4 & TC4	835.00	70%/30%	4	73	171
TCC5 & TC5	867.85	80%/20%	4	73	143

4 EXPERIMENTAL RESULTS

A comprehensive laboratory testing campaign was conducted on the samples to determine their short-term and long-term intact rock strength and deformability parameters.

4.1 Short-term strength and deformation

To determine the appropriate stress levels to be applied on the siltstone samples for the long-term creep tests, typical short-term uniaxial and triaxial tests under different confining pressures were initially performed for neighboring siltstone samples. These short-term strength and deformation results were then compared to the long-term strength and deformation data obtained from long-term creep tests. The results of the short-term tests were analyzed and presented in Table 2, where n is the number of tested samples, σ_3 is the confining pressure, $\overline{\sigma_p}$ is the average peak strength, $\overline{\varepsilon_p}$ is the average strain value at peak strength and $\overline{\mathrm{E}}$ is the average modulus of elasticity. The results show that with increasing confining pressure, the short term $\overline{\sigma_p}$, $\overline{\varepsilon_p}$ and $\overline{\mathrm{E}}$ values of siltstone increased, indicating that the rock becomes stronger, tougher, and stiffer at higher confining pressures.

4.2 Long-term strength and deformation from triaxial creep tests

In triaxial creep tests (TCC), the samples exhibit time-dependent deformation (creep strain) with an associated reduction in apparent modulus $\mathrm{E_T}$ at the end of the test. At 5 MPa confining pressure, the estimated value of the apparent modulus $\mathrm{E_T}$ at the end of the triaxial creep tests is equivalent to around 82% of their instantaneous Young modulus $\mathrm{E_i}$ and 71% of the average short-term Young modulus $\overline{\mathrm{E}}$, based on 5 triaxial creep tests (Figure 2 and Table 3).

Table 2. Short-term mechanical uniaxial and triaxial parameters for siltstone samples.

n	σ_3 (MPa)	$\overline{\sigma_p}$ (MPa)	$\overline{\varepsilon_p}$ (10^{-6})	$\overline{\mathrm{E}}$ (GPa)
71	0	70	-	44
36	2	91	1908	50
36	5	109	2283	51
42	10	122	2613	52
39	20	157	3235	54
30	40	227	4566	56

Table 3 presents the properties related to the creep curves in Figure 2: σ_1 is the axial applied stress at first stage; σ_3 is the applied confining pressure; ε_c is the creep axial deformation; Ei is the instantaneous modulus that refers to the initial response during loading; E_T is the apparent modulus that refers to the total "static" response of the sample at the end of the creep tests before failure.

Table 3. Summary of triaxial creep test results for siltstone samples with 45 MPa differential stress.

Test name	σ_3 (MPa)	σ_1 | σ_p | Ratio (MPa)	Duration (days)	ε_c (x 10-6)	E_i (GPa)	E_T (GPa)	$(E_i - E_T) / E_i$ (%)
TCC1	5	50 | 111 | 45%	29	312	30	25	17%
TCC2	5	50 | 114 | 43%	29	295	42	33	22%
TCC3	5	50 | 121 | 41%	29	245	38	31	17%
TCC4	5	50 | 171 | 29%	29	141	74	60	19%
TCC5	5	50 | 143 | 34%	29	162	58	48	17%
Average values		50 | 132 | 38%	29	231	48	39	18%

At 5 MPa of confining pressure, the 5 triaxial creep samples (Table 3) have an average compressive strength of approximately 132 MPa (loaded at 38% of max. strength) compared to the average compressive strength of 109 MPa for standard triaxial tests in Table 2. The samples show a maximal creep axial strain of approximately 0.0231%, an instantaneous modulus Ei of 48 GPa and an apparent modulus E_T of 39 GPa compared to the short-term modulus of elasticity $\overline{\mathrm{E}}$ of 51 GPa.

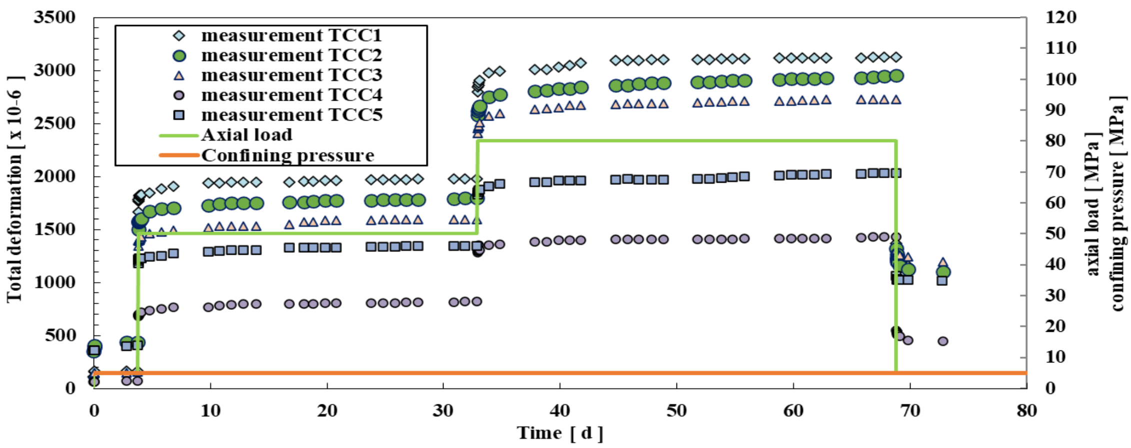

Figure 2. Multistage creep triaxial results (5 MPa confining pressure) with differential stress of 45 & 75 MPa.

4.3 Comparison between uniaxial and triaxial creep results

In Figure 3, the 5 triaxial creep tests are compared with the uniaxial creep tests (UCC) #9, 10 and 11 from Abou Kheir et al. (2023). The confining pressure effect is evident on the creep behavior.

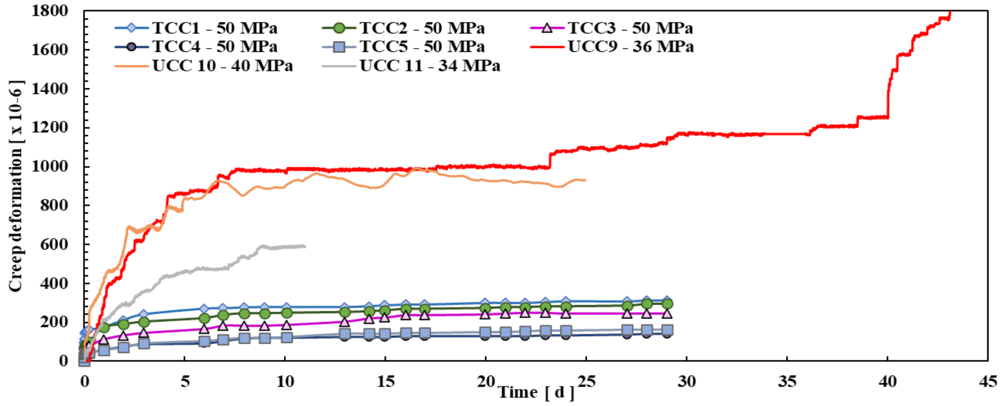

Figure 3. Comparison between 5 triaxial creep tests with 45 MPa differential stress and uniaxial creep tests from Abou Kheir et al. (2023). UCC: uniaxial compressive creep test. TCC: triaxial compressive creep test.

4.3.1 Primary creep investigation

The uniaxial and triaxial creep tests expressed both a primary creep behavior. UCC #10 and 11 showed primary creep equivalent to 0.1% of axial deformation at a loading ratio of 77% of their UCS. However, the triaxial creep samples deformed in average 0.023% at 38% of their compressive strength and 0.051% at 65%. This comparison between uniaxial and triaxial creep tests shows that the effect of confining pressure on creep behavior in siltstone is considerable, as it reduces the creep strain amplitudes. Additionally, the results suggest that at a constant confining pressure, the creep strain amplitudes are proportional to the ratio of applied load to compressive strength.

4.3.2 Secondary creep investigation

Uniaxial creep results of samples n.10, and n.11 along the 5 triaxial creep tests are used to study the existence of a secondary creep stage. The primary creep can be clearly identified in all the test as the creep strain rate decreases with time. For the uniaxial creep tests, the creep rates decreases to a negligible value that is lower than the existing background noise in the results. This rock has a very low porosity of 0.5 to 1.5% that leaves few spaces to a secondary creep to happen. However creep rates at the end of the triaxial creep tests are recorded with values between 0.63 με/d and 3.27 με/d and are judged to be in a continuous decrease based on the uniaxial tests. In conclusion, a secondary creep with steady strain rate cannot be assumed, and it is considered not present for this siltstone.

To estimate creep strains at longer timescale of the test, in Figure 4 the logarithmic empirical model is tentatively run in parallel with several rheological Burgers model for TCC2 triaxial creep test and then the models are extrapolated to approximately 365 days.

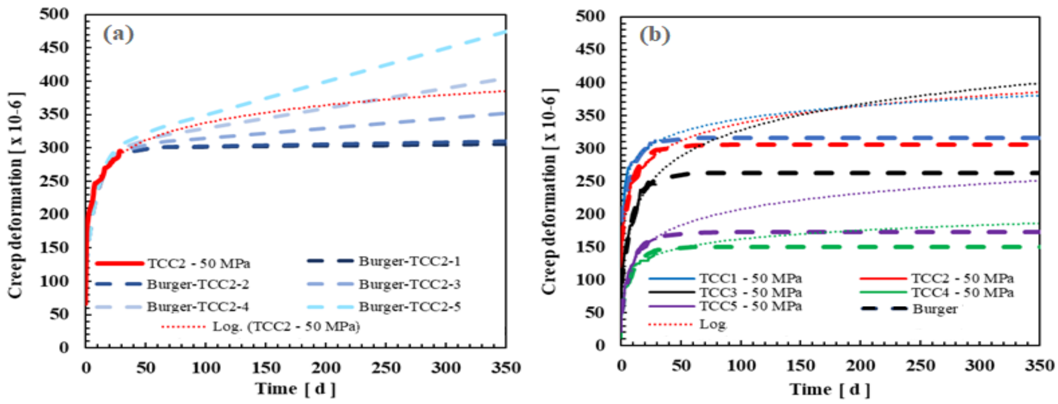

Figure 4. Comparison between (a) the empirical logarithmic curve and multiple rheological Burgers fits to TCC2 triaxial creep tests - all with $R^2 > 0.9$; and (b) the empirical logarithmic curves and Burgers fits to axial strain creep of each of the TCC triaxial creep tests. All the curves have an $R^2 > 0.9$.

Both a logarithmic and the Burger's model can be fit to data with components of primary and secondary creep, although the simpler logarithmic fit (2 parameters) will tend to overpredict long term strain bas on shorter test durations (Figure 4b). The Burgers model (4 parameters) is more flexible, mechanistically sound, and can provide better fit to the data, resulting in a more constrained long-term prediction, provided that secondary creep phase is adequately represented in the test duration. Figure 4a illustrates that the R^2 of the Burgers model is insensitive to a slight modification of its parameters but presents significant change in its extrapolation prediction. It is advised for future creep tests to load the samples up to a duration until a steady creep rate is well evidenced i.e. where the steady state represents more than half of the recorded creep data (Abou Kheir et al. 2023).

4.3.3 Tertiary creep investigation

The uniaxial creep test number 9 represents the tertiary creep of the siltstone rock type. It is compared in Figure 3 to the triaxial creep tests that didn't exhibit any brittle deformation in contrary to the uniaxial creep tests where 5 of 15 tests brittlely deformed. It is estimated that the confining pressure in the triaxial tests inhibits any brittle deformation of intact siltstone.

5 CONCLUSIONS

The article highlights the significance of comprehending the time-dependent behavior of rocks in underground structures, particularly in the context of the Snowy 2.0 project. It compares the results of long-term triaxial creep tests with uniaxial creep tests to provide insight into the primary, secondary, and tertiary creep behavior of the siltstone formation. The experimental program consisted of 71 UCS tests, 183 conventional triaxial tests, 15 uniaxial creep tests, and 5 long-term triaxial creep tests.

The results of the long-term triaxial creep tests on siltstone rock type samples revealed that the time-dependent behavior was influenced by various factors, including confining pressure, axial load to compressive strength, and loading duration, and presented different responses between loading and unloading stages. For modeling purposes, the rock mass creep behavior was assumed equal to the intact rock creep and was captured by reducing the Young modulus by 30% based on the triaxial and uniaxial creep results. This approach only accounts for primary creep and excludes secondary creep, tertiary creep, and the presence of joints. Considering the influence of the confining pressure on creep, it is recommended that future investigations mainly use triaxial creep tests as they better capture the in-situ stress regime.

A logarithmic empirical model is run in parallel with the rheological Burgers model concluding that the logarithmic model tends to overestimate any forecasted creep strains and the rheological Burgers model is more flexible and can provide better fit to the data, though it has more parameters and requires sufficient duration of data for adequate accuracy. It is thereafter advised for future creep tests to load the samples up to a duration until a steady creep rate is well evidenced.

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